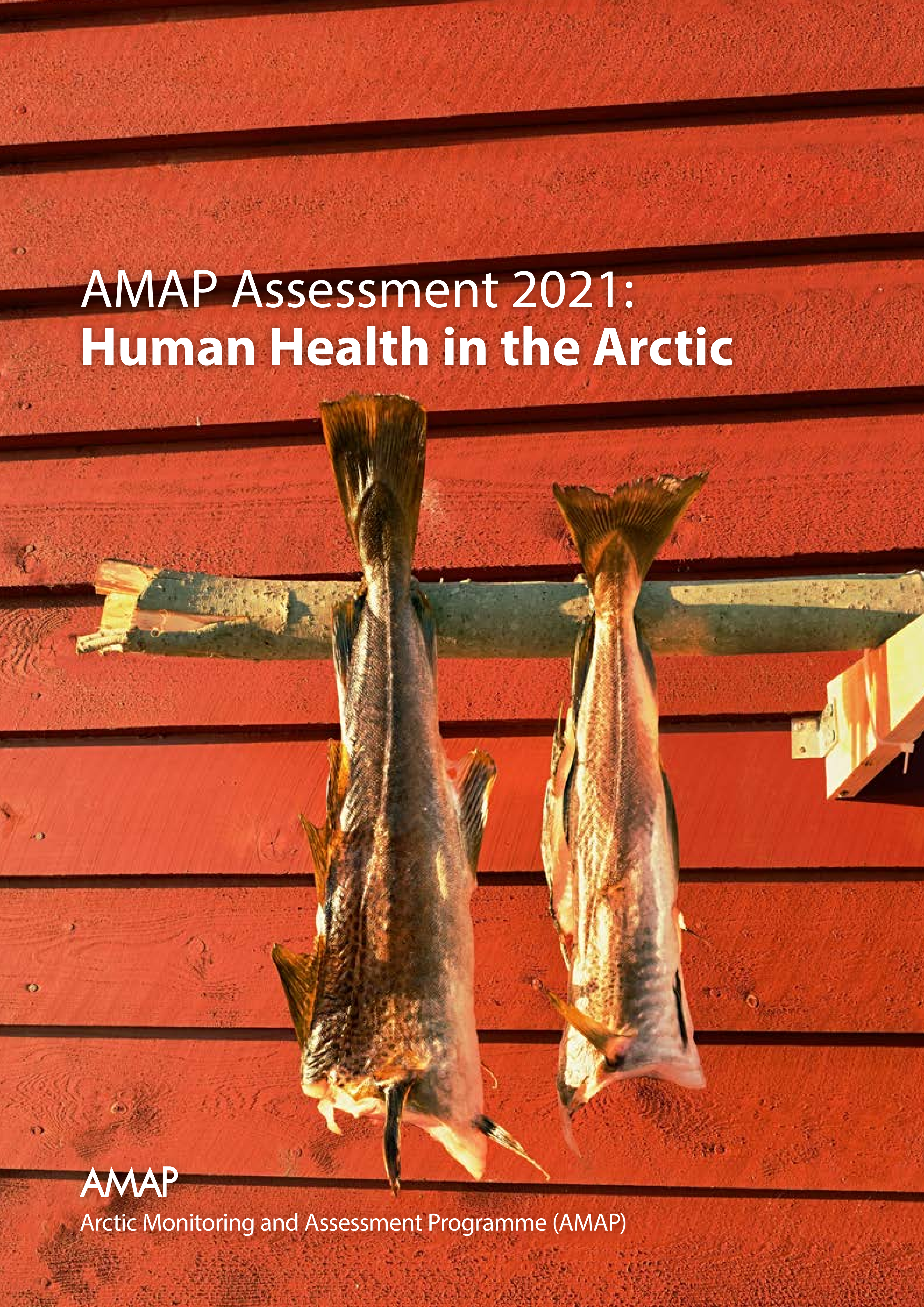
AMAP Assessment 2021: **Human Health in the Arctic**



AMAP

Arctic Monitoring and Assessment Programme (AMAP)

AMAP Assessment 2021: **Human Health in the Arctic**

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Arctic Monitoring and Assessment Programme (AMAP)
Tromsø, 2021

AMAP Assessment 2021: Human Health in the Arctic

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Preface

This assessment report presents the results of the 2021 AMAP Assessment of Human Health in the Arctic. This is the fifth AMAP assessment dealing with this issue in a sequence and updates the assessments delivered in 1998, 2002, 2009, and 2015.

The Arctic Monitoring and Assessment Programme (AMAP) is a Working Group under the Arctic Council. AMAP's work is directed by the Arctic Council. The AMAP mandate is established in the Arctic Environmental Protection Strategy (AEPS) and Arctic Council Ministerial Declarations and related reports of the Arctic Council Senior Arctic Officials.

The *AMAP Strategic Framework 2019+* describes the strategic direction for AMAP's work, covering mission and vision, guiding principles, strategic goals, and implementing the AMAP Strategic Framework 2019+. Under this framework:

> *"AMAP's mission is to monitor and assess the status of the Arctic region with respect to pollution and climate change issues by (i) facilitating and advancing the coordinated implementation of relevant circumpolar monitoring and research, (ii) documenting levels and trends, pathways and processes, and effects on ecosystems and humans, (iii) distinguishing human-induced changes from changes caused by natural phenomena, and (iv) proposing actions to reduce associated threats for consideration by governments and relevant organizations."*

AMAP's vision is to advance understanding of Arctic pollution and climate change issues, and to help transform Arctic knowledge into action. AMAP will achieve this vision by building on its legacy as an authoritative source of high-quality science-based assessments, comprehensive analyses, and public outreach products on a range of environmental issues for the circumpolar region. In the coming decades of anticipated environmental change, AMAP will continue to provide strong, policy-relevant recommendations, based on best available science and other relevant knowledge, to inform decisions regarding the protection and sustainability of Arctic ecosystems and inhabitants.

Access to reliable and up-to-date information is essential for the development of science-based decision-making regarding ongoing changes in the Arctic and their global implications. This report provides the accessible scientific basis and validation for the statements and recommendations made in the *Human Health in the Arctic 2021: Summary for Policy-makers* report that was delivered to Arctic Council Ministers at their meeting in Reykjavik, Iceland in May 2021. The Summary for Policy-makers presents the key findings of this assessment report and contains recommendations that focus on policy-relevant actions to address contaminant impacts on Arctic human populations, as well as proposals for filling gaps in knowledge and research priorities. The assessment lead authors have confirmed that both this report and its Summary for Policy-makers accurately and fully reflect their scientific assessment. All AMAP assessment reports are freely available from the AMAP Secretariat and on the AMAP website: www.amap.no, and their use for educational purposes is encouraged.

This assessment of Arctic human health impacts of contaminants and ongoing dietary transitions was conducted between 2017 and 2020 by an international group of over 70 experts. AMAP Human Health Assessment Group members, comprising the group of lead authors, are appointed following an open nomination process coordinated by AMAP.

An open nomination process coordinated by AMAP was also used to select international experts who independently peer-reviewed each chapter of this report and the report as a whole. Information contained in this report is fully referenced and based first and foremost on peer-reviewed and published results of research and monitoring undertaken since 2015. It also incorporates some new (unpublished) information from monitoring and research conducted according to well-established and documented national and international standards and quality assurance/quality control protocols. Care has been taken to ensure that no critical probability statements are based on non-peer-reviewed materials.

AMAP would like to express its appreciation to all experts who have contributed their time, efforts and data, in particular the lead authors who coordinated the production of this report. Appreciation is also due to the reviewers who contributed to the human health assessment peer-review process and provided valuable comments that helped to ensure the quality of the report. A list of contributors is included in the acknowledgements at the start of this report and lead authors are identified at the start of each chapter. The acknowledgements list is not comprehensive. Specifically, it does not include the many national institutes, laboratories and organizations, and their staff, which have been involved in various countries in human health-related monitoring and research. Apologies, and no lesser thanks, are given to any individuals unintentionally omitted from the list.

The support from the Arctic countries and non-Arctic countries implementing research and monitoring in the Arctic is vital to the success of AMAP. The AMAP work is essentially based on ongoing activities within these countries, and the countries that provide the necessary support for most of the experts involved in the preparation of the AMAP assessments. In particular, AMAP would like to acknowledge Canada and the Kingdom of Denmark for taking the lead country roles in this assessment and also thank Canada, Denmark, and Norway for their financial support to the human health assessment work. The contribution of the Inuit Circumpolar Council (ICC) to the preparation of this assessment is also greatly appreciated.

The AMAP Working Group is pleased to present this assessment to the Arctic Council and the international scientific community.

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Tromsø, August 2021

1. Introduction

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Summary

The 2021 Human Health Assessment Report is the fifth health assessment report to be published by the Arctic Monitoring and Assessment Programme. This report offers the current state of the science regarding environmental contaminants and human health in the Arctic using science-based data from regions across the circumpolar Arctic, together with some Indigenous perspectives. The report includes updates on information gaps identified in past reports (AMAP, 1998, 2003, 2009, 2015) including a focus on dietary transitions in the Arctic. The AMAP human health assessments assist decision- and policy-makers in understanding and addressing the impacts of contaminants on human populations in the Arctic.

1.1 Arctic Monitoring and Assessment Programme

The Arctic Monitoring and Assessment Programme (AMAP) was established in 1991 and has completed various reports addressing the status of the Arctic with respect to climate and pollution issues since its inception. AMAP's work is directed by the eight Arctic States in consultation with the Permanent Participants. The aim of this work is to document, monitor and assess pollution and climate change issues and trends in the Arctic, to identify actions to mitigate threats to ecosystems and humans, and to produce assessments and products to inform policy and decision-making based on the best available knowledge, which should include other knowledge forms (such as Indigenous Knowledge) as well as the findings of scientific research.

The work of the AMAP Human Health Assessment Group (HHAG) is made possible by active, collaborative participation from the eight Arctic Council member states: Canada, the Kingdom of Denmark (Greenland and the Faroe Islands), Finland, Iceland, Norway, Russian Federation, Sweden, and the United States of America, and the Indigenous Permanent Participants, such as the Inuit Circumpolar Council.

The HHAG produces assessment reports at regular intervals. These are written to address AMAP's mandate, which includes reporting on the status and trends of contaminants (Box 1.1), detecting emerging issues and potential risks, and recommending actions to reduce risk to Arctic populations (AMAP, 2019). By providing a contaminants and health perspective, the work of this group complements other AMAP assessments on radioactivity (AMAP, 2010), climate change and persistent organic pollutants (POPs; UNEP/AMAP, 2011), mercury (AMAP, 2011), obesity (Hansen et al., 2014), POPs (AMAP, 2016), biological effects of contaminants on Arctic wildlife and fish (AMAP, 2018) and contaminants of emerging Arctic concern (AMAP, 2017).

1.2 Approach

This assessment is not a risk assessment, but rather an update and analysis of research published since 2015. It follows in the series of regular AMAP Human Health Assessments dating back more than twenty years. It constitutes a compilation of current knowledge about the Arctic region, an evaluation of this information, and statements on key findings and recommendations. The assessment presented in this report was prepared in a systematic and uniform manner to provide a comparable knowledge base that builds on earlier work and can be extended through continuing work in the future.

Information contained in this report is fully referenced and based first and foremost on peer-reviewed and published results of research and monitoring undertaken since 2015. It also incorporates some new (unpublished) information from monitoring and research conducted according to well-established and documented national and international standards and quality assurance / quality control protocols.

The assessment is based on work conducted by a large number of scientists and experts from the eight Arctic countries, together with contributions from Indigenous Peoples' organizations. Much of this work has been facilitated by the establishment

Box 1.1 Contaminants of concern in the Arctic fall into three main groups

Persistent organic pollutants (POPs): Chemicals that are listed under the Stockholm Convention based on evidence of their environmental persistence, bioaccumulation, long-range transport, and toxicity. Their presence in the Arctic mainly stems from long-range transport. Examples include pesticides (e.g., DDT) and industrial chemicals such as flame retardants (e.g., PBDEs) or surface protectants (PFOS, PFOA).

Metals: Examples include lead, mercury, and cadmium.

Chemicals of emerging Arctic concern: A large group of chemicals that are not currently (as of 2020) listed under the Stockholm Convention but have been recognized as a potential concern based on their documented occurrence in Arctic ecosystems. Most are current-use chemicals that are largely unregulated, and some are alternatives for banned chemicals. Some are found in consumer products and their presence in the Arctic is likely to originate from both long-range transport and local sources within the Arctic. Examples include PFASs not already listed under the Stockholm Convention, current-use pesticides (CUPs), and organophosphate esters (OPEs).

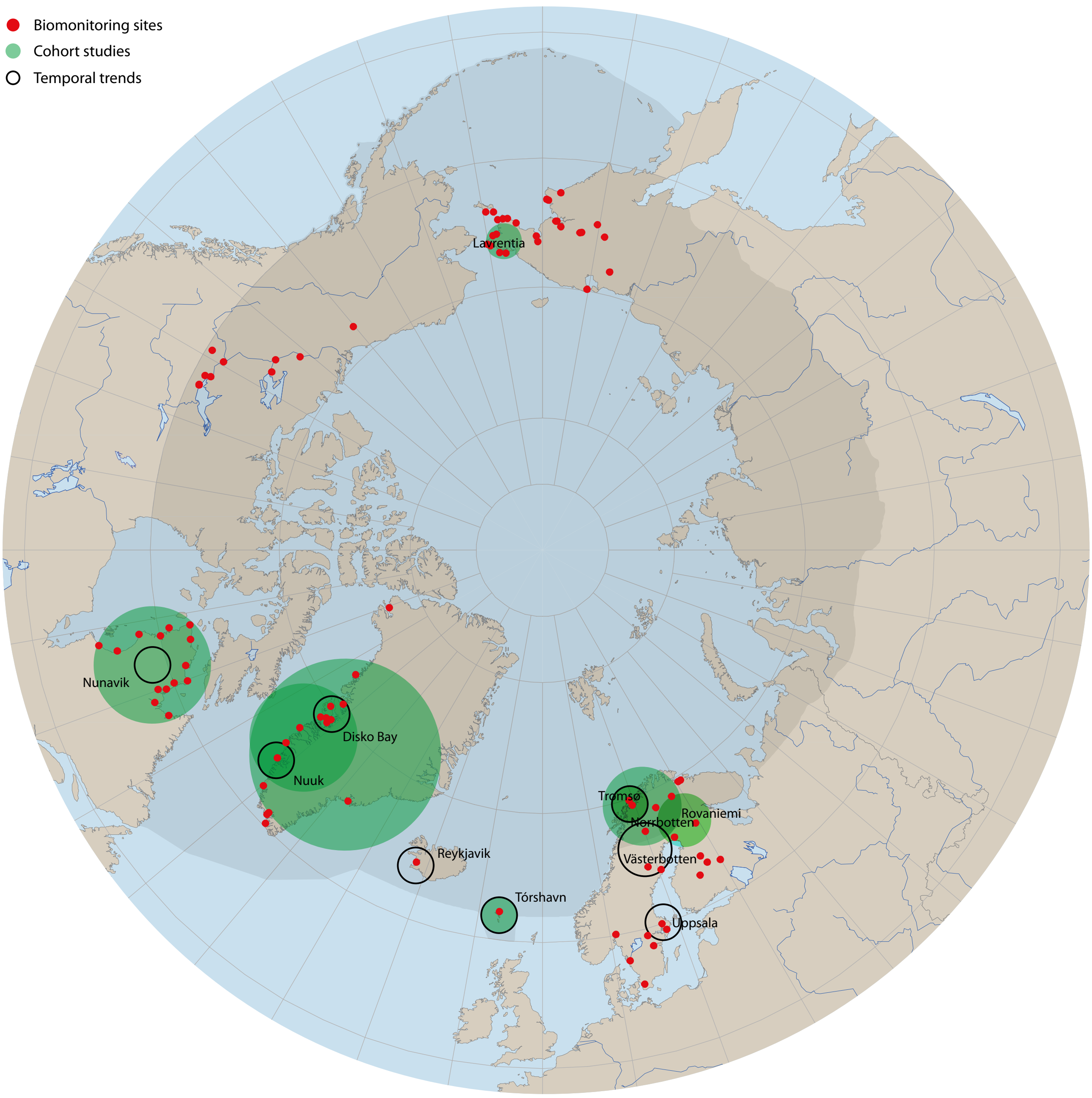

Figure 1.1 Location of recent and ongoing blood monitoring and human cohort studies in the Arctic.

of cohort studies (see Figure 1.1). These studies, described in Box 1.2 and Table 1.1, contribute to results reported throughout the assessment. Cross-sectional studies, surveys and regional studies with a focus on Arctic Indigenous populations are also described in this table and reported on throughout the assessment. Contaminants addressed in this assessment are listed in Annex 1. For an overview of these contaminants and their properties, the reader is referred to other sources of information (e.g., Health Canada, 2019; UNEP, 2019; AMAP, 2020; HMB4EU, 2020).

Terminology varies across the Arctic regions, particularly with respect to describing food such as hunted animals and plants gathered from the land. In this assessment, the terms 'traditional food', 'country food', 'traditional country food', 'subsistence foods' and 'local foods' are all used. These terms may be interchangeable in some regions, but have distinct meanings in others. Even within regions, different definitions may be preferred by different groups. Therefore, for this assessment, all phrases are used, with the choice of terminology determined by the context of the results being described. This is discussed in Chapter 2.

1.3 Background

Since 1998, AMAP human health assessments have provided evidence for contaminant levels and trends in the Arctic. The first assessment provided some of the first regional comparisons of quality assured data and reiterated the importance of sustaining reliable biomonitoring programs in the Arctic (AMAP, 1998). Since then, assessments have helped to identify differences in exposures and exposure levels across the Arctic, but have also continued to highlight the importance of country foods to the diets of Arctic inhabitants and Indigenous populations.

Box 1.2 Overview of human health cohorts, surveys and regional studies in the Arctic

This box provides an overview of human health studies in the Arctic, with an emphasis on key details of the study design, such as year established, sample size, as well as the contaminants measured in the study. Additional details of each study are presented in Table 1.1.

Canada

The **Nunavik Child Development Study (NCDS)**, a prospective mother-child cohort study in Nunavik, Canada, studied the effects of contaminants on child health and development by following up a sample of mother-child dyads prenatally and postnatally exposed to high levels of POPs and heavy metals. There were several phases. The Nunavik Cord Blood Monitoring Program analysed cord blood from almost all Nunavik infants born between 1994 and 2001. The first follow-up tested 190 infants at 6 and 12 months of age. Between 2005 and 2010, 294 eleven-year-old children were tested. The cohort is currently being followed-up at adolescence (2013–2016). The analytes include chlorinated pesticides, PCBs, older PFASs, Hg, Pb, Se, PUFAs and total plasma lipids.

The **Maternal Temporal Trends (MTP)** project was a biomonitoring study that took place between 2007 and 2013 to study changes over time in the exposure of pregnant women in Nunavik to POPs and metals. A total of 247 pregnant women were recruited over that period. Analytes included Hg, Pb and Se, and chlorinated pesticides, PCBs, PFASs, PUFAs and total plasma lipids.

The **Nutaratsaliit Qanuingisiarningit Niqituinnanut (NQN)** – Pregnancy Wellness with Country Foods project was developed in association with the MTP biomonitoring project to examine temporal trends in POPs and metal exposure among pregnant women in Nunavik; to improve understanding of pregnant women's exposure to contaminants from traditional foods; to determine seasonal variation in Hg exposure and traditional food intake responsible for these variations; and to support the development of local clinical interventions aimed at mitigating Hg exposure while promoting country foods for enhancing the nutritional and food security status of pregnant women and children. A total of 97 pregnant women were recruited between October 2016 and March 2017 from 14 Inuit communities in Nunavik. Analytes included chlorinated pesticides, PCBs, PFASs, Hg, Pb, Mn, Se, selenoneine, PUFAs, and iron status.

The **Santé Québec health survey** among the Inuit of Nunavik in 1992 was the first survey to assess concentrations of POPs and metals among Inuit in Nunavik. Adults (between the ages of 18 and 74 years) were recruited, and concentrations of heavy metals and POPs were measured in blood samples from 492 individuals. Plasma samples were analyzed for PCBs and chlorinated pesticides, whereas blood samples were analyzed for Hg, Cd, and Pb.

The **Qanuippitaa? 2004 Nunavik Health Survey** conducted between August and October in 2004 involved 917 adults from 14 communities in Nunavik, Canada. Analytes included the POPs, Hg, Cd, Pb, Se and PUFAs measured in the 1992 Santé Québec Health Survey plus new halogenated hydrocarbons such as PBDEs, PFOS, hydroxy-PCBs, methyl-sulfone PCBs and chlorophenols.

The **Qanuilirpitaa? 2017 Inuit Health Survey** was conducted between August and October 2017, and designed as a follow-up to the Qanuippitaa? 2004 Inuit Health Survey. The 2017 survey recruited a total of 1198 Inuit adults (18 years of age and above) from 14 Inuit communities of the Nunavik region, as well as 127 Inuit youth (16 to 17 years of age) unlike the previous survey. The survey collected information on indicators and determinants of physical, mental and community health, and included an environmental health component involving sample analysis for chlorinated pesticides, PCBs, PFASs, Hg, Pb, Se, selenoneine, and PUFAs.

The **International Polar Year (IPY) Inuit Health Survey** was a comprehensive study examining links between contaminant intake, body burden, and various health outcomes. Blood samples from 2172 participants from 36 communities in Nunavut, Nunatsiavut, and the Inuvialuit Settlement Region in Canada were analyzed for heavy metals (e.g. Hg, Cd, Pb, Se) and POPs (e.g. PCBs, DDT, DDE, toxaphene, chlordane, PBDEs).

The **Northwest Territories Mackenzie Valley Regional Biomonitoring Study** conducted between 2016 and 2018 involved nine First Nations communities from the DehCho and Sahtú regions of the Northwest Territories in Canada. Blood samples from adult men and women (over 18 years of age) were analyzed for POPs (n=246) and metals (n=250). Urine samples were analyzed for metals (n=180).

The **Yukon Contaminants Biomonitoring Study** was conducted in Old Crow, Yukon to determine POPs and metal levels in Gwich'in people. The study involved 77 adult community members from Old Crow, and samples were collected to analyze POPs and metals in blood (n=54) and metals in urine (n=47).

Greenland

The **Greenland Child Cohort IVAAQ** involved 403 mothers and newborn children in western Greenland and took place between 1999 and 2005. Since then there have been several follow-up studies, including at 6 to 10 years of age. Analytes: POPs and heavy metals.

The **Adaptation to Climate Change, Environmental Pollution, and Dietary Transition (ACCEPT) project** used a Greenlandic mother-child cohort to explore exposure to environmental contaminants during pregnancy and the development of the fetus and child as well as health effects later in life in the Greenlandic population. It formed a part of the FETOTOX international network of mother-child cohort studies (Norway - the MISA study, Denmark, and Shanghai, China). In total, 587 pregnant women were enrolled in the ACCEPT cohort over the period 2010–2015. Analytes: heavy metals (e.g. Hg and Pb), POPs and chemicals of emerging Arctic concern.

There have been five **Health Studies in Greenland** of the adult Indigenous population since the early 1990s: 1993–1994 (1728 participants, 264 adults gave blood), 1999–2001 (1317 participants), 2005–2010 (3011 participants), 2014 (2102 participants, ca. 500 gave blood) and 2017-2019 (2539 participants). The analytes were Hg and POPs.

The **INUENDO cohort** was established in 2002–2004 and used to study the effects of persistent organochlorines in the diet on human fertility. It involved 1400 pregnant women from Greenland, Poland and Ukraine and 600 fertile couples from Sweden. Analytes included PCB153 and *p,p*'-DDE.

The **Climate Change, Environmental Contaminants and Reproductive health (CLEAR) project** modeled climate change effects on long-range contaminant transport and used cross-sectional studies on males and females to study reproductive health, with a follow-up study on childhood growth and development at 6–9 years of age in a cohort of about 1400 mothers, fathers and offspring from Greenland, Poland and Ukraine. The original INUENDO cohort was established in 2002–2004 and the CLEAR follow-up on the children was in 2009–2012. Analytes: PCBs, DDE, PFASs, PBDEs, phthalates, bisphenol A, Hg, Pb, Cd.

Faroe Islands

The Faroe Islands birth cohorts were used to examine contaminant exposure in relation to neurobehavioral development and immunological parameters. **Birth Cohort 1 in the Faroe Islands** includes 1022 singleton births from 1986–1987. Analytes: POPs, MeHg, Se, PFASs. Follow-up studies at ages 7, 14, 22 and 28 years. **Birth Cohort 2 in the Faroe Islands** was established in 1994–1995 and included 182 singleton births from consecutive births in Tórshavn. Analytes: POPs, MeHg, Se. **Birth Cohort 3 in the Faroe Islands** was based on 656 consecutive births in Tórshavn between 1997 and 2000. Analytes: POPs, MeHg, PFASs. Children were examined at ages 11 and 18 months and age 5, 7 and 13 years. **Birth Cohort 5 in the Faroe Islands** from 2007 to 2009 had a total number of 501 mother-child pairs. Analytes: POPs, MeHg, PFASs. The children were examined at age 18 and 42 months and 5 years.

The **septuagenarian cohort of the Faroe Islands** was used to examine the health status of 713 Faroese residents aged 70 to 74 years via their lifetime exposure to marine pollutants. Analytes: POPs.

Type 2 Diabetes in middle-aged Faroese residents was studied in 3324 people from three different groups: 460 with diabetes or prediabetes in a cross-sectional population-based study in 2007–2008; 577 from the septuagenarians cohort; and 2187 randomly selected adults aged 40 to 70 years.

Norway

The northern Norway mother-and-child contaminant cohort study – **The MISA study** – was a cross-sectional study with longitudinal aspects that explored links between contaminant exposure and diet. 515 women were enrolled in early pregnancy between May 2007 and June 2009, with 391 completing the study protocol. The study continued from 2017 and is still ongoing. Biological samples are obtained in the second trimester of pregnancy, just after delivery, and six weeks postpartum. The matrices analyzed are whole blood, urine, hair, cord blood and meconium. Analytes include organochlorines (*p,p*'-DDE, HCB, *trans*-Nonachlor, *cis*-Nonachlor), hydroxylated polychlorinated biphenyls (PCB99, PCB101, PCB118, PCB138, PCB163, PCB153, PCB156, PCB170, PCB180, PCB183, PCB187, PCB194) and selected essential and toxic elements (As, Cd, Co, Hg, Pb, Cu, Mn, Mo, Se, Zn). 'MISA 2' will focus more on nutritional aspects, as 'MISA 1' revealed a serious lack of some trace elements in the diet and low levels of the same elements (e.g., iodine) in samples from the delivering women.

The Tromsø Study was a population-based health survey initiated in 1974 to investigate the reasons for high mortality due to cardiovascular disease in northern Norway. Several additional surveys have since taken place. 40,051 people participated in at least one survey and 15,157 participated in three or more surveys. Changes on an individual basis were examined in 54 men that had participated in all surveys. The matrix analysed was serum. Analytes comprised a range of PCBs and organochlorine pesticides (chlordanes, HCHs, HCB, *p,p*´-DDT and its metabolites, toxaphenes).

Sweden

The Northern Sweden **MONICA Study** is based in the two northernmost counties of Sweden, Norrbotten and Västerbotten. Health surveys have been conducted at roughly five-year intervals since 1986. 11,800 randomly selected people aged 25 to 74 years have taken part, with 3500 involved in more than one survey. The matrices analyzed are whole blood, erythrocytes and urine for a proportion of the participants. The following organic pollutants have been analyzed in urine for a proportion of participants: phthalate metabolites, bisphenol A, bisphenol F, triclosan, pesticides (3-phenoxynenzoic acid, trichloropyridinol), 1-hydroxypyrene. Pb, Cd and Hg in blood have been followed since 1990.

The Västerbotten Intervention Program began in 1985. Participants in Västerbotten are invited for counseling on lifestyle modifications in the year they turn 40, 50 and 60 years old. By April 2018, 107,500 people had participated with 41,900 people participating more than once. Blood samples have been stored for potential prospective studies of environmental contaminants.

Riksmaten Adolescents was a school-based dietary survey in Sweden, with students in grades 5, 8 and 11 (mean ages 12, 15 and 18 years) recruited from representative Swedish schools in 2016–2017. A total of 3477 respondents participated in the dietary study. 40% of the schools were randomly selected, and 1305 of the 2377 invited students participated in a blood and urine sampling component of the survey. Complete dietary information and valid blood and urine samples were available from 1105 of those students.

The Swedish Food Agency has conducted recurrent sampling of breastmilk and blood from primiparous women in Uppsala since 1996, in the so-called **POPUP study** (Persistent Organic Pollutants in Uppsala Primiparas). Samples are collected three weeks after delivery and the main aim of the study is to investigate temporal trends of exposure to POPs among pregnant and nursing women.

Finland

The aim of the **Northern Finland Birth Cohort** study was to promote the health and wellbeing of the population in the provinces of Oulu and Lapland. 12,058 live-born children were born into the cohort in 1966 and 11,637 were still alive in 1997. Data were collected by questionnaire, from hospital records, registers and databases, and by interview and clinical examination at birth, age 1 year, 14 years and 31 years. 250 whole blood samples from the age 31 years sampling were analyzed for toxic and essential elements (As, Cd, Co, Hg, Pb, Cu, Mn, Mo, Se, Zn) to establish levels in persons born and living for the last five years in the eastern and western part of Lapland.

Russian Federation

The **Chukotka dietary and exposure study** was a cross-sectional study examining POPs (PCBs, DDTs, HCB, HCHs, chlordanes, toxaphenes, mirex), Hg, Cd and Pb contamination of different local foods and indoor materials in 2001–2003 in Chukotka (Russia). Exposure to the same contaminants was evaluated in human serum (POPs) and whole blood (metals) in Indigenous People from coastal and inland regions. The 218 participants ranged in age from 15 to 81 years and included men (38 samples), women (54 samples) and pregnant women (126 samples).

The **Chukotka birth cohort study** (2001-2003) was the prolongation of the **Chukotka dietary and exposure** study. Blood was sampled from 126 Indigenous pregnant women (68 coastal, 58 inland) and analyzed for POPs and metals to investigate links between pollutant exposure and reproductive effects. Effects include adverse birth outcomes (premature birth, low birth weight, stillbirth, congenital malformations), sex ratio of newborns, and in women, earlier menarche, shortened menstrual cycle and prolonged bleeding.

A follow-up **Chukotka coastal mother-child study** took place in 2007 on the basis of the Chukotka birth cohort study (2001-2003) to examine levels of the same POPs and metals in blood from 17 mothers and cord blood from the corresponding 17 babies born 2001–2002. Levels were compared with those in blood from the same women and their five-year old children in 2007 to study the influence of breastfeeding on maternal POPs serum levels and the link between children's POPs blood levels and the frequency of infectious diseases.

The **Kola Lapland POPs and diabetes mellitus study** became possible in 2006, when under the framework of the International Barents Secretariat project 'Revealing the hidden diabetes mellitus in Lovozero district of Murmansk Oblast', 4359 residents of Kola Lapland in Murmansk Oblast were interviewed and had their blood glucose levels analyzed. This comprised 2736 rural and 1623 urban, including Indigenous Saami (694), Komi (910), and Nenets (80). Data collected in the Lovozero district of Murmansk Oblast as part of the Russian Arctic PTS study (2001–2003) on blood POPs levels in Indigenous residents (83 residents had blood sampled for PTS analyses) made it possible to compare the results of both projects.

The second assessment (AMAP, 2003) had an emphasis on new epidemiological approaches to examine the combined effects of environmental contaminants, such as mercury, on the health of Arctic populations, including interactions between nutrients and contaminants from country foods. The database on contaminant trends and levels in country foods continued to grow and low-dose health effects were reported. A successful Faroese public health messaging campaign about reducing the burden from mercury was described. This assessment highlighted that most Indigenous populations in circumpolar regions of the Arctic had significantly lower levels of health than non-Indigenous populations.

In the third assessment (AMAP, 2009), there was a focus on health outcomes and the genetic background of the Arctic populations. New evidence indicated that health effects could be observed at lower levels of POPs and metals than previously reported. The potential for climate change to affect contaminants was discussed and the need for more information was described. As a result of new data from Russia, the 2009 assessment was the first to include a comparison of all Arctic regions. Data echoed previous observations of high levels of POPs and metals in some populations, while the overall trend was towards declining levels in Arctic populations. However, the presence of compounds of emerging Arctic concern was noted. A change in dietary patterns in Arctic communities was also reported due to increased consumption of store-bought foods, and cultural and economic changes. This shift towards imported foods has significant health implications, and it was concluded that more research was needed to study the interactions between contaminants and health status (e.g., POPs and obesity). An emphasis was placed on the need for a partnership approach with communities when developing dietary advice, which must be culturally appropriate and locally relevant.

The fourth assessment (AMAP, 2015) documented a continued general decline in contaminant levels, but high levels above health guidelines were still observed in some Indigenous populations in the eastern Canadian Arctic and Greenland. More evidence of contaminants of emerging concern was presented. The health effects of contaminants on fetal growth and neurodevelopmental endpoints were reported, as well as a description of the possible mechanisms of effects of contaminants on human health. An overview of risk communication efforts across the circumpolar Arctic was presented, some of which were effective in helping reduce exposure to contaminants, but this came with the risk of a loss of cultural identity. It was also found that risk communication messages were complex to develop, difficult to disseminate, and easily misconstrued. In order to evaluate the success of risk communication messaging and to determine best practices, an evaluation of effectiveness in risk communication activities was suggested. A chapter was dedicated to climate change adaptation, and conclusions from the ArcRisk project (Arctic Health Risks: Impacts on health in the Arctic and Europe owing to climate-induced changes in contaminant cycling; arcrisk.amap.no) suggested that human exposure to contaminants will be affected more by changes in sources and activities in the Arctic than by increased long-range transport of contaminants to the Arctic. As in previous assessments, it was reiterated that a reduction in contaminants in the Arctic requires continued global risk management efforts.

Table 1.1 Human health cohorts, surveys and regional studies in the Arctic.

Country/Study	Primary source	Year(s)	Sample size	Population	Matrices	Corresponding section, AMAP (2015)
Canada						
NCDS	Weihe et al., 2016	1994-2001 2005-2010 2013-2016	<500	Children	Blood (maternal, child, cord), child hair	2.2.9
MTP	N/A	2007, 2011, 2012, 2013	<100 each	Pregnant Inuit women	Blood (maternal)	N/A
NQN	Littoral Chair Research Project, 2020	2016-2017	<100	Pregnant Inuit women	Blood (maternal), hair, urine	N/A
Santé Québec health survey	Jetté, 1994	1992	<1000	Adult Inuit (including pregnant women)	Blood	2.2.10
Qanuippitaa? 2004 Nunavik Health Survey	Rochette and Blanchet, 2007	2004	<1000		Blood, nails	2.2.10
Qanuilirpitaa? 2017 Inuit Health Survey	Nunavik Regional Board of Health and Social Services, 2020	2017	>1000		Blood, urine	N/A
IPY Inuit Health Survey	Saudny et al., 2012	2007-2008	>2000		Blood	2.2.10
NWT Mackenzie Valley Regional Biomonitoring Study	Ratelle et al., 2018	2016-2018	>200	Adult First Nations peoples	Blood, urine, hair	N/A
Yukon Contaminants Biomonitoring Study	N/A	2019	<100	Adult First Nations peoples	Blood, urine, hair	N/A
Greenland						
IVAAQ	Bjerregaard et al., 2007	1999-2005	<500	Pregnant women, newborn children	Blood (maternal, cord), hair	2.2.13
ACCEPT / BioSund	Knudsen et al., 2015; Long et al., 2015; Terkelsen et al., 2018; Bank-Nielsen et al., 2019; Hjermitslev et al., 2020	2010-2015	>500	Pregnant women, newborn children, fathers, children	Blood (whole, serum), hair, maternal milk, plasma lipids, paternal blood (whole, serum), child PKU blood, hair, nails	2.2.14
Greenland Health Studies						
Population survey	Bjerregaard et al., 1997	1993-1994	>1000	Adult Indigenous Peoples	Clinical samples	2.2.16
Population survey	Bjerregaard et al., 2003	1999-2001	>1000		Blood (whole)	2.2.16
Inuit Health in Transition (IHIT)	Bjerregaard, 2011	2005-2010	>1000		Blood (whole)	2.2.16
Population survey	Dahl-Petersen et al., 2016	2014	>1000		Clinical samples	2.2.16
Population survey	Larsen et al., 2019	2017-2019	>1000		Blood (whole)	N/A
Greenland, Poland and Ukraine						
INUENDO / CLEAR	Toft et al., 2005; Bonde et al., 2008; CORDIS, 2015	2002-2004 2009-2012	>1000	General population, pregnant women, fathers, children	Blood (whole), plasma lipids, maternal and paternal serum, offspring buccal swabs	2.2.11 2.2.12

Table 1.1 continued

Country/Study	Primary source	Year(s)	Sample size	Population	Matrices	Corresponding section, AMAP (2015)
Faroe Islands						
Follow up of cohort 1	Weihe and Grandjean, 2012	1986-1987	>1000	Pregnant women, children, men	Blood (cord, child), hair, cord tissue, semen	2.2.17
Follow up of cohort 2		1994-1995	<500	Post-partum, children	Blood (maternal, child, cord), hair, maternal milk	2.2.18
Follow up of cohort 3		1998-2000	>500	Post-partum, children	Blood (maternal, child, cord), hair, maternal milk	2.2.19
Follow up of cohort 5		2007-2009	<500	Post-partum, children	Blood (maternal, child, cord), hair, maternal milk	2.2.20
Septuagenarians cohort		2008-2009	>500	Elderly	Blood, hair, nails	2.2.21
Type 2 Diabetes project of middle-aged Faroese		2011-2013	>1000	Pre-diabetic, diabetic	Blood, hair	2.2.22
Norway						
The MISA Study	Veyhe et al., 2012	2007-2009, 2017-ongoing	>500	Pregnant women, post-partum, newborn children	Blood (whole & cord), urine, hair, meconium, nails	2.2.1
The Tromsø Study	Jacobsen et al., 2012	1979, 1986-1987, 1994, 2001-2002, 2007-2008	<100	Men who participated in all survey points	Serum	2.2.2
Sweden						
MONICA Study	Eriksson et al., 2016	1986, 1990, 1994, 1999, 2004, 2009, 2014	>1000	Adults	Blood and/or urine	2.2.4
Västerbotten Intervention Program	Norberg et al., 2010	1985-ongoing	>1000	Adults	Blood	2.2.4
Riksmaten Adolescents	Moraeus et al., 2018	2016-2017	>1000	School children	Blood, urine	N/A
POPUP	Gyllenhammar et al., 2018	1996-ongoing	>500	First time mothers	Breast milk, blood, urine	N/A
Finland						
Northern Finland Birth Cohort	Rantakallio, 1969	1966-ongoing	>10,000	Newborn child and 3 follow-up times	Blood (whole)	2.2.3
Russia						
Chukotka dietary and exposure study	Dudarev, 2012; Dudarev et al., 2012a,b,c	2001-2003	<500	Indigenous men, women, pregnant women	Local foods, indoor materials, blood (whole), serum	2.2.5
Chukotka birth cohort	Dudarev and Chupakhin, 2014	2001-2003	<500	Indigenous pregnant women, fetus	Blood (whole, cord), serum, cord serum	2.2.7
Follow-up Chukotka coastal mother-child study	Dudarev et al., 2010, 2011	2007	<100	Indigenous pregnant women, children	Blood (whole), serum	2.2.6
POPs and diabetes mellitus study	Dudarev et al., 2012c	2001, 2006	<100	Indigenous men and women	Blood (whole), serum	2.2.8

1.4 Gaps and recommendations from previous assessments

More than twenty years of research and analysis on contaminants and human health in the Arctic has identified gaps and recommendations for future research. While advances have been made to address many of these areas, gaps in knowledge remain and, therefore, some recommendations have remained unchanged over time.

1.4.1 Monitoring

The AMAP human health assessment reports provide consistent evidence that the impacts of contaminants across the circumpolar Arctic vary spatially across regions. Monitoring of chemicals of emerging concern is also an ongoing necessity, as stated in all AMAP assessment reports. These observations stress the importance of maintaining and developing monitoring projects that generate temporal and spatial trend data. Coordinated monitoring and common measurement tools can create comparable data across the circumpolar Arctic.

1.4.2 Holistic health

The health and wellness of Indigenous populations in the Arctic is often lower than that of other inhabitants in other communities across the Arctic. This has been shown in all circumpolar nations, to varying degrees, for lifestyle-related diseases such as obesity, diabetes or metabolic diseases.

Incorporating a more holistic health impact assessment has been recommended in every AMAP human health assessment. In the 2015 report it was recommended that research to address holistic health should incorporate environmental, social, economic and cultural factors (AMAP, 2015). Building sustainable research projects means that the health effects and impacts from various sources can begin to be observed (i.e., climate change, dietary change). Systematically collecting, analyzing and reporting on the health status of Arctic populations, and especially Indigenous populations of the North, continues to be a priority. As concluded in 2009 (AMAP, 2009), a unified approach to reporting the key health status indicators should occur every three to five years, including trend data, and should be broken down by age and gender.

1.4.3 Genetic and epigenetic factors

The role of genetic and epigenetic factors was first identified as a research gap in the second human health assessment (AMAP, 2003). More data on genetics and the combined effects of pollutants were available for the third human health assessment (AMAP, 2009), while the fourth highlighted the need for an increased focus on genetic factors and epigenetics, their influence on individuals and regional populations, and how genes may respond to environmental contaminant exposure (AMAP, 2015).

1.4.4 Risk communication

The importance of risk communication programs has been clear since the second human health assessment (AMAP, 2003) and the third included a full chapter on this topic (AMAP, 2009). However, ongoing efforts to improve health communication programs by working directly with affected communities and finding strategies that are culturally sensitive and locally relevant continue to be a challenge. The fourth human health assessment identified the need for more evaluation studies of risk communication (AMAP, 2015). More work in this area could improve current health and risk communication projects by identifying successful methods, tools or best practices for conveying health messages to Arctic populations.

1.4.5 Climate change

Determining ways to incorporate climate change and its impacts on human health and environmental contaminants into AMAP reports has been a recommendation in every human health assessment (AMAP, 1998, 2003, 2009, 2015). For example, the second assessment concluded by calling for more research on the influence of climate change on POPs, heavy metals and radionuclides (AMAP, 2003), while the fourth included recommendations to assess the impact of climate change in relation to extreme weather events, the impact of climate change on food and water security, and to develop regional models of contaminant transport, especially local release from thawing permafrost (AMAP, 2015).

1.5 Influence of COVID-19

This assessment report was being finalized as the COVID-19 pandemic was evolving. The work presented here was completed prior to the pandemic. COVID-19 has exposed general vulnerabilities that already existed before the pandemic and which were exaggerated as a result. Recently, many publications have outlined how society has been impacted by the pandemic and have further revealed the heightened inequitable challenges that Indigenous Peoples are facing (e.g., IUCN, 2020). While presenting a challenge to cultural norms, COVID-19 illustrated that Indigenous Knowledge is an important factor for adaptive responses to pandemics and is key to increased resilience. The impact of the COVID-19 pandemic on Arctic populations and the links between contaminants and response to rapid changes, including COVID-19, other zoonotic diseases, climate change and other stressors, may be the focus of future AMAP work.

1.6 Scope of the 2021 human health assessment

The present report updates the four previous human health assessment reports (AMAP, 1998, 2003, 2009, 2015) and has a particular focus on dietary transitions: what changes have been observed, what is driving them, and what impact are these changes having on Arctic populations. This information is presented in parallel with human biomonitoring data including new data for metals and POPs, and evidence of human exposure to chemicals of emerging concern previously identified by AMAP (AMAP, 2017). Health effects associated with these exposures in the Arctic are presented. An overview of risk assessment tools and examples of their use in the Arctic is also given. Ongoing risk communication efforts and the success and challenges of these measures are discussed. Finally, Arctic research and collaborations within a global context are presented. All of this work is summarized in order to identify knowledge gaps and recommendations for further work.

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2. Dietary transition

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Key findings

- *Most Arctic populations have experienced a transition towards more imported foods.*
- *The dietary transition has had adverse impacts on health in some populations, such as an increase in obesity or impaired dental status.*
- *Intakes of vitamin D and iodine have decreased due to lower fish and/or milk consumption. These nutrients should be monitored in Arctic populations.*
- *Positive health impacts of the dietary transition include significantly reduced levels of contaminants in the blood of pregnant women.*
- *Whether dietary transition is negative or positive for health depends on the composition of the new diet, as well as the extent to which the traditional diet is maintained.*
- *Communication about dietary risks and benefits is vital.*
- *Food insecurity is a growing concern in some Arctic populations and collaboration between countries should be established to address this.*
- *There are gaps in the research field of dietary studies within Arctic Indigenous populations. More studies are needed, especially within the many Arctic populations in Russia.*

2.1 Introduction

Diet and cultural transition in the circumpolar North have been influenced by contact with western culture, and the development of technology and communications (Kuhnlein et al., 2004; Berner, 2008).

By the 1970s it was clear that Inuit on Greenland had a low prevalence of coronary heart disease and mortality (Dyerberg et al., 1978). Their diet, mainly consisting of marine foods, was noted and formed the starting point for intense research leading to conclusions on the benefits of omega-3 fatty acids in marine foods for cardiovascular health (Innes and Calder, 2020), as well as for other health outcomes such as neurodevelopment and cognition (Alex et al., 2020; DiNicolantonio and O'Keefe, 2020). Marine foods are also a good source of many other important nutrients, such as iodine, vitamin D and protein of high quality.

The discovery of anthropogenic organohalogen contaminants and heavy metals in the late 1980s and 1990s, first in breastmilk and then in Arctic marine mammals and fish, raised concerns about the safety of consuming traditional marine foods within the Arctic populations. These concerns may have accelerated the transition to other protein sources of lesser nutritional quality. Contaminant exposure from the traditional diet and the counterbalancing nutritional/ social/ cultural importance of the same foods is known as 'The Arctic Dilemma'. Changes in diet may have both negative and positive impacts but how they will balance is often difficult to ascertain.

Poor food security (i.e., food insecurity) has been identified as an issue in some Arctic populations. Food security can be defined as physical and economic access to sufficient, safe and nutritious food that meets the dietary needs and food preferences for an active and healthy life (Shaw, 2007). Food security is linked to many factors, including education, food preferences, poverty, unemployment, household crowding, food costs, harvesting costs, and environmental conditions. Food means more than getting the necessary nutrition, it is also essential for social life. How food is produced, how it is prepared and how it is consumed are important in any community, important to the individual and for the way people come together.

The Arctic Monitoring and Assessment Programme (AMAP) has undertaken four assessments on Human Health in the Arctic since the late 1990s. Concerning diet, the first assessment (AMAP, 1998) provided information on exposure to contaminants through subsistence foods as well as foods available commercially in the Arctic countries. The subsequent assessments (AMAP, 2003, 2009) gave greater detail on dietary intake, nutrient intake and contaminants for several Arctic populations. Changes in the proportions of traditional local foods had very significant impacts on nutrient intake in many of these regions. The latest assessment (AMAP, 2015) continued to provide information on traditional local foods and market basket intakes in the circumpolar nations.

The traditional diet varies among the eight Arctic nations. Marine mammal consumption by Indigenous Peoples is significant in Alaska, Canada, Greenland, and the far east of

Russia, while land mammal consumption by Indigenous People is significant in Norway, Finland, Sweden, and western central Arctic Russia. Fish consumption is significant in Indigenous and non-Indigenous populations in many Arctic countries.

This chapter describes the dietary transition that has taken place in populations across the Arctic and highlights the consequences of this transition for nutrition and health. Information gaps are also identified. Because the terminology used for traditional foods varies between regions, use of the terms 'traditional foods', 'country foods', 'traditional country foods', 'subsistence foods' and 'local foods' is determined by the context of the results being described.

2.2 Dietary transition in the Arctic regions

2.2.1 Alaska

2.2.1.1 Traditional diet

The traditional diet of the Alaskan Natives includes bowhead whale, walrus, seals, fish, berries, waterfowl, caribou, moose, and Arctic hare. These foods are considered country foods or local foods and are an important part of the Native diet of Arctic Alaska (Caulfield, 2000). In the southwestern region, the most commonly consumed traditional species are the various species of Pacific salmon that migrate up coastal rivers to spawn (Fall, 2016). The health and diet of the Alaska Native Yupik residents of the southwest region of the state, located in the delta between the Yukon River and Kuskokwim River (YKD), has been much studied since the 1960s. An overview of major study results, and the main impacts of a transition from the traditional diet to a mixed diet, is summarized in the following sections.

2.2.1.2 Dietary changes

The rural Alaska Native diet, like that of most other Arctic Indigenous residents, has gradually transitioned from a predominantly traditional subsistence diet, based on seasonally available plants and wildlife, to a mixed diet of imported and local foods (Heller and Scott, 1967). Over the seven decades since the end of the Second World War, the development of a basic transportation and communication system has connected even the smallest villages, by air transport, with regional hub communities. This has resulted in a gradual increase in availability of processed and high sugar food items, albeit at significant expense. Local wildlife species remain an important source of calories and key nutrients in many of the most remote communities. Data on subsistence food use shows a marked difference, by region of Alaska, in per capita subsistence harvest. The lowest harvest is recorded in urban and more populated regions, and the highest is still seen in the more remote Arctic and southwest Alaska regions. For most Alaskan regions, but not all, the amount of subsistence harvest has decreased over time (Figure 2.1).

2.2.1.3 Consequences of dietary transition

While the negative health impacts of organohalogen contaminants and metals in the traditional marine diet continue to be studied, the negative impact of lower consumption of

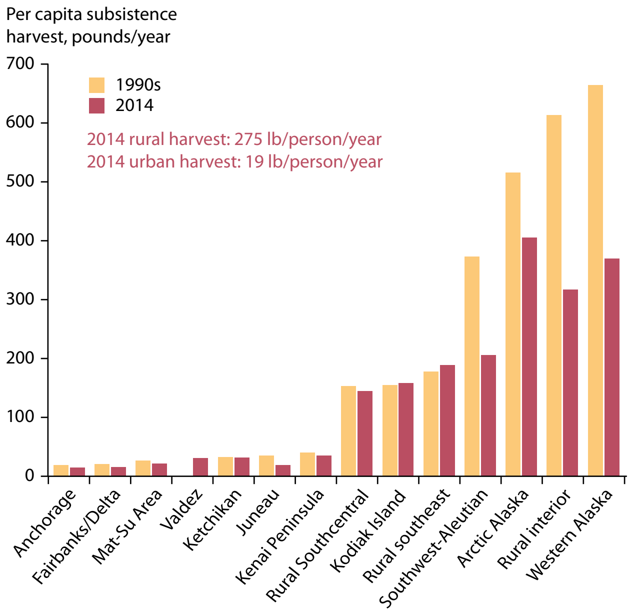

Figure 2.1 Subsistence food harvest in a range of Alaskan regions in the 1990s (Caulfield, 2000) and 2014 (data from the Division of Subsistence, Alaska Department of Fish and Game, Anchorage, Alaska).

marine species has only fairly recently begun to be intensively studied. As imported food items become increasingly widely available, rates of obesity, Type 2 diabetes mellitus, and associated chronic diseases have become more prevalent in the Alaskan population, with rates matching the general population at lower latitudes (IBIS, 2019).

In the YKD region of southwest Alaska, a decline in traditional food consumption, especially marine species, has resulted in a steady decrease in blood levels of the marine stable isotope of nitrogen (^{15}N) in young Yupik women, and also partly explains the decrease in exposure to contaminants and micronutrients (O'Brien et al., 2017).

Early studies documented the increase in dental caries in YKD residents, especially in infants and young children, associated with the increased availability of high sugar snack foods (Singleton, et al., 2019). Infant and early childhood dental disease is a significant health disparity in the YKD (Klejka et al., 2011). The rising prevalence of obesity and Type 2 diabetes mellitus has been mentioned, and the rate of increase in both conditions is greater in the YKD than in many other regions of Alaska. The rise in clinically apparent infant and childhood vitamin D deficiency was noted in the 1990s and early 2000s, and is now twice that of the US all-races rate (Singleton et al., 2015). As shown in Figure 2.2, a study of blood levels of the ^{15}N stable isotope ratios, a marker of marine protein intake, and vitamin D, in Yupik women in the five decades between the 1960s and 2000–2010 showed a decade by decade parallel drop in ^{15}N and vitamin D from the 1960s to the late 1980s, which stabilized in the 1990s (O'Brien et al., 2017). An analysis of vitamin D levels in the YKD MOM Study cohort 3, recruited between 2009 and 2012 (156 women, 76 newborn cord blood samples, average age 26 years) showed a significant percentage of women entering prenatal care with low vitamin D levels, and an even greater percentage of infants with cord blood in

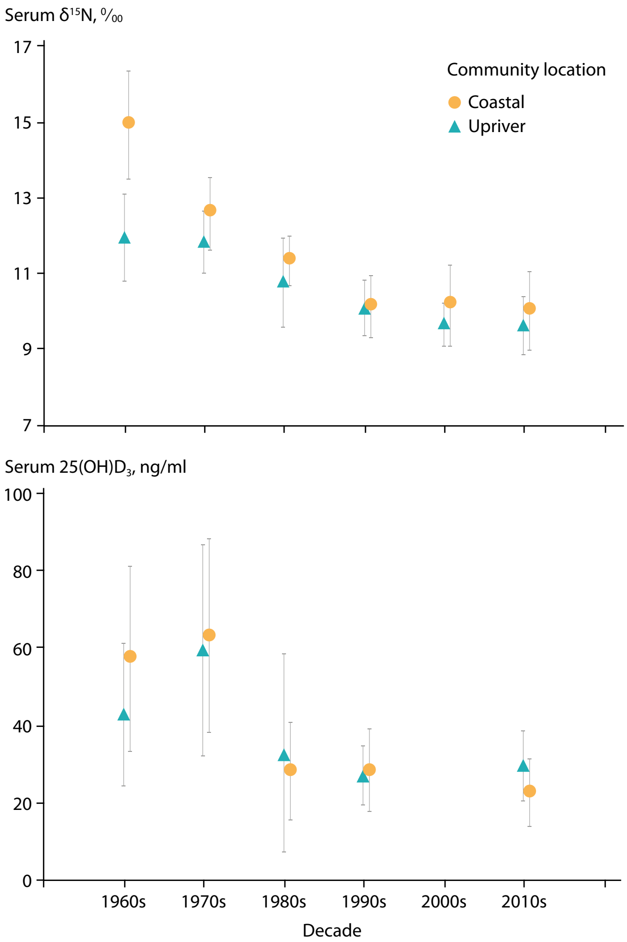

Figure 2.2 Multi-decade decrease in blood levels of ^{15}N and vitamin D in Alaska Native Yupik women of childbearing age by decade 1960s to 2010s: comparison of coastal versus upriver residents (O'Brien et al., 2017).

the Deficient (<30 ng/ml) and Severe Deficiency (<12 ng/ml) range. Subsequent study of dental clinic health records on the infant cohort revealed that the risk of severe dental disease in vitamin D deficient newborn is 2.5-fold greater than for those with sufficient vitamin D levels (Singleton et al., 2019).

A preliminary analysis of the MOM Study cohort 3 data revealed that the marine isotope biomarker ^{15}N, total blood mercury, total omega-3 fatty acids, and vitamin D were all significantly positively correlated. HemoglobinA1c (HbA1c), a marker of blood glucose levels over the previous two to three months, was only associated with vitamin D and the correlation was negative, indicating that a lower vitamin D level in prenatal blood was associated with a higher HbA1c (Berner pers. comm., 2019). This preliminary finding is being further explored in the clinical data, and would indicate that there may be a risk of increased insulin resistance associated with lower vitamin D levels in pregnancy. Vitamin D deficiency has also been proposed as a possible risk factor for developing autism spectrum disorder (Principi and Esposito, 2020). In the data from the MOM Study, there is no indication thus far of an adverse impact of the traditional diet. There is a need to improve awareness among Alaska Native residents, as well as among all Alaska residents, regarding the benefits of traditional marine species in the diet, and the importance of ensuring adequate intake of vitamin D in each stage of life.

2.2.1.4 Food security

A review addressing food security in Alaska (Walch et al., 2018), concluded that food insecurity is a growing public health concern for many Alaskans. Future research should use a common tool to measure traditional food access across all communities and especially among Alaska Native people. Research has shown that climate change may limit the availability of traditional foods due to the impact of unpredictable temperatures on game mating and hunting timing, and changing migration patterns of some fish species.

2.2.1.5 Gaps in knowledge

There is a need for research on food security in Alaska. More recent data on dietary intakes in Indigenous populations in Alaska are needed.

2.2.2 Canada

2.2.2.1 Traditional/country food diet

Indigenous People living in Arctic Canada are primarily Inuit and refer to their homeland as 'Inuit Nunangat'. Inuit Nunangat encompasses the land claims regions of the Inuvialuit Settlement Region, Nunavut, Nunavik and Nunatsiavut (Figure 2.3). In subarctic Canada, the Indigenous People are primarily First Nations and Métis in the Yukon Territory and Northwest Territories. By tradition these Indigenous People have been nomadic hunter-gatherers. Their subsistence or traditional/country food diets comprised a diverse range of largely protein-based foods, such as caribou, Arctic hare, seal, fish, birds (e.g., ptarmigan, goose), along with plants and berries, which they could gather locally (Draper, 1977; Kuhnlein et al., 2001). In the Inuit community, subsistence foods have long been considered as the basis of their age-old cultural traditions (Sharma, 2010). Food-sharing systems have defined Inuit identity by creating and reinforcing social bonds and ensuring the survival of extended family and community members (Condon et al., 1995; Collings et al., 1998). Hunting, gathering, and consumption of country food are foundational to spiritual, cultural, physical and mental health for northern Indigenous populations, as they foster a connection to the land, the cultural benefits of sharing the harvest, and a nutritious food source (Council of Canadian Academies, 2014; Tremblay et al., 2020).

2.2.2.2 Dietary changes

There has been inconsistent monitoring of diet through national surveys in Canada over time, and even more challenging is that data collected from Canadian Arctic populations have not been included in the national surveys that have been conducted. The Total Diet Study, which estimated levels of exposure to chemicals that Canadians in different age-sex groups accumulated through the food supply in six periods between 1969 and 2007, focused on urban and southern populations, with the exception of data collected from Whitehorse, Yukon in 1998 (Dabeka and Cao, 2013). In 2015, the Canadian Community Health Survey had a nutrition focus which included a 24-hour dietary recall and a household food security survey, and was the first time national nutrition data had been collected since the Nutrition

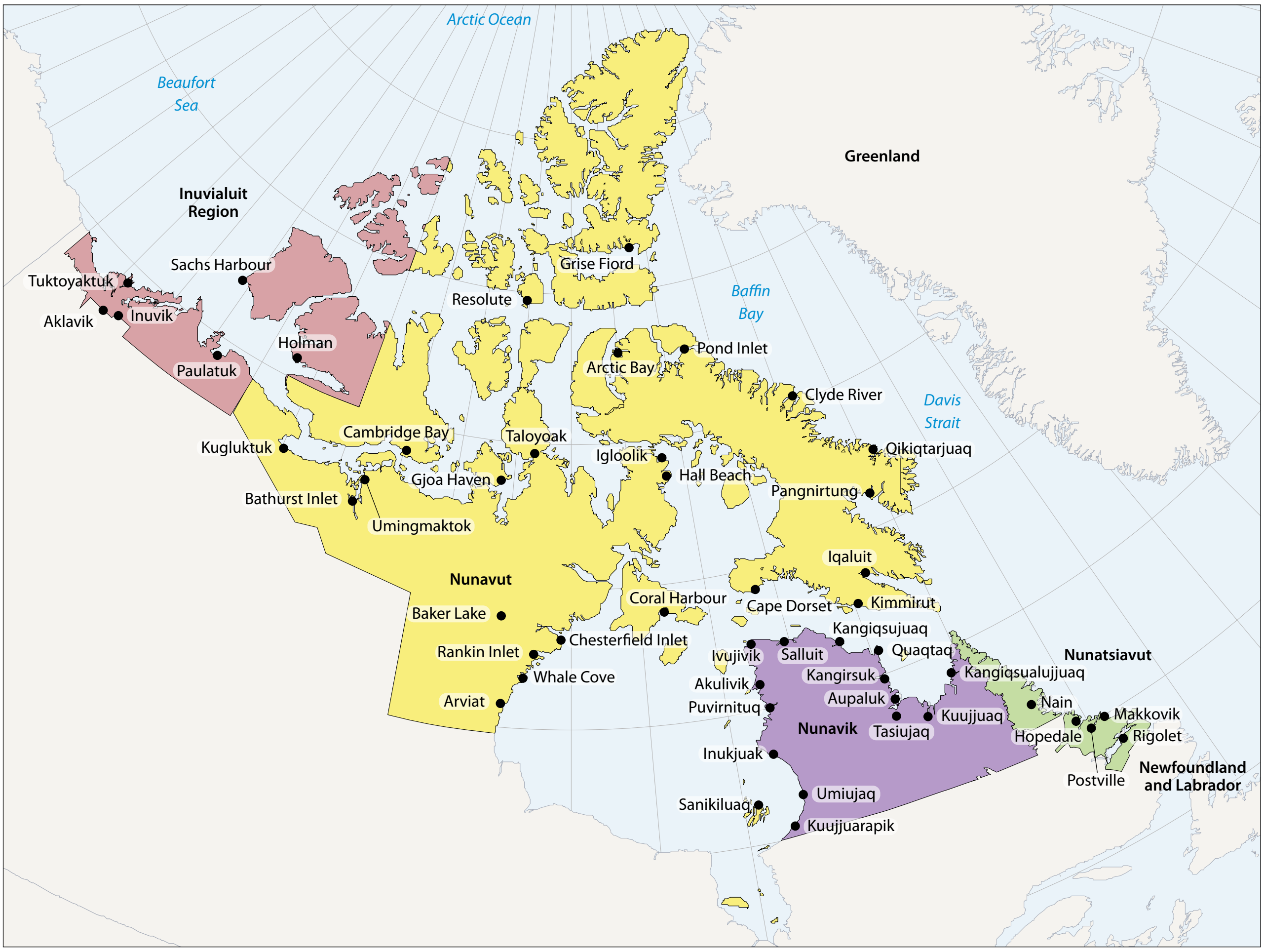

Figure 2.3 Inuit regions of Canada.

Canada survey 35 years prior (Government of Canada, 2017). Unfortunately, the Canadian Community Health Survey excludes the Canadian territories Yukon Territory, Northwest Territories, and Nunavut, thus leaving Arctic Canada out of this national nutrition data set. Monitoring of diet in Arctic Canada has generally been piecemeal and, except for the Inuit Health Survey, data on Arctic dietary patterns are collected through more discrete regional or community-based individual studies by small teams of researchers. The Inuit Health Survey conducted in the Northwest Territories (only the Inuvialuit Settlement Region), Nunavut, and Nunatsiavut from 2007 to 2008 focused broadly on health and wellness and covered questions on the home environment, living conditions, smoking behavior in the home, employment, income and expenses, food security and access to country food, including a 24-hour dietary recall and food frequency questionnaire (Saudny et al., 2012). A version of the Inuit Health Survey was conducted in Nunavik in 2004 and 2017. The second phase is currently underway and planned to be conducted in all four Inuit Nunangat regions at the same time – including Nunavik – starting in 2021 and then repeated every five years.

Despite the critical importance of country foods to health and wellbeing for Indigenous Peoples in Canada, along with their role as part of social and cultural systems that hold many of these communities together, there has been a dietary transition with a significant decline in country food consumption over time. Van Oostdam conducted a review of the Canadian Northern Contaminants Program and the AMAP assessments from the 1990s to 2017, and found clear evidence of a dietary transition in Arctic populations, with declining overall country food consumption and fewer species consumed (Van Oostdam pers. comm., 2020).

The first Canadian Arctic Contaminant Assessment Report (CACAR, 1997) highlighted traditional food intakes ranging from 82 to 562 g/person/day depending on age, gender, ethnicity and location of the community. Higher country food intakes were generally seen in older age groups and more remote communities. Although these country foods were often responsible for only 10% to 40% of the energy intake of the entire diet, they were still a very significant source of important nutrients such as protein, iron, omega-3 fatty acids, vitamin A and calcium. Historical information on trends in caribou consumption were noted in this assessment through early work on radiocesium exposures in Baker Lake indicating that caribou consumption in 1989 was only one quarter of that in 1967. The country food diet was also described as the source of increased contaminant exposure due to bioaccumulation of contaminants such as polychlorinated biphenyls (PCBs), DDT/DDE and various other persistent organic pollutants (POPs) and mercury in the marine mammal food chain and some freshwater fish.

The second Canadian Arctic Contaminant Assessment Report (CACAR, 2003) presented additional dietary data which showed how variable the country food diet could be, with over 250 species included. Even though many species are consumed, it was a small number (whitefish, caribou, moose, beluga, narwhal, seal, char) that contributed most of the dietary nutrients and contaminant exposure.

The third Canadian Arctic Contaminant Assessment (CACAR, 2009) provided data on contaminant trends and dietary change in the Canadian Arctic, showing that contaminant concentrations in First Nations and Inuit mothers decreased between the 1990s and early 2000s. The composition of the diet also changed, with Inuvialuit mothers consuming less marine mammal fat and more fish and marine mammal meat.

The fourth Canadian Arctic Contaminant Assessment (CACAR, 2017) included a significant modeling effort to establish how data could be better used to describe how human contaminant concentrations in Inuit and Dene/Métis peoples could be correlated with theoretical human exposure models. Binnington and colleagues developed these models by combining models for contaminant fate, transport, and bioaccumulation to simulate PCB exposure in female participants of the 2007–2008 Inuit Health Survey, in addition to calculating daily mercury and nutrient intake rates (Binnington et al., 2016a,b). Theoretical dietary change assessments by Binnington also noted that short-term dietary changes for contaminants with long half-lives such as PCBs did not allow significant changes in human body burdens of contaminants but did allow for some significant increase in various essential nutrients. For contaminants with shorter half-lives such as mercury the actual human body burden changes correlated well with theoretical short-term dietary changes. The possibility that country-food food frequency questionnaires could tend to overestimate dietary exposures through country foods and their contaminant load was noted. This assessment concluded that the theoretical dietary data assembled often gave a better description of changes in contaminant concentrations in the human body than the empirical dietary data obtained from dietary assessments such as food frequency questionnaires.

According to the 2009 AMAP assessment of human health in the Arctic (Vaktskjold et al., 2009), country food items provided 10% to 36% of energy intake in Arctic Canada, with lower intakes of country foods in children. Researchers also found that the major dietary shifts in larger, more urban communities had taken place prior to 1950 while in smaller more rural communities, country food intake had remained high until the early 1970s. The 2015 AMAP assessment of human health in the Arctic reported on dietary changes and possible contaminant exposures related to decreasing availability of country foods such as caribou (Gibson et al., 2015).

An International Polar Year-funded study included a comparative analysis of the factors that influence dietary choice among Inuit living in Cape Dorset, Iqaluit and Kimmirut in Nunavut and found that socio-cultural factors (e.g., food sharing practices and networks difficult to sustain over time), available resources (e.g., economic) and environmental conditions (e.g., changing ice conditions impacting harvesting) were the most important factors influencing dietary choice. Other factors, such as time and convenience, knowledge, nutritional factors, taste and variety, also influenced dietary choice to a certain extent (Donaldson et al., unpubl.).

Little and colleagues (2020) conducted a systematic scoping review on the drivers and implications of dietary changes among Inuit in the Canadian Arctic. Studies included in the review indicated an increase in market food and declining country food consumption. Similar to Donaldson et al. (unpubl.), drivers of the transition found by Little et al. (2020) included historical colonial processes, poverty and socio-economic factors, changing food preferences and knowledge, along with climate change. Increased consumption of non-nutrient dense market foods exacerbates micronutrient deficiencies and dietary inadequacy leading to health implications, such as overweight, obesity, and related cardio-metabolic health outcomes. Food insecurity was a growing public health concern and, with declining country food consumption, there are implications for psychological, spiritual, social and cultural health and wellbeing (Little et al., 2020).

A human biomonitoring Mackenzie Valley project funded by the Northern Contaminants Program reported estimated country foods consumption behaviors for Dene First Nations in the Sahtú and Dehcho regions of the Northwest Territories (Ratelle et al., 2018a,b). In this area, country food consists of harvested food from the land and waterways, primarily large land animals (such as moose, caribou) and fish, along with birds, small land animals (such as rabbit, beaver), berries, and plants. The research team worked with nine local partnering communities to implement the project from 2016 to 2018. This work involved the collection of three biological samples (human hair, urine, blood), administration of two dietary surveys (a food frequency questionnaire and a 24-hour dietary recall), and a health messages survey to characterize knowledge awareness, risk perception, and communication preferences. The 24-hour dietary recall results were then compared to the last available data from the 1990s collected by the Centre for Indigenous Nutrition and Environment (CINE) in the same regions, in order to document potential changes in patterns of traditional food preparation and consumption over the prior two decades. The 24-hour dietary recall was completed by 37% (n=199) of all participants from the larger project. Of these, 66% were from the Dehcho and 34% from the Sahtú. Participating individuals were 49.8% men and 50.3% women, from 7 to 85 years old. Overall, this project provides knowledge on country food consumption in an Indigenous population, and reports the frequency, portion sizes, and nutrients of the country foods consumed in Dene communities in two regions of the Northwest Territories. One way to characterize the importance of the contribution of country food to nutrition and health is to examine the contribution of energy and macronutrients from country food. In Table 2.1, adult participants (n=100) who consumed country food on the day of the 24-hour dietary recall are compared to people who did not consume country food on that day. When comparing some of the CINE results from the 1990s with the Mackenzie Valley study more than two decades later, findings indicate similar contributions of energy and macronutrients (carbohydrate, protein, fat) for participants who did and did not consume country food between the two time-points about 25 years apart. Thus, over time, country food continues to make an important contribution to nutritional health for Dene people in the Dehcho and Sahtú regions of the Northwest Territories.

Table 2.1 Energy and nutrient intake by Dene/Métis adults in the Dehcho and Sahtú regions of the Northwest Territories, on days with and without consumption of country food for two time-points about 25 years apart.

Nutrients (average)	1994 Centre for Indigenous Peoples' Nutrition and Environment (Kuhnlein and Receveur, 2007)		2016-2018 Mackenzie Valley Study (Skinner et al., 2021)	
	With country food (n=661)	Without country food (n=346)	With country food (n=35)	Without country food (n=65)
Energy, kcal	2261	2085	2144	1959
Carbohydrate, E%	35	47	39	44
Protein, E%	31	20	25	17
Fat, E%	34	39	37	40

2.2.2.3 Consequences of dietary transition

Many Arctic Indigenous populations experience an increase in obesity and other metabolic diseases when decreasing consumption of local traditional foods (Bjerregard, 2004), and this is also the case for the Indigenous populations in Arctic Canada (Galloway et al., 2010; Reeds et al., 2016). Large health disparities have been noted between Indigenous and non-Indigenous People in Canada that manifest as shorter life expectancy, increased rates of chronic disease (Gittelsohn et al., 1998; Veenstra, 2009), increased rates of fractures (Leslie et al., 2004) and increased prevalence of rickets (Ward et al., 2007) in the Indigenous populations. A review on effects of dietary transition found prevalence of vitamin D deficiency to range from 14% to 76% among Canadian Indigenous populations in summer and that mean intake of vitamin D was below the estimated average requirement in all age groups (El Hayek Fares and Weiler, 2016). However, trends toward increasing height have been reported among Canadian Inuit children (Roth et al., 2008).

In the Inuit Health Survey (n=2095 adults, 2007–2008) it was found that despite a modest contribution to total energy intake (6.4–19.6%, by region), country foods contributed 23–52% of protein and a large proportion of many important nutrients, for example, up to 73% of vitamin D, 50–82% of vitamin B12 and 28–54% of iron. The three most popular energy-yielding market foods (sweetened beverages, added sugar, bread) contributed approximately 20% of energy but minimally to most nutrients (Kenny et al., 2018a). From the Inuit Health Survey in Nunavik in 2004 (Anctil, 2008), consumption of country foods was still important, although lower than in 1992 (16% of energy intake in 2004 vs 21% in 1992) and food insecurity was a major issue for many Inuit households. In 2004, nearly a quarter of Inuit in Nunavik (24%) reported lacking food in the month prior to the survey (Anctil, 2008). Supporting country food habits is clearly beneficial to the health of Indigenous populations in Arctic Canada and can help increase food security.

2.2.2.4 Food security

The focus of daily life for Indigenous People living in northern Arctic and subarctic communities has shifted from a simple subsistence livelihood to a more complex dual food system with both country food and market food. Country food harvesting and consumption has been decreasing over the past half century, with a greater reliance on store-bought food. However, the import system for store-bought food is neither a viable nor sustainable strategy for addressing food insecurity in remote communities as it will always be expensive and does not contribute to self-sufficiency or to broader food security constructs such as sustainable livelihoods and food sovereignty. The 'values of giving, sharing and trading are at the heart of land care and food sovereignty' and 'the core of food sovereignty is reclaiming decision-making power in the food system' (Food Secure Canada, 2011). In the Indigenous context, food sovereignty encompasses acquiring foods in culturally acceptable ways, such as through traditional practices (Schuster et al., 2011). An Indigenous food sovereignty framework connects the health properties of food with the health of the environment and identifies past and present social injustice (Power, 2008). It addresses aspirations for collective wellbeing, along with acknowledging land rights, cultural integrity, gender equity, and adequate nutrition, all while often addressing structural racism and restructuring of socio-political processes (Cidro et al., 2015).

2.2.2.5 Gaps in knowledge

In the review by Little et al. (2020) a number of gaps in knowledge were identified. Many are a result of inadequate national monitoring of diet over time, especially for Arctic populations in Canada, and only very few longitudinal studies (e.g., the Inuit Health Survey) to examine long-term dietary and lifestyle changes and resulting impacts on health and wellbeing. The priorities for dietary research must be harmonized between academics and Arctic Indigenous communities and organizations, along with an active effort to incorporate Indigenous knowledge into all aspects of the research. Methods for assessing dietary intake, food security, health outcomes, and northern food environments need to be standardized to enable more accurate comparisons across populations and over time, and need to consider gender- and age-based differences in consumption. Studies are needed that include actionable risk-benefit analyses for country food versus market food while considering health, cost, local contexts, and sustainability. The impacts of climate change on food security for both country food and market food, and potential adaptation strategies need to be investigated. These strategies will require an examination of, and respect for, community-led initiatives that can provide solutions that support Indigenous knowledge, preferences, practices, traditions, and priorities.

2.2.3 Greenland

2.2.3.1 Traditional diet

The traditional diet of the Inuit in Greenland consisted of what could be harvested locally from the sea (mostly marine mammals, fish, wildfowl), supplemented by terrestrial species such as caribou, muskox and ptarmigan. Some local plants were also consumed (seaweed, berries). Meat, fat and organs were all consumed. One Inuit resident explained that in her childhood after the Second World War, the traditional diet – or *kalaalimernit* – was more diverse than today with meat now forming the greater part of *kalaalimernit*. Traditionally, the harvest was boiled or eaten raw, whereas other ways of preparing the food such as frying and baking are now also used. Since the 18th century the locally harvested food has been supplemented with imported grain, rice, sugar, dried peas and dried fruit, but around 1900 locally harvested food was still responsible for 82% of the total energy intake (Bertelsen, 1937).

Table 2.2 Contribution of the top ten food groups to total energy intake in Greenland in 2018. Analyses from the Population Health Survey 2018 (n=2335) (Larsen et al., 2019).

Rank	Food item	Energy, %	Cumulated energy, %
1	Imported red meat	14.5	14.5
2	Refined grain	10.2	24.7
3	Whole grain	9.3	34.0
4	Soda pop	8.1	42.2
5	Dairy, eggs	6.9	49.1
6	Fish	6.6	55.6
7	Sweets	6.5	62.2
8	Fruit	5.3	67.4
9	Sugar in coffee or tea	4.4	71.8
10	Potatoes	4.2	76.0

2.2.3.2 Dietary changes

The dietary transition in Greenland is well documented. A number of dietary surveys conducted since 1953 have focused on the proportion of locally harvested food in the diet, and since 1993 the diet in Greenland has been followed in regular health interview surveys. A household survey from 1953 showed that in towns 21% of the diet was based on locally harvested food compared to 45% in villages. The locally harvested food was predominantly seal meat, Greenland cod and Greenland halibut (Uhl, 1955). In a population health survey from 2005 to 2010, the proportion of locally harvested food among the Inuit had decreased to 17% (towns) and 32% (villages), and in 2018 further to 14% (towns) and 21% (villages) (Bjerregaard pers. comm., 2019).

The modern diet in Greenland comprises 15% locally harvested food (caribou meat, cod, Greenland halibut, seal meat, *muktuk*) and 85% food imported from overseas, often from or via Denmark. In the capital and the larger towns, the same choice of food is available as in any major town in Denmark although at higher cost. The ten food groups contributing the most energy to the present-day diet of Inuit in Greenland and which accounted for 76% of the total energy intake are listed in Table 2.2. There were strong geographical differences as well as differences by age group and gender (Knudsen et al., 2015; Terkelsen et al., 2018; Larsen et al., 2019).

Based on the dietary guidelines of the Greenland Council for Diet and Physical Activity, five measurable indicators for a healthy diet have been developed for the Greenland Public Health Programme (Table 2.3). These indicators of frequency of consumption have been measured since 2005–2010 by the same food frequency questionnaire and the results show that an increasing proportion of the population consumed vegetables on a daily basis, as advised by the Council, but that contrary to the advice of the Council fewer consumed fish and more consumed fruit syrup and soda pop. The consumption of marine mammals and fruit did not change. Only 15% of survey participants adhered to four or more of the indicators.

2.2.3.3 Consequences of dietary transition

In Greenland, the decreased consumption of traditional food has been accompanied by an increased consumption of sugar and saturated fat and a decreased intake of omega-3 fatty acids ('fish oils') (Jeppesen and Bjerregaard, 2012). On the positive side, the intake of dietary fiber has increased and a reduced consumption of meat and organs of marine mammals and wildfowl has meant a lower intake of methylmercury. Although diseases due to the changing diet have not been identified in

Table 2.3 Dietary advice and indicators of the Greenland Council for Diet and Physical Activity. Population Health Surveys in Greenland for the periods 2005-2010 and 2018 (Larsen et al., 2019).

Advice	Indicator	2005–2010, % (n=2746)	2018, % (n=2236)	Ratio (confidence interval)
Eat fruit and vegetables daily	Daily consumption of fruit	37.2	38.8	1.04 (0.95, 1.04)
	Daily consumption of vegetables	23.9	29.6	1.24 (1.11, 1.39)
Eat local food, often fish	Fish eaten at least once a week	56.0	42.8	0.76 (0.71, 0.83)
	Marine mammals eaten once to three times per week	35.9	33.3	0.93 (0.84, 1.02)
Drink water – drink less fruit syrup and soda pop	Fruit syrup and soda pop drunk daily	24.4	43.9	1.80 (1.62, 2.00)

Greenland to date, a dramatically increasing trend in obesity has taken place in parallel with and probably partly due to this dietary transition (Bjerregaard and Larsen, 2018).

2.2.3.4 Gaps in knowledge

The dietary transition in Greenland is well studied at the national level but further studies of demographic, geographic and social subgroups of the population are needed. Studies are also needed on the economic aspects of diet and qualitative studies of the reasons for dietary choices. Questions on food security have only recently been added to the health interview surveys and the results are yet to be analyzed.

2.2.4 Iceland

2.2.4.1 Traditional diet

Lack of firewood influenced the traditional diet of Icelanders, where domestically produced animal foods, mostly fish, dairy and mutton, constituted the mainstay of the diet. All cereals, mainly rye but also barley and oats were imported from Denmark, and by the late 1800s became increasingly available. Other carbohydrate-rich foods like potatoes did not become a common crop until the late 19th century (Jonsson, 1998).

Cow's milk and dairy, including the cheese-like product *skyr* made from skimmed milk were the main staple, contributing almost half the caloric intake until the 1820s according to the food historian Gudmundur Jónsson (Steingrimsdottir, 2018). Ewe's milk was also common in this country of sheep farmers. As late as 1900 the average milk and dairy consumption was estimated at 1.4 kg/person/day. According to the first Icelandic nutrition survey in 1939, milk consumption was still equally high in rural areas but lower in fishing towns, as distribution methods from the countryside were limited.

Another characteristic was the extraordinarily high consumption of fish, including fresh, dried and salted fish. The average consumption of fish, based on food supply statistics, was as high as 430 kg/male equivalents/year in 1900, which translates to around 650 g of edible fish/day. Fish, mainly stockfish, was a main staple food along with dairy for the poor as well as those of better means, and was commonly eaten with butter for daily meals, serving a function comparable to bread in many other societies. By 1939, average fish intake had reduced to 200–300 g/day. Higher values were found in fishing villages, while intake was lower in the rural countryside. By this time, fresh and salted fish had replaced the stockfish of earlier times.

Bread did not become a common staple food in Iceland until the late 19th century. Until the early 18th century grain was limited, such that the diet could be described as low carbohydrate. Much of the grain was consumed as porridge rather than bread because fuel was scarce in this unforested land, and less fuel was needed to cook porridge than bake bread. As grain imports rose in the 19th century, rye and grains gradually became a staple food in Iceland as in most other countries, and by the start of the 20th century grains had replaced dairy as the main source of calories in the diet.

Meat was almost exclusively lamb or mutton. As animals were mostly slaughtered during autumn, meat had to be conserved, either by smoking or in salt. Pickling in whey was another method used almost exclusively in Iceland. Liver and blood sausages containing rye, as well as pieces of meat, were stored in liquid whey, a side product from making *skyr*. These pickled innard sausages were among the most common foods in the Icelandic diet and consumed every day in most households. Meat as well as butter were often sold both domestically and internationally in return for other necessities.

Despite these common features of the Icelandic traditional diet, there were large variations according to local conditions as well as means. For example, seabirds and their eggs were important foods in many coastal areas where sea cliffs were teeming with birds. Seal was also a valued and important food source in coastal areas, and was consumed fresh, salted and pickled in whey. Another important coastal food was the seaweed dulce, while the lichen 'Iceland moss' was collected and used in porridge and sausages in place of grain.

2.2.4.2 Dietary changes

National nutrition surveys were conducted in Iceland in 1939, 1990, 2002, 2010/11 and there is an ongoing survey that is planned to be completed in 2021. In addition to the national surveys, smaller studies and food consumption statistics provide information on trends and directions in the nation's diet.

Table 2.4 Food consumption statistics for Iceland since the mid-1950s (Icelandic Directorate of Health, 2020).

Foodstuff	Food consumption, kg/person/year		
	1956–1960	1986–1990	2014
Dairy, total	343.5	230.5	118.2
Milk	341.3	162.7	94.7
Mutton/ lamb	46.2	36.1	20.1
Poultry	0.3	5.6	27.1
Vegetables	15.9	39.3	69.5
Fish and shellfish	61.8	41.5	NA
Grains	76.4	63.4	76.4

Table 2.5 Caloric intake from macronutrients for dietary surveys since 1990 (Steingrimsdottir et al., 2014).

Macronutrient	Mean energy intake, % (SD)		
	1990 (n=1240)	2002 (n=1174)	2010/2011 (n=1312)
Protein	17.4 (3.3)	17.9 (5.5)	18.1 (4.5)
Fat	41.0 (6.8)	35.3 (9.4)	36.2 (7.3)
Saturated fatty acids	20.0 (4.4)	14.7 (5.0)	14.5 (3.9)
Trans-fatty acids	2.0 (1.2)	1.4 (0.9)	0.8 (0.4)
Carbohydrate	40.7 (7.3)	45.3 (10.0)	42.2 (7.9)
Added sugar	8.4 (6.1)	10.6 (8.6)	8.9 (6.2)

Table 2.6. Consumption of selected major foods in Iceland according to the latest national surveys. Data are means covering both sexes and an age range of 8 to 80 years (Steingrimsdottir et al., 2014).

Food item	Mean intake (SD), g/day			
	2002 (n=1174)	2010/2011 (n=1312)	p-value, t-test	Difference
Milk and milk products total	388 (377)	300 (232)	<0.001	-23%
Whole milk	95 (205)	59 (138)	<0.001	-39%
Cheese	36 (42)	35 (31)	0.3	-5%
Bread, total	117 (94)	95 (61)	<0.001	-19%
Bread, whole grain	12 (28)	22 (33)	<0.001	80%
Cakes and cookies	59 (106)	47 (62)	0.001	-19%
Oat meal porridge	14 (64)	29 (70)	<0.001	106%
Vegetables, total	101 (109)	120 (100)	<0.001	19%
Fruits and berries, total	77 (113)	119 (120)	<0.001	54%
Fish and fish products	41 (77)	46 (62)	0.08	12%
Meat and meat products	111 (114)	130 (103)	0.001	17%
Highly processed meat	28 (62)	22 (39)	0.001	-24%
Butter, butter products	12 (19)	12 (14)	0.7	-2%
Margarine	6 (13)	4 (5)	<0.001	-32%
Vegetable oils	2 (8)	2 (5)	0.8	4%
Cod liver oil	1.3 (3.1)	1.8 (3.3)	<0.001	40%
Soft drinks, total	261(429)	238 (339)	0.1	-9%
Sugared soft drinks	180 (373)	127 (249)	<0.001	-29%
Protein and diet drinks	8 (63)	15 (65)	0.007	83%
Sweets	16 (41)	17 (28)	0.8	2%
Chips and popcorn	8 (26)	6 (16)	0.02	-25%

The nutrition transition in Iceland has been described (Steingrimsdottir et al., 2014, 2018), and illustrates the shift from a mainly animal-based diet toward a more varied, western mainstream diet (Table 2.4).

In 1990, food of animal origin still dominated the diet; fish intake was 73 g/person/day on average, meat was 106 g/person/day, poultry only 9 g/person/day, while dairy was 589 g/person/day. Grain, fruit and vegetables were on the other hand less common than in other Nordic countries. As a consequence, protein and fat, especially saturated fat, accounted for a large proportion of caloric intake in Iceland (Table 2.5).

Ironically, sugar intake was quite high. Milk, dairy, fish and lamb/mutton became less common during the decades that followed and are no longer as dominant in the diet, while fruit and vegetables have both become more abundant (Table 2.6). Lamb and mutton, while still popular have largely been replaced by chicken, pork, and even beef. At the same time, butter and hard margarine, previously the main fat sources, have been replaced by vegetable oils and olive oil. As a result, trans fatty-acid intake has decreased considerably as has intake of saturated fatty acids (Table 2.7). Intake of soda and sugared drinks rose rapidly in the 1970s and 1980s to almost record levels by Nordic comparison, but have since decreased according to the latest surveys.

Roughly half of all available foodstuffs in Iceland are domestically produced and that proportion has remained unchanged since 1990. Owing to import restrictions, almost all milk and dairy, meat, fish and eggs are domestic, as well as about half the vegetables. In contrast, all fruit and grain are imported even though some barley is grown for human consumption and wild berries are still collected locally. Other foods from nature, such as birds (mostly ptarmigan and seabirds) are still consumed, but in small amounts by most, as are whale meat and seabird eggs.

Changes in the diet over the past decade have not been properly documented, but a national nutrition survey is ongoing and will be completed in 2021. In the absence of firm data, the media and restaurant menus provide some indication that dietary choices are becoming more varied, with vegan and vegetarian diets, low-carbohydrate and even ketogenic diets being more common alternatives to the varied diet recommended by the authorities. Sushi is a popular 'fast food' choice, and international cuisine is growing, partly in response to the thriving tourist trade.

The Directorate of Health in Iceland publishes nutrition recommendations that are mostly based on the Nordic Nutrition Recommendations. The main difference between them is that the Directorate of Health recommends a higher vitamin D intake: 15 μg/day for adults and 20 μg/day for the elderly. Previous recommendations were also higher: 10 μg/day, as compared with 7 μg/day in the older Nordic Nutrition Recommendations. These higher intakes are achievable, as

Table 2.7 Dietary intake of selected nutrients in Iceland according to the latest nutrition surveys. Data are means covering both sexes and an age range of 8 to 80 years (Steingrimsdottir et al., 2014).

Nutrient	Mean intake (SD) per day			
	2002 n=1174	2010/2011 n=1312	*p*-value, t-test	Difference
Energy, kcal	2130 (996)	2059 (725)	0.06	-3%
Protein, g	90 (41)	90 (35)	0.04	0%
Fat, total, g	88 (52)	85 (37)	0.2	-3%
Saturated fatty acids, g	36.8 (24.1)	34.2 (16.6)	0.002	-7%
Omega-3 long-chain polyunsaturated fatty acids, g	0.7 (1.1)	0.8 (1.2)	0.003	19%
Trans fatty acids, g	3.4 (2.9)	1.8 (1.2)	<0.001	-46%
Carbohydrate, total, g	233 (118)	213 (82)	<0.001	-9%
Sugar, total, g	102 (73)	95 (50)	0.005	-7%
Added sugar, g	59 (64)	47 (40)	<0.001	-20%
Fiber, g	16.7 (7.9)	16.8 (7.1)	0.6	1%
Vitamin A, retinol equivalents	1649 (3599)	1146 (2241)	<0.001	-31%
Vitamin D, µg	6.1 (9.8)	8.1 (9.3)	<0.001	33%
Vitamin E, α-tocopherol equivalents	7.8 (6.5)	10.5 (6.6)	<0.001	35%
Vitamin C, mg	80 (85)	102 (81)	<0.001	28%
Calcium, mg	1071 (624)	923 (428)	<0.001	-14%

cod liver oil has traditionally been common in the diet. Use of cod liver oil is more common among the older population and among preschool children, who often receive this as part of the school meal. According to the 2010/2011 nutrition survey, 40% of men aged 61 to 80 years but only 12% of young women took cod liver oil daily.

Food-based recommendations were published in 2014, where the focus is on the diet as a whole and the importance of a varied diet. The recommendations can be summarized as follows: fruit and vegetables (500 g/person/day, at least half of which should be vegetables, juice not included); whole grains at least twice per day; fish two to three times per week, of which fatty fish once a week; meat in moderation (maximum of 500 g/red meat/week); low fat milk without added sugar two portions per day; healthier fat (oil instead of butter or margarine in cooking); lower salt intake (maximum of 6 g/day); less added sugar; vitamin D daily, either as cod liver oil or other vitamin D supplement); The Keyhole – healthy choices made easy (www.livsmedelsverket.se).

The extent to which the public follow these recommendations is determined by the national nutrition surveys, the Nordic Monitoring System, the Health and Wellbeing Survey of the Directorate of Health, and the annual surveillance of selected health impact factors (www.landlaeknir.is). According to the 2012 Health Survey, only about 10% of men and 20% of women eat fruit or berries twice a day or more, and even fewer, or about 7% of men and 20% of women, eat vegetables twice a day or more. There were no major changes in these proportions between 2007 and 2012, and the same for fish, although almost half the respondents did report eating fish twice a week or more. According to the annual monitoring, the proportion of women eating fruits and berries twice a day had increased to 30% by 2018 and 36% for vegetables, while the equivalent proportions for men were 21% and 28%.

2.2.4.3 Consequences of dietary transition

The most obvious sign of the nutrition transition in Iceland is the rapid increase in obesity, evident in the national nutrition survey data from 1990 to 2010/2011. Icelanders now rank highest of the Nordic nations in the proportion of overweight and obese people, with 59.6% of adults overweight (BMI ≥ 25) and 21% obese (BMI ≥ 30) (Matthiessen et al., 2016). At the same time, coronary heart disease has decreased dramatically, while Type 2 diabetes is rising. Dietary iodine has also decreased significantly and iodine status has worsened, especially among young women who eat less fish than previously and use less dairy (Adalsteinsdottir et al., 2020). Fish and dairy have been the two major sources of iodine in the Icelandic diet as iodized salt is not widely available and has not been specially recommended by health authorities.

2.2.4.4 Gaps in knowledge

Nutrition status for essential nutrients is not known as it has not been measured in a random or representative sample of the population. This includes vitamin D, iodine and folate status, where intake data suggest that status may be compromised. Also, information on salt intake needs to be improved using biological samples rather than nutrient intake data only. Finally, the Icelandic Food Composition Database (ISGEM) requires urgent updating to include new foodstuffs as this important tool has received little attention over the past decade.

2.2.5 Faroe Islands

2.2.5.1 The traditional diet

The traditional Faroese diet consists of fish, seafood, lamb, and vegetables such as potatoes and turnips (Joensen, 2015). From early times and until home freezers became common in the Faroes in the late 1960s, the usual ways to preserve animal products were by drying and fermenting. Mammals, birds and fish were wind-dried; salt was not used. This took place in a *hjallur*, a storehouse where one to all four sides of the house was made of laths so that the sea breeze could pass through (Svanberg, 2015). The Faroe Islands today constitutes a modern society with a living standard similar to that of the other Nordic countries. The *hjallur* is still built on most private sites, and fermented and dried meat and fish are cherished in the Faroese cuisine.

Pilot whale meat and blubber have been part of the Faroese diet for centuries. Due to high mercury levels in the whale meat and high organohalogen levels in the blubber, dietary recommendations have since the 1970s become progressively more restrictive. In 2008, a recommendation was issued stating that pilot whale meat and blubber were considered unfit for human consumption (Weihe and Joensen, 2012). More detailed information on this can be found in Chapter 6.

2.2.5.2 Dietary changes

The Department of Occupational Medicine and Public Health has conducted studies for more than 30 years on environmental exposure to toxic substances, mainly through intake of marine mammals, and effects on human development. The studies have included questions to participants about dietary intake, usually in the form of short questions about whale meat and blubber, seabirds and fish. Two in-depth dietary surveys were completed at the department.

General dietary intake was assessed in three studies in the Faroe Islands at three time-points: 1981/1982 (Vestergaard and Zachariassen, 1987), 2000/2001 (Veyhe, 2006) and 2013–2016 (Weihe, pers. comm., 2020).

There have been significant changes in dietary habit in the Faroe Islands. Table 2.8 presents the daily intake of seven major food groups, as well as whale meat and blubber. Intake of fish, potatoes, oils and grains has decreased since the early 1980s, while meat and vegetables have increased over this period. Despite the heterogeneity of the study groups, in that they represent different stages in life and do not include identical age groups, it is likely that the changes presented are representative for the Faroe Islands as a whole.

2.2.5.3 Estimated intake from the 1930s to 2010s

Intake of whale meat, whale blubber, seabirds and fish has been recorded in five different studies, involving 4711 participants (Veyhe, 2006; Choi et al., 2009; Veyhe et al., 2018, 2019; unpublished data). The studies are as follows: ‘Dietary survey’, including 148 pregnant women born 1959–1984; ‘Whalers’, including 162 men born 1924–1984; ‘Time-to-pregnancy’, including 1225 index women born 1966–1976 and 1225 index women’s mothers born 1921–1958; and ‘Type-2 diabetes’, including 1230 men and women born 1934–1971. The estimated consumption period was childhood, youth, until first pregnancy (question posed to women), adulthood, the year before sample collection and two months before sample collection. The same questions were asked in all projects: How often have you eaten whale meat, whale blubber, seabirds and fish with four options: never; times per year; times per month;

Table 2.8 Daily intake of major food groups in the Faroe Islands over recent decades; 1981–1982 (Vestergaard and Zachariassen, 1987), 2000–2001 (Veyhe, 2006), and 2013–2016 (Weihe, pers. comm., 2020).

Food group	Daily intake, g/day		
	1981–1982 men and women, ≥14 years, 52% participation rate (n=331)	2000–2001 pregnant women, 50% participation rate (n=148)	2013–2016 28-year follow-up of 1986/87 birth cohort, 71% participation rate (n=703)
Dairy products	390	505[a]	179
Meat	68	80	87
Fish	72	40	28
Oils and dressings	40	22	18
Potatoes	192	140	112
Grains and cereals	215	323	124
Vegetables	32	69	78
Whale meat	12	1.5[b]	9[c]
Whale blubber	7	0.6[b]	[d]

[a]Pregnant women were advised to drink half a liter of milk daily during pregnancy or equivalent intake of dairy products; [b]dietary recommendations issued in 1998 advised pregnant women in particular not to eat whale meat and blubber (Weihe and Joensen, 2012); [c]whale meat and seabirds; [d]daily intake of blubber cannot be calculated, but a total of 65% reported abstaining from blubber, 15% reported consumption once a month and 20% reported consumption more than once a month.

Table 2.9 Overview of the number of participants and distribution of birth years for each decade and estimated food intake for dietary surveys in the Faroe Islands.

	Decade food consumed								
	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Sample size	40	457	1646	2257	1787	1856	1713	349	2259
Year born	1921–1929	1921–1939	1924–1949	1933–1959	1940–1969	1950–1976	1960–1984	1924–1984	1934–1987

times per week? All responses were converted to intake 'times per year'. Table 2.9 presents the number of participants and the distribution of birth years for each decade of estimated intake.

As presented in Figure 2.4, the intake of whale meat and blubber has decreased nearly 80% since the 1930s, albeit with a small increase from the 2000s to 2010s. Half the participants from the period 2000–2009 are pregnant women in their third trimester, participating in a dietary survey (Veyhe, 2006). The dietary recommendation at that time was to avoid consuming whale meat and blubber during pregnancy (Weihe and Joensen, 2012) and these studies may, therefore, underestimate intake during this period. However, the latest dietary information (Veyhe et al., 2018, 2019; unpublished data) collected five to eight years after the last recommendation indicates that the steady decline seen from the 1930s to 1990s may have plateaued or even reversed during 2010–2019. The reason for the increase is not yet known. In fact, over the past few years there has been strong international opposition to whaling in the Faroe Islands, which might have resulted in a contradictory response in the Faroese population, especially among men as men consume pilot whale meat and blubber more frequently at all age groups.

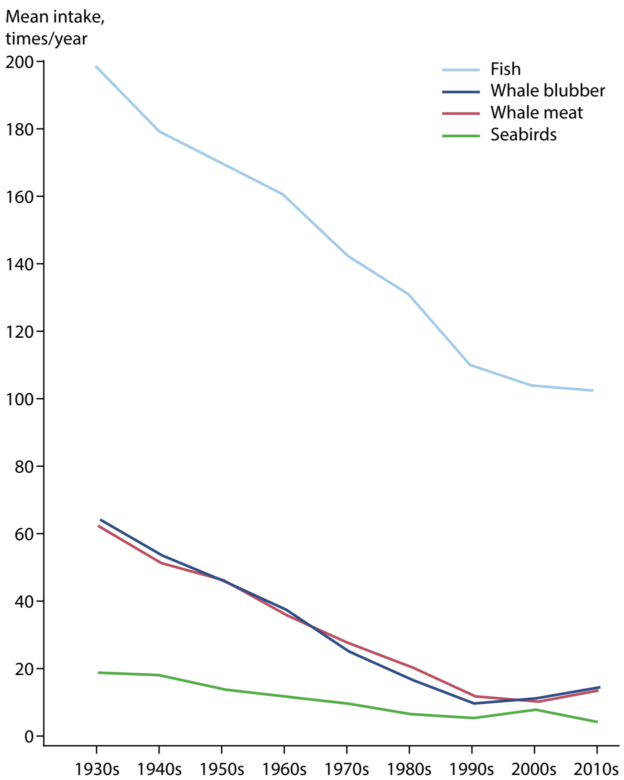

Figure 2.4 Estimated mean annual intake of four important food groups in the Faroe Islands since the 1930s.

The annual intake of seabirds is estimated at about a third of whale intake but shows a similar pattern over time to whale meat and blubber with a nearly 80% reduction. The small increase in the 2000s is believed to represent increased intake in the millennium decade because the participants from the different studies present at this decade all record the same pattern of increased intake. However, the food frequency questionnaire used in the dietary study (Veyhe, 2006) included some extra questions about seabird intake compared to the questionnaires used in the projects for the Whalers (Choi et al., 2009), Time-to-pregnancy (unpublished data) and Diabetes projects (Veyhe et al., 2018, 2019). Nevertheless, the same seabird questions were used at the 28-year follow-up for 1986/1987 birth cohort (Grandjean et al., 1992) and their intake is similar to that recorded by participants in the Whalers, Time-to-pregnancy and Diabetes studies, which did not include the detailed information.

There has been a steady decline in fish intake since the 1930s, from nearly four meals per week to less than two meals per week. This pattern is similar to the observations presented in Table 2.8 with a mean intake of 72 g/day in 1981–1982 and 28 g/day in 2013–2016, a fall of more than 60% in the past 30 years. Furthermore, the levelling off seen in the last decade (see Figure 2.4) can be attributed to the study group representing intake for this decade. The dietary information is from the Diabetes project (Veyhe et al., 2018, 2019) including participants born from 1934 to 1971 and from the 28-year follow-up birth cohort (Grandjean et al., 1992), the former group 40 years senior to the latter. The older group reported eating fish 128 times per year, equal to 2.5 times per week, while the younger group reported eating fish 1.1 times per week ($p<0.001$), see fish intake in Figure 2.4.

Part of the campaign against eating contaminated whale meat and blubber has been to inform people about the good nutritional qualities in fish low in contaminants, including lean fish such as cod and haddock and fatty fish such as herring, mackerel and salmon. The Faroes Board of Health recommends that people eat low-contaminated fish with no upper limit on weekly servings. Nevertheless, fish intake shows the same decline as whale meat and blubber. This can be interpreted such that when the authorities advise against one marine food item other marine items tend to follow and are replaced by non-marine foods, as seen here. From a public health perspective, this is unfortunate owing to the range of marine food items low in contaminants. However, the driving force behind the transition of diet in the Faroe Islands over the past four decades has not been the recommendation on pilot whale consumption. The changes in the Faroese diet are likely to reflect changes in societies' ability to import food from other countries. Such imports have increased significantly due to greater transportation capacity and frequency, and to better household economy.

2.2.5.4 Consequences of dietary transition

Reduced exposure to contaminants due to lower consumption of whale meat and blubber as well as increased intake of vegetables is likely to have had beneficial health consequences. However, the apparent replacing of fish intake by meat is likely to have had a detrimental impact on health. As in many other countries, body mass index (BMI) has increased over time (personal communication with Pál Weihe, chairman of the Board of Public Health in 2014). It is not clear whether this is due to dietary transition or to decreased energy expenditure, or to a combination of both.

2.2.5.5 Gaps in knowledge

It is difficult to follow time trends in diet when different groups are included in the studies compared. New studies are planned and will take place in the near future. All projects will include dietary questions; the four main items: whale meat, whale blubber, seabirds and fish; as well as intake specified to highlight single vitamins and minerals and food intake in general. The study populations will be both specifically targeted groups and a random sample from the general population.

2.2.6 Sápmi

2.2.6.1 The Sápmi area

Saami people are the Indigenous People of northernmost Norway, Sweden, Finland and the Kola Peninsula of Russia. Sápmi, the traditional homeland area of the Saami people, is to the largest extent Arctic. However, it also extends further south than the political Arctic borders of Norway and Sweden, including the entire Scandinavian mountain area and neighboring reindeer grazing lands (Figure 2.5). The estimated size of the Saami population is roughly 80,000 to 100,000 (Samer, 2020). This can only be a rough estimate because an ethnic census is no longer performed.

Figure 2.5 Sápmi, the traditional Saami area, is not clearly defined. This figure is an approximate description of the area (Nilsson pers. com., 2020).

2.2.6.2 Traditional diet

In this section, data describing a traditional Saami diet and health are based on data from Norway, Sweden (diet and health) and Finland (health). From a macronutrient perspective, the traditional Saami diet can be described as a diet high in protein and fat and low in carbohydrates compared to a general westernized diet of a Nordic model (Håglin, 1999). Saami people used to collect wild plants and berries and preserve and prepare them in ways minimizing the need for adding refined sugar. Drying and water preservation are examples of these techniques, the latter only applicable to berries naturally rich in benzoic acid, such as cloudberries and lingonberries (Nilsson, 2018). Fish was either prepared fresh by boiling or grilling, or preserved by drying or fermenting (Nilsson et al., 2011). Reindeer and game meat were prepared in ways that maximized the caloric and nutritional exchange, that is, all edible parts were utilized. Depending on season, drying or freezing was the main preservation method for meat.

Table 2.10 Elements of a traditional Saami diet in Sápmi in the period 1990–2004.

Population	Reindeer meat[a], % (Brustad et al., 2008b)	Carbohydrate, E% (Nilsson et al., 2011)	Protein, E% (Nilsson et al., 2011)	Fat, E% (Nilsson et al., 2011)
Norway				
Saami	92	-	-	-
Non-Saami	11	-	-	-
Sweden				
Herding Saami	-	43	15	37
Non-herding Saami	-	47	14	34
Non-Saami	-	48	14	34

[a]Based on a cluster analysis of food frequency questionnaire data from the SAMINOR study (Brustad et al., 2008b), designed to describe a traditional and local diet of northernmost Norway.

2.2.6.3 Dietary changes

In the late 1980s, the macronutrient pattern of a traditional Saami diet was still visible when comparing the diet of Saami with the diet of non-Saami in northernmost Sweden (Håglin, 1988, 1991, 1999). During the period 1990–2000, studies from Norway and Sweden provide further dietary data (Brustad et al., 2008a,b; Ross et al., 2009; Nilsson et al., 2011) and show a higher level of traditional diet among Saami compared to non-Saami (Table 2.10).

Changes in Saami dietary habits over time are likely to be synchronized with general trends in the national states, today described as 'the neoliberal food regime', and characterized by globalization, market liberalization and increased disconnect between domestic food production and food security (Pechlaner and Otero, 2010).

2.2.6.4 Consequences of dietary transition

From a public health perspective, the consequences of a dietary transition are commonly discussed in relation to adverse metabolic health outcomes. Three such measures are summarized in Table 2.11: obesity, cancer morbidity and all-cause mortality. The data refer to the situation pre-2004.

For obesity, results are contradictory. In Norway obesity is more frequent among Saami women compared to the general population, but less frequent among Saami men (Brustad et al., 2008b). In Sweden no statistical differences have been observed between Saami and non-Saami (Nilsson et al., 2011). Cancer morbidity is generally lower in the Saami population, although in Finland and Sweden this is only statistically significant for Saami men (Sjolander, 2011). In terms of all-cause mortality, there are currently no differences between Saami people and the general population of the Sápmi area (Soininen and Pukkala, 2008; Sjolander, 2011).

2.2.6.5 Gaps in knowledge

Lack of modern data on dietary transitions in the Saami, especially for Saami populations in Finland and the Kola Peninsula (Russia), is a major knowledge gap. In Sweden, knowledge of Saami health is sparse and out of date. Thus, longitudinal follow-up of data on dietary transitions in the Saami population after 1996 is not possible, due to later restrictions in the use of registers for defining individuals as Saami (Anderson et al., 2016). Indications suggest that this is also the case in Finland.

In Norway, however, due to the continuation of the SAMINOR study, with planned additional cross-sectional data collection within the next few years, dietary trends will be possible to follow in a more modern setting. A major strength with the SAMINOR study is the self-identification of ethnicity, making it possible to compare Saami and non-Saami inhabitants in the Norwegian parts of Sápmi. This, combined with biobank sampling, clinical measures and data on diet and lifestyle, will allow for more detailed studies on Saami diet and health in the future (Brustad et al., 2014).

A Swedish reply to the SAMINOR study, the Health and Living Conditions in Sápmi (HALDI) project, is under preparation. This aims to bridge the knowledge gap on Saami health in Sweden in close collaboration with the SAMINOR study, the Saami Parliament in Sweden, and Swedish healthcare authorities. This would provide data for the Swedish parts of Sápmi to make more evidence-based decisions related to health issues of Saami inhabitants in a similar way as is the case in the Norwegian parts of Sápmi (Umeå University, 2021).

2.2.7 Norway – general population

The northernmost counties of Norway, Nordland, Troms and Finnmark, are considered as the Arctic parts of Norway. The following sections are not restricted to these parts of Norway but describe dietary intake in the whole country from nationwide dietary surveys. Information on dietary changes in the Saami population in Norway can be found in Section 2.2.6.

2.2.7.1 Dietary changes

The diet in the Norwegian population is monitored using different sources: nationwide dietary surveys, food supply statistics (import and export) and consumer surveys.

Table 2.11 Frequency of obesity, cancer morbidity and general mortality in Sápmi for the period 1990–2010. The health measures are expressed as 1 (reference group within country), - (less frequent than in the reference group), + (more frequent than in the reference group), and 0 (no statistically significant difference compared to the reference group).

Population	Obesity (Brustad et al., 2008b; Nilsson et al., 2011)		Cancer (Hassler et al., 2008)		All-cause mortality (Soininen and Pukkala, 2008; Sjolander, 2011)
	Men	Women	Men	Women	
Norway					
Saami	-	+	-	-	0
Non-Saami	1	1	1	1	1
Sweden					
Herding Saami	0	0	-	0	0
Non-herding Saami	0	0	NA	NA	NA
Non-Saami	1	1	1	1	1
Finland					
Saami	NA	NA	-	0	0
Non-Saami	NA	NA	1	1	1

Nationwide dietary surveys among adults, infants, toddlers, children and adolescents have been conducted several times in the past three decades, see Table 2.12.

Food supply statistics have been regularly gathered and analyzed for more than four decades and a consumer survey was last conducted in 2012. A new nationwide dietary survey among adults in Norway is planned and will be conducted in the period 2021–2023.

Dietary changes in adults

Summary data from the three nationwide dietary surveys among adults are presented in Table 2.13: Norkost 1 (1993–1994; Johansson, 1997), Norkost 2 (1997; Johansson and Solvoll, 1999) and Norkost 3 (2010–2011; Totland et al., 2012).

Cereals are a staple food in Norway. Food supply statistics show that in the late 1950s the intake of cereals was a little below 100 kg/person/year. This declined in the 1960s and 1970s to about 70 kg/person/year, increased to 90 kg/person/year in the 1990s and is now about 80 kg/person/year (Norwegian Directorate of Health, 2020). In accordance with this, the nationwide dietary surveys show the intake of bread and cereals to have fallen between 1993 and 2011. Production of whole grains has increased in Norwegian mills since 2000, which implies increased use of whole grain. This is also evident in the nationwide dietary surveys, which show increased intake of dietary fiber over time, of which cereals are an important source.

The food supply statistics show a steady increase in intake of fruit, berries and vegetables, from the late 1950s and until today (Norwegian Directorate of Health, 2020). In the period 1993 to 2011, men and women increased their intake of fruit, berries, vegetables and juice by approximately 100 g/day (men) and 150 g/day (women). As the food supply statistics show a small decrease in supply of fruit and berries over the past decade, this may suggest a small recent decline in intake compared to 2015.

Table 2.12 Overview of the Norwegian national dietary surveys, 1993 to 2019.

National survey	Age group	Year
Spedkost 1, 2 and 3	6 and 12 months	1998–1999, 2006–2007, 2018–2019
Småbarnskost 1, 2 and 3	2 years	1999, 2007, 2019
Ungkost	4 years	2000, 2016, 2018–2019
Ungkost	9 years	2000, 2015, 2018–2019
Ungkost	13 years	1993, 2000, 2015, 2018–2019
Ungkost	18 years	1993
Norkost 1 and 2	16 to 79 years	1993–1994, 1997, 2010–2011
Norkost 3	18 to 70 years	1993–1994, 1997, 2010–2011

Potato intake has decreased steadily since the 1950s. This is seen in both the nationwide dietary surveys and the food supply statistics (Norwegian Directorate of Health, 2020). In contrast, both the food supply statistics and the nationwide dietary surveys show meat intake has increased steadily, including both red and white meat consumption (see Table 2.13). Food supply data show fish consumption was approximately 34 to 35 kg/person/year in the period 2008–2015. The nationwide dietary surveys showed a stable fish intake of about 80 g/day (men) and 60 g/day (women) in the period 1993–2011. However, food supply data suggest there may have been a recent decline in fish consumption of more than 10% (Norwegian Directorate of Health, 2020).

Table 2.13 Estimated intake of selected food groups in adult men and women in Norway, from the nationwide dietary surveys Norkost 1 (Johansson, 1997), Norkost 2 (Johansson and Solvoll, 1999) and Norkost 3 (Totland et al., 2012).

Food group	Men			Women		
	Norkost 1 1993-1994	Norkost 2 1997	Norkost 3 2010-2011	Norkost 1 1993-1994	Norkost 2 1997	Norkost 3 2010-2011
Energy, MJ/day	11.7	10.9	10.9	8.4	8.0	8.0
Bread and cereal products, g/day	292	284	272	197	198	179
Potatoes, g/day	158	147	83	110	100	50
Vegetables, g/day	124	123	154	135	146	155
Fruit, berries and juice, g/day	212	218	282	216	225	344
Meat and meat products, g/day	129	125	181	91	87	116
Fish and fish products, g/day	78	72	79	57	56	58
Milk, cream, yoghurt, g/day	632	545	406	463	386	270
Cheese, g/day	34	32	46	29	30	42
Egg, g/day	20	19	28	15	15	23
Sugary sodas, g/day	316	351	282	248	254	202
Coffee, g/day	528	501	591	420	400	454
Wine, g/day	14	16	44	11	18	46

Table 2.14 Estimated intake of energy-providing nutrients, and alcohol, given in energy percentage E% per day in adult men and women from the nationwide dietary surveys Norkost 1 (Johansson, 1997), Norkost 2 (Johansson and Solvoll, 1999) and Norkost 3 (Totland et al., 2012).

Energy-providing nutrient	Energy percentage E% per day					
	Men			Women		
	N1 1993-94	N2 1997	N3 2010-11	N1 1993-94	N2 1997	N3 2010-11
Protein	15	16	18	16	16	18
Fat	31	31	34	30	30	34
Carbohydrates	52	51	43	53	52	44
Sugar	9	10	7	9	9	7
Alcohol	2	2	3	1	1	2

The estimated intakes of egg increased for both men and women through Norkost 1, 2 and 3, with a daily intake in 2011 of 28 g/day (men) and 23 g/day (women). This increase is also seen in the recent food supply data report (Norwegian Directorate of Health, 2020). Intake of milk and dairy products has decreased over recent decades, except for white cheese which has increased slightly. In Norkost 3, the total intake of dairy products was approximately 450 g/day (men) and 310 g/day (women).

Consumption of butter and margarine in recent decades has decreased alongside an increase in consumption of plant oils (Norwegian Directorate of Health, 2020). Data from Norkost 2 to Norkost 3 show decreased intake of sugary soda from 1997 to 2010/2011. Food supply statistics suggest that this trend has continued, with a reduction of as much as 19% in the period 2015–2019 (Norwegian Directorate of Health, 2020).

The latest food supply and nationwide dietary surveys among adults show that the Norwegian population exceeds the recommended intakes of saturated fat and salt and that the intake of protein and fiber has increased over the past decade, while the intake of sugar has decreased (Table 2.14).

Dietary changes in children and adolescents

The latest nationwide dietary survey for infants of 12 months of age was conducted in 2019 (Paulsen et al., 2020) and showed that 48% of 12-month old children were breastfed. The intake of sweet beverages and sugar has decreased in this group compared to the 2007 survey, whereas the intake of vegetables, fruit and berries has increased (Paulsen et al., 2020). For infants 6 months of age, the latest survey showed that breastfeeding practices have been largely stable since 2006, with 80% and 78% of the infants being breastfed at 6 months of age in 2006 and 2018, respectively (Myhre et al., 2020). Compared to the survey in 1998 (Lande, 2003), more infants had consumed fish and fruit and fewer had taken juice with sugar in 2006. This trend has increased even more in Spedkost 3 with 84% being introduced to composite meals with fish, vegetables, and potatoes at 6 months of age (Paulsen et al., 2020).

Similar to the surveys at 6 and 12 months of age, nationwide dietary surveys have been conducted three times among 2-year-olds. The last survey showed several positive trends, including intake of bread and cereals, fruit, berries, vegetables, meat, fish yoghurt and milk within the Norwegian recommendations. Intakes of nutrients were also mainly in line with recommendations, with the exceptions of saturated fat (above recommendation) and iron (below recommendation). The intakes of sweet beverages and sugar have also decreased, which is very positive.

The second nationwide dietary survey among 4-year-olds, completed in 2016, showed the diet in this age group was mainly in line with the health authorities' recommendations. However, the intake of fruit and vegetables was too low and saturated fat too high (Hansen et al., 2017).

The results of the latest nationwide dietary survey conducted among 9- and 13-year-olds in Norway show that the diet of children and adolescents who participated in Ungkost in 2015 was largely in line with the recommendations of the health authorities (Hansen et al., 2016). The nutritional weaknesses in the diet consisted of an excessive intake of saturated fat and added sugar, while the intakes of fruit, vegetables and fish were lower than recommended.

2.2.7.2 Consequences of dietary transition

There have been several dietary changes in Norway in recent decades of benefit to health. The reduced intake of sugar, and increased intake of fruit and vegetables, and dietary fiber are positive changes that may over the long-term have a beneficial impact on the risk of non-communicable lifestyle diseases. However, there are still nutritional challenges, which are associated with increased risk of non-communicable diseases such as cancer, cardiovascular disease and Type 2 diabetes. Intake of red and processed meat is higher than recommended and, although increased, the intakes of dietary fiber, fruit and vegetables are still too low.

The decrease in fish intake may partly explain the low intake of iodine in certain sub-groups, especially young Norwegian women. The reduced intake of milk and dairy products is on the one hand positive when considering it may contribute to lower intakes of saturated fat, but on the other hand it may also reduce the intake of other important nutrients, especially iodine intake. Lean marine fish and milk and dairy products are the two most important sources of iodine in the Norwegian diet and changes observed in the past decade are thus of concern. Iodized table salt is not widely used in Norway. The traditional diet dominated by dairy products, as well as lean fish in coastal areas, was thought to provide the population with enough iodine. This may no longer be the case (Henjum et al., 2019). As much as 80% of the 197 women in the Northern Norway Mother-and-Child contaminant Cohort Study (MISA 1) had urinary iodine concentrations below the recommended level (Berg et al., 2017). Low maternal iodine status has been associated with impaired neurodevelopment in offspring in the Norwegian Mother and Child Cohort Study (Abel et al., 2019).

2.2.7.3 Gaps in knowledge

The most recent national dietary survey on adults took place in 2010–2011 and can now be considered old. The next survey is planned for 2021–2023.

2.2.8 Sweden – general population

The two northernmost counties of Sweden, Norrbotten and Västerbotten, are considered as the Arctic parts of Sweden. The following sections are not restricted to these parts of Sweden but also describe dietary intake in the whole country from nationwide dietary surveys. Information on dietary changes in the Saami population in Sweden can be found in Section 2.2.6.

2.2.8.1 Dietary changes

The Swedish Food Agency conducts nationally representative dietary surveys of the general population. The latest survey on adults was performed in 2010–2011 (Riksmaten Adults 2010-11, n=1797, 18–80 years). Previous national dietary surveys were undertaken in 1989 (Becker, 1994) and 1997–1998 (Becker and Pearson, 2020). Different dietary assessment methods were used in the surveys, making direct comparisons over time difficult. Nevertheless, the survey data do suggest several positive dietary changes in the Swedish population. For example, fruit and vegetable intake has increased, as has fish and shellfish consumption and the proportion of oil-based fats (Amcoff et al., 2012). But despite this, a large proportion of the population did not reach the dietary recommendations in the 2010–2011 survey. In short, the intake of fruit, vegetables and whole grain was too low and the intake of foods high in sugar, fat and salt too high. It is also important to note that the participation rate in Riksmaten Adults 2010-11 was only 36% and that participants had higher educational levels than non-participants. As education is often associated with health consciousness, there is thus a risk that the survey may give an overly positive view of dietary habits in Sweden.

In 2016–2017, the Swedish Food Agency performed a national youth dietary survey (Lemming et al., 2018a; Moraeus et al., 2018), which included a total of 3099 children in grade 5 (age 11–12 years), grade 8 (age 14–15 years), and second grade in 'high school' (age 17–18 years). Around 60% of the invited adolescents participated. Results for the participants in grade 5 can be compared to a previous dietary survey on children from 2003 (Barbieri et al., 2006) and some positive changes are evident. Consumption of vegetables and wholegrain foods increased and the proportion of energy from sweets, soda and snacks decreased. But despite these positive trends, children and youth in Sweden do not eat enough fruit, vegetables and fish and still consume more sweets, soda and snacks, as well as red and processed meat, than desirable. Children from homes with lower education levels had poorer dietary intake.

Dietary trends in northern Sweden (Västerbotten and Norrbotten) have been studied within the Northern Sweden Health and Disease Study over 25 years, from 1986 to 2010 (Johansson et al., 2012). Two trend breaks were observed in both sexes for total fat consumption: a decrease from 1986 and an increase from 2002 in women and 2004 in men. The increase in fat consumption coincided with a decrease in intake of carbohydrates and is believed to be due to a trend in a 'low carb high fat' diet that got much attention in Swedish media around this time. During the 1990s, the decrease in fat was mainly in the form of saturated fat due to a switch to dairy products with a lower fat content, as well as a switch from 80% fat content to 40% fat content in spread fats and an increase in the use of vegetable oils (Krachler et al., 2004). Other interesting trends were an increase in wine consumption, especially for women, while consumption of beer increased in men (Johansson et al., 2012).

In a recent study on participants from the Västerbotten Intervention Program, food patterns were compared between 2000–2007 (n=47467) and 2008–2016 (n=53040). Findings indicate a shift away from recommended food habits as a greater proportion of participants were classified into food intake patterns characterized by high-fat spread and high-fat dairy in 2008–2016 compared to 2000–2007. Also worrying was that the proportion classified with high consumption of fruit, vegetables and fiber was lower in the later study period (Huseinovic et al., 2019).

2.2.8.2 Consequences of dietary transition

According to Riksmaten Adults 2010-11, most adults had a satisfactory intake of vitamins and minerals. Compared to the earlier dietary surveys, intakes of vitamin D and selenium were higher in 2010-11, due to increased consumption of fish and increased fortification of dairy products and margarines with vitamin D. Intake of folate and vitamin C was higher in the 2010-11 survey due to increased consumption of fruit and vegetables. These are all consequences of favorable dietary changes, but despite this, intake of vitamin D, folate and iron was still low, especially in young women. Intake of iron decreased from 1989, probably because the process of supplementing flour with iron was stopped in 1994/1995.

In Riksmaten Adolescents 2016-17, it was found that most individuals had a satisfactory intake of nutrients, but almost a third of girls in grade 8 and grade 2 in high school had low iron stores. A majority of the participants ate too much saturated fat and not enough polyunsaturated fat and most participants did not eat enough fiber and whole grain. A socio-economic association was clear, with higher intakes of fiber and many important vitamins and minerals observed in the children of parents with higher levels of education (Lemming et al., 2018b).

In the 1970s and early 1980s, northern Sweden had among the highest prevalence of cardiovascular disease in the world (Tuomilehto et al., 1987). The decrease in fat consumption, and especially the change to more unsaturated fats, was a contributory factor to decreasing cholesterol levels from 1986, which contributed to the decrease in cardiovascular disease (Eriksson et al., 2011).

Despite improvements in dietary habits in the Swedish population favorable for cardiovascular risks, BMI has increased. In Riksmaten Adults 2010-11, 42% of women and 57% of men were overweight or obese. In Riksmaten Adolescents 2016-17, around 21% of participants were overweight or obese. Recent data indicating a shift towards higher fat consumption and lower consumption of fruit and vegetables (Huseinovic et al., 2019), as well as the finding of poorer dietary habits in younger compared to older adults (Amcoff et al., 2012), are worrying for the future and indicate the need for strong interventions to improve dietary habits, especially in groups with lower education levels. Low iron stores in young women also warrant attention.

2.2.8.3 Gaps in knowledge

The most recent dietary survey for adults at the national level can already be considered old (2010–2011). The Swedish Food Agency is planning two new surveys: toddlers in 2021–2024 and adults 2026–2028.

2.2.9 Finland – general population

The northernmost part of Finland, Lapland, is usually considered as the Arctic part of Finland. The following sections are not restricted to Lapland but also describe dietary intakes in the whole country from nationwide dietary surveys. Some information on dietary changes in the Saami population in Finland can be found in Section 2.2.6.

2.2.9.1 Dietary changes

The Finnish Institute for Health and Welfare (THL, former National Public Health Institute) has undertaken national dietary surveys at regular five-year intervals since 1992. The first was in 1982 as part of the WHO-driven MONICA project (Uusitalo et al., 1987), and in later years (1992 to 2012) as part of the National FINRISK Studies (Kleemola et al., 1994; Anttolainen et al., 1998; Männistö et al., 2003; Paturi et al., 2008; Helldán et al., 2013; Borodulin et al., 2018) and in 2017 as part of the FinHealth Study (Valsta et al., 2018a; Koponen et al., 2018). The aim of the cross-sectional FinDiet Surveys has been to monitor food consumption and nutrient intake in the adult population.

The FinDiet Survey samples are roughly 30% subsamples (n=2000–3000) of the large population-based health surveys (Borodulin et al., 2018; Koponen et al., 2018). Participation rates (i.e., those with a successfully completed dietary assessment) decreased from 87% in 1982 to 53% in 2017. The age ranges of the FinDiet Survey participants were 25 to 64 years (surveys 1982–2002), 25 to 74 years (surveys 2007–2012) and 18 to 74 years (survey 2017). The main dietary assessment methods have included three-day food records (1982–1992), and 24-hour dietary recall interviews concerning all foods and beverages consumed during the previous day, previous two days, or two non-consecutive days (1997–2017). Two non-consecutive 24-hour dietary recalls in the 2017 FinDiet Survey enabled usual intake modeling (i.e., estimation of the average long-term intake) of the population, and thus more reliable estimation of the proportions of the population meeting dietary recommendations (Valsta et al., 2018a).

Overall, the results of the FinDiet Surveys are generalizable to the Finnish adult population. However, non-participation may affect the results (Reinikainen et al., 2018), and this is in part corrected by survey weights. Use of different dietary assessment methods over the years, and changes in food classification in the food composition database, warrant careful interpretation of changes over time. With these limitations in mind, the following paragraphs summarize the dietary changes in Finland over recent decades.

In general, the dietary habits of men and women have differed over the years. Women have mostly led the way to new dietary habits. The women's diet has usually been closer to the Nordic and thereby also the Finnish dietary recommendations (National Nutrition Council, 2014; Nordic Council of Ministers, 2014). Consumption of vegetables, fruit, and berries has steadily increased in the working-age population since 1997, and the consumption of red and processed meat, as well as fish, has on average remained stable. Subjects in the highest educational group continue to consume more vegetables and fruit than people in the lowest educational group (Raulio et al., 2017). According to the FinDiet 2017 Survey, 86% of men, and 78% of women did not reach the recommended consumption level for vegetables, fruit, and berries (500 g/day) (Kaartinen et al., 2018). Moreover, while 74% of women met the recommendation to consume less than 500 g/week of red and processed meat, only 21% of men did so.

Over time, butter consumption has declined and milk consumption has switched from high-fat milk to low-fat milk (Männistö et al., 2010). In the past 20 years, butter consumption has been higher in participants with a lower level of education compared to more highly educated participants (Raulio et al., 2017). In men, this difference increased between 2007 and 2012. In contrast, consumption of vegetable oil-based fat spreads and vegetable oils has increased in all educational groups.

Across the surveys, there has been some fluctuation in the macronutrient composition of the diet. The proportion of energy (percentage of the energy consumed = E%) from fat decreased from 37 to 39 E% in 1982 to 34 E% in 1992 (Pietinen et al., 1994). During the 2010s, fat intake started to increase again reaching the same level as in the early 1980s (mean intake 39 E% in men and 38 E% in women in 2017) (Valsta et al., 2018b). The proportion of energy from saturated fatty acids decreased from 20 E% to 12 E% between 1982 and 2007 (Männistö et al., 2010; Vartiainen et al., 2016). Mean intake of saturated fatty acids then increased and was 15 E% in men and 14 E% in women in 2017 (Valsta et al., 2018b). The intake of monounsaturated and polyunsaturated fatty acids also increased over the past decade. In 2017, mean intakes were 15 E% (men) and 14 E% (women) for monounsaturated fatty acids and 6.8 E% (men) and 6.9 E% (women) for polyunsaturated fatty acids (Valsta et al., 2018b). In 2017, 35% of Finnish adults exceeded the recommended intake for total fat (25–40 E%) and 95% exceeded the recommendation for saturated fatty acids. Overall, at least nine out of ten Finnish adults reached the recommended level for monounsaturated fatty acids (10–20 E%) and polyunsaturated fatty acids (5–10 E%).

From 1997 onwards, the proportion of energy obtained from carbohydrates has decreased. A clear shift to a lower proportion of energy from carbohydrates occurred between 2007 and 2012, a time when low-carbohydrate diets received much attention in the media. In 2017, the proportion of energy from carbohydrates was 41 E% in men and 43 E% in women (45–60 E% is recommended) (Valsta et al., 2018b). The daily intake of dietary fiber increased over the past decade and was 22 g in men and 20 g in women in 2017 (25–35 g/day is recommended). The proportion of energy from sucrose has on average remained near the recommended maximum of 10 E% in recent decades. In 2017, the mean intake of sucrose was 8 E% in men and 9 E% in women. Overall, around 70% of both men and women had a lower intake of dietary carbohydrates and dietary fiber than recommended (Valsta et al., 2018b).

Depending on the definition of added sugars, at least a quarter of the population exceeded the recommended intake of added sugars (Valsta et al., 2018b).

2.2.9.2 Consequences of dietary transition

Over recent decades, goal-oriented nutrition policy actions have addressed the intake of those vitamins and minerals that are critical to health in the Finnish population (Pietinen et al., 2010). These include salt, vitamin D, and iodine.

After low intakes of vitamin D were detected in the early 2000s, the National Nutrition Council began a fortification program for liquid milk products and fat spreads. The recommendations regarding vitamin D supplements were updated in 2011. As a consequence, vitamin D intake from food doubled between 2007 and 2017 (Raulio et al., 2017; Valsta et al., 2018b). When dietary supplements are taken into account, 7% of the population falls below the average requirement level (7.5 µg/day) (Valsta et al., 2018b).

Daily salt intake decreased by a third between the 1970s and 2007. This was largely achieved through intensive public health interventions, information steering, and health education begun in the North Karelia Project and continued in several activities within the health and nutrition sector (Jousilahti et al., 2016a; Laatikainen et al., 2016; Vartiainen, 2018). There has been successful interaction between the private and public sector and non-governmental organizations. However, there have been no major changes in salt intake since 2007 (Niiranen et al., 2019). In 2017, 98% of men and 86% of women exceeded the recommended intake of <5 g/day (Valsta et al., 2018b).

In Finland, the soil is largely low in iodine. Fortification of cow fodder and table salt began in the late 1940s and led to a stable iodine status in the population between 1960 and 1990 (Nyström et al., 2016). Due to shifts in dietary habit, such as lower milk consumption and increased consumption of industrial food products containing non-iodized salt, low concentrations of iodine in urine were again measured in national health surveys. In 2015, the National Nutrition Council launched a recommendation for citizens, catering services, and the food industry to switch to iodized salt. As a consequence, the iodine status of Finnish adults (measured from urine spot samples) has improved and is now considered adequate according to the WHO recommendation (median iodine concentration in urine 100–199 µg/L) (Erlund et al., 2018).

Mean serum cholesterol in Finnish adults decreased strongly between the early 1970s and 2007. It then increased slightly to 2012 (Jousilahti et al., 2016b). Between 2012 and 2017, a decrease was again observed (Laatikainen et al., 2019). At the population level, 80% of the serum cholesterol decrease could be explained by a healthy diet and 20% by the use of drugs (statins) to treat high cholesterol (Valsta et al., 2010). The most important dietary factors affecting cholesterol level include the transition from fatty milk to low fat and skimmed milk, the substantial decrease in butter consumption, the increase in consumption of vegetable oils, and the increased consumption of vegetables and fruit. The increase in total fat, and increase in saturated fatty acids originating from dairy-based fats in some population groups in the 2010s presumably explain part of the halt in the downward trend. The slight serum cholesterol increase during 2007 and 2012 was exclusively due to the change in fat quality from vegetable oils to dairy-based fats in some parts of the population (Vartiainen et al., 2016). The adverse dietary change might be due to the increased popularity of low carbohydrate (and high fat) diets in Finland at this time.

Blood pressure levels have decreased significantly in Finland since the 1970s (Laatikainen et al., 2016, 2019). A further decrease is still warranted, however. This may be achieved through improved care (better identification of high risk individuals, effective treatment paths in healthcare, medication, and support to lifestyle change), and prompt improvement in diet. Key actions are to lower salt levels in industrial food products and publicly catered meals. Foods prepared outside the home account for about 80% of salt intake in Finns. The main sources are bread, cheese, meat products, and convenience food (Valsta et al., 2018b).

Mean BMI in Finland increased continuously from the 1970s (men) and 1980s (women) to 2007. Although Finland is among those few countries where obesity trends have recently halted, the prevalence of obesity has remained consistently high (Männistö et al., 2015). In 2017, 72% of men and 63% of women were at least overweight (BMI 25 kg/m^2 or over), while the prevalence of obesity (BMI 30 kg/m^2 or over) was 26% in men and 28% in women and every second adult (46%) was abdominally obese (waist circumference 100 cm or over in men and 90 cm or over in women) (Lundqvist et al., 2018).

2.2.9.3 Gaps in knowledge

Food consumption and nutrient intakes of Finnish adults have been monitored in nationally representative population-based samples repeatedly since 1982. However, comparable monitoring systems for children and adolescents, as well as the elderly (over 74 years in age), are currently lacking.

2.2.10 Russia

2.2.10.1 Traditional diet

Historically, the circumpolar Arctic Indigenous Peoples consumed only what they were able to obtain themselves locally by hunting, fishing, reindeer-breeding and gathering. From the first 'waves' of subjugation of the Arctic by Europeans, the Indigenous diet was referred to as the 'traditional diet', despite the newcomers also consuming some of the local foods. Today, the Russian Arctic Indigenous Peoples are still strongly dependent on the traditional diet, while the non-Indigenous population consumes local foods to a much lesser extent. The share of 'imported' (store-bought) foods is much higher in the diet of the non-Indigenous population compared to the Indigenous total diet.

The traditional diet of the Arctic Indigenous Peoples has developed over centuries through a combination of many factors – geographic, ethnic, genetic, cultural, and lifestyle factors, among others. Economic conditions, proximity to civilization and transport connections are important present-day factors. It is impossible to make generalizations about the traditional diet across the Russian Arctic as a whole (20,000 km

Figure 2.6 Dietary transition data in the Russian Arctic are available for populations in the Chukotka Autonomous Okrug, Yakutia (Sakha) Republic, Nenets Autonomous Okrug, Arkhangelsk Oblast and Komi Republic. Red circles indicate territories where data are available.

of coastline) because this is a region populated by multiple ethnic groups residing in coastal as well as inland areas, and characterized by unique patterns of food collection that have developed over generations within the different tribes. For example, marine mammal hunting is inherent only to coastal Chukchi and Inuit in Chukotka (Dudarev et al., 2019a,b), while reindeer herding, fishing, and the gathering of berries and mushrooms are widespread. In some communities the harvesting of seaweed, mussels or ascidians is widespread, in others it is not; some ethnic groups are wild plant eaters while others have no such tradition.

There are few recent studies on dietary habits in Russian Arctic communities, especially in terms of dietary shifts. A follow-up assessment of dietary patterns of Indigenous People in the Russian Arctic was carried out in coastal Chukotka (2016 vs 2001–2002) (Dudarev, 2012; Dudarev et al., 2019a) and indirect (collected from statistics) or direct (collected via questionnaires in the field studies) information is available on dietary transition for a few populations. Their locations in the Chukotka Autonomous Okrug, Yakutia (Sakha) Republic, Nenets Autonomous Okrug, Arkhangelsk Oblast and Komi Republic are shown in Figure 2.6.

2.2.10.2 Dietary changes

Chukotka Autonomous Okrug (coastal settlements of Chukotka peninsula)

The total amount of local foods consumed per year by people in settlements in the eastern coastal part of Chukotka (Enmelen, Nunligran and Sireniki in Providensky district) in 2016 (192 kg/person/y) was about 30 kg less than in eastern coastal settlements (Uelen, Chukotsky district) in 2001–2002 (226 kg/person/y). Comparing consumption of local foods between the two periods, marine mammal consumption roughly halved while fish consumption showed little change (Figure 2.7). There may be several reasons for lower consumption of local foods in 2016 compared to 2001–2002, not least being that the villages examined in 2001–2002 (Uelen) are known for their highly skilled hunting crews and ability to secure harvest quotas. Also, in 2001, locally harvested food was often the most reliable source of nutrition in Chukotkan villages still recovering from the severe socio-economic crisis following the collapse of the Soviet Union. As the economy strengthened, the availability of store-bought foods (although still limited) increased and the share of local foods went down.

Indigenous residents of Chukotka currently consume a mix of Indigenous and Slavic/Eastern European foods, plus a

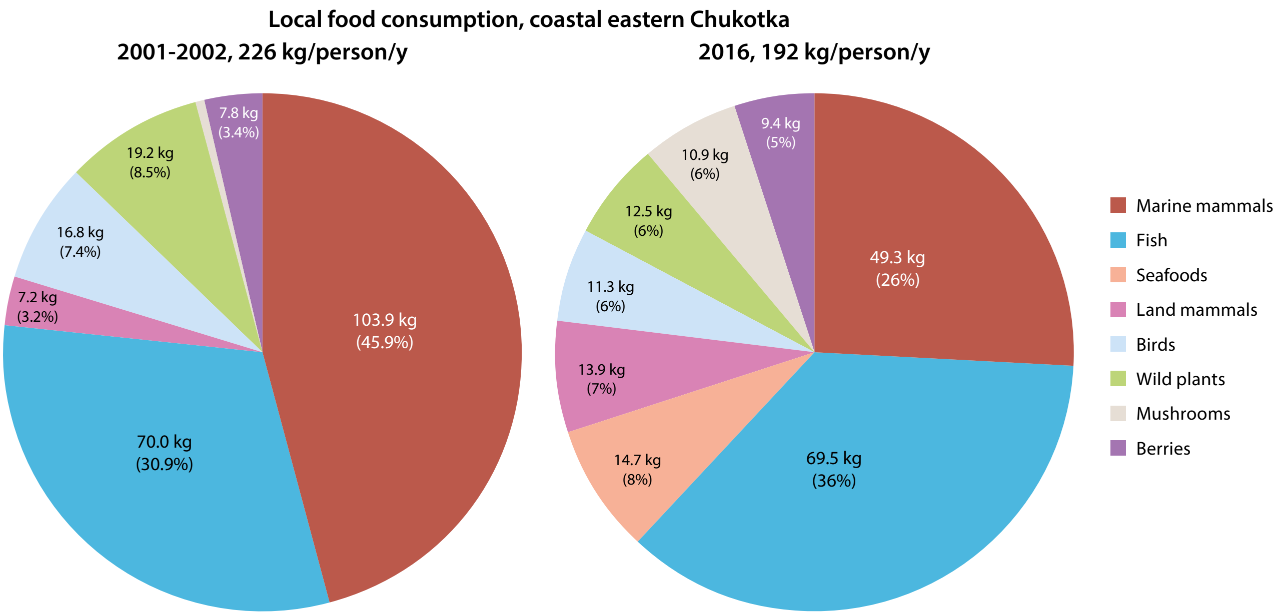

Figure 2.7 Average annual consumption of local foods by Indigenous People residing in coastal eastern Chukotka in (*left*) the settlement Uelen, data obtained by questionnaire in 2001–2002 (adapted from Dudarev, 2012); and (*right*) the settlements Enmelen, Nunligran and Sireniki (Providensky district), data obtained by questionnaire in March–April 2016 (adapted from Dudarev et al., 2019a).

limited amount of mass-manufactured convenience foods. The village stores are infrequently serviced due to poor communications and prices are high. It is common for frozen and canned foods sold at village stores to be past their expiry date and for frozen meat and chicken to show discoloration. Most families use the village store for periodic bulk purchases of pasta, instant noodle soup, flour, grains, powdered milk and egg, dehydrated potato, cooking oil, tea and coffee. It is common for families to be cash-poor and frequently unable to afford store-bought food, thus relying more on locally harvested food (Dudarev et al., 2019a). Availability of freshly baked bread is good because there has been a municipally managed bakery in every village since Soviet times. These bakeries produce crispy sourdough and rye bread on a daily basis. Climate change is contributing to food insecurity as increasingly unreliable sea ice conditions are making it more difficult to hunt local foods.

Yakutia (Sakha) Republic

From 2002–2010, data were collected on the diet of Indigenous and Russian lactating women living in Yakutia rural settlements and in Yakutsk city (Burtseva et al., 2013). The Indigenous women had a lower protein intake than the Russian women in both the rural settlements and Yakutsk city (Table 2.15).

Table 2.15 Daily intake of macronutrients and calories for Indigenous and Russian lactating women living in Yakutia, averaged for 2002–2010 (adapted from Burtseva et al., 2013).

Macronutrient	Rural settlements		Yakutsk city		RDA[a] g/day
	Indigenous (n=133)	Russian (n=10)	Indigenous (n=26)	Russian (n=28)	
Proteins, g	59.8	70.7	53.0	69.9	71
Fats, g	63.2	65.5	59.4	68.3	nd
Carbohydrates, g	257.6	238.3	205.4	233.9	210
Energy, kcal	1819.6	1820.9	1549.1	1824.6	-

[a]Recommended dietary allowances (Institute of Medicine, 2005).

Consumption of food items (as a proportion of total energy consumption) was compared for approximately 300 lactating women in 2013–2016 (Table 2.16). Indigenous women were compared to women living in non-Arctic rural settlements, Arctic rural settlements (Chokurdakh, Saskylakh) and in a more urban area (Yakutsk). The diet of lactating women residing in the Arctic rural settlements (Indigenous and Russian) was characterized by high contributions from milk, butter and macaroni, and low contributions from sausages, chicken, fowl and vegetables – compared to Yakutsk city and non-Arctic rural settlements (Khandyga, Churapcha). Sugar consumption was higher (4% vs 2%) among Indigenous women compared to Russian women in all study groups (Table 2.16).

Nenets Autonomous Okrug

The daily diet of Indigenous children studying and living in the boarding school in Naryan-Mar city showed a significant increase in some types of food, especially potato, vegetables, bread and biscuits, between 2012–2013 and 2017–2018, while sugar intake decreased by 8% (Table 2.17). Consumption of all foods by Indigenous children in Naryan-Mar city in 2017–2018 was broadly in line with the recommended standards for students in general educational schools.

A different situation was seen with the daily diet of Indigenous children studying and living in the boarding schools in rural

Table 2.16 Percentage contribution of different food items in the daily diet for lactating women in Yakutia, average for 2013–2016 (Burtseva and Chasnyk, pers. comm.).

Food	Non-Arctic rural settlements (Khandyga, Churapcha)		Arctic rural settlements (Chokurdakh, Saskylakh)		Yakutsk city	
	Indigenous, n=159	Russian, n=38	Indigenous, n=13	Russian, n=6	Indigenous, n=26	Russian, n=28
Milk	36	36	40	45	28	28
Butter	2	1	3	2	1	1
Meat, store-bought	5	4	5	4	5	4
Meat, wild	1	1	1	2	1	-
Sausages	2	3	1	1	4	4
Chicken and fowl	1	2	1	1	2	3
Fish, wild	2	2	2	3	1	3
Potato	6	7	5	8	6	8
Vegetables, other	10	7	5	5	18	9
Bread	7	6	8	6	6	6
Macaroni	8	9	9	11	6	8
Cereals	10	9	8	4	13	14
Biscuits	2	2	2	2	2	1
Sugar	4	2	4	2	4	2
Other	4	9	6	4	3	4
Total	100%	100%	100%	100%	100%	100%

Table 2.17 Daily diet of Indigenous children (11–17 years) studying and living in the boarding school in Naryan-Mar city, Nenets Okrug, 2012–2013 and 2017–2018 (Shepeleva and Dedkova, pers. comm.).

Food item	Daily diet, g or ml/person/day		Change in 5 years, %	Standard[a], g or ml/person/day	Difference in consumption 2017–2018 from the standard, %
	2012–2013	2017–2018			
Milk and sour milk	475.2	488	+2.7	480	+1.7
Curd and curd products	56.3	60	+6.6	60	0
Sour cream	9.2	10.3	+12	10	+3
Cheese	11.5	11.5	0	11.8	-2.5
Butter	33.8	35.8	+5.9	35	+2.3
Vegetable oil	17.5	18.5	+5.7	18	+2.8
Meat (beef)	81.7	77.5	-5.1	78	-0.6
Sausages	21	19.6	-6.7	19.6	0
Chicken	55	52.4	-4.7	53	-1.1
Eggs	40	38.5	-3.8	40	-3.8
Fish	79.7	74.7	-6.3	77	-3
Potatoes	155	195.8	+26.3	188	+4.1
Vegetables	242.3	330.3	+36.3	320	+3.2
Fruit	170.2	186	+9.3	185	+0.5
Dried fruit	20	19.8	0	20	-1.0
Juice	170	200	+17.6	200	0
Bread, black	69.7	118	+69.3	120	-1.7
Bread, white	131.8	191	+44.9	200	-4.5
Cereals, beans	50	52.2	+4.4	50	4,4
Macaroni	20	20.1	0	20	+0.5
Biscuits	12.3	15	+22.0	15	0
Sugar	50	46	-8.0	45	+2.2

[a]SanPiN (2008).

settlements of Nenets Okrug (Table 2.18). Intake of many food items increased between 2012–2013 and 2017–2018 (curd, sour cream, biscuits, sugar, vegetable oil, meat, sausages, chicken), while the intake of others decreased substantially (milk, dried fruit, macaroni, fish). Consumption of the majority of foods by Indigenous children in rural settlements of the Nenets Okrug in 2017–2018 was characterized by extremes, either falling well below recommended standards (fish, bread, eggs, dairy) or exceeding them by a relatively large margin (sugar, potatoes, meat). Exceedances for biscuits (45%) and sugar (35%) were especially concerning, particularly in light of the low intake of fish, vegetables and fruit.

Arkhangelsk Oblast

Information is available from the Russian Federal State Statistics Service on the diet of the general population of Arkhangelsk Oblast for the period 1998–2017. Unlike data for other regions, these were not collected via questionnaire. The data show a significant increase in consumption of the main food types, especially meat and meat products, eggs and fruit, as well as a general increase in vegetable consumption and a slight decrease in potato intake. Sugar consumption also increased while the intake of baked goods and pasta remained stable. Consumption of some foods by the general population of Arkhangelsk Oblast in 2017 exceeded the recommended standards: vegetable oil by 11.7%, flour products by 9.4%, and sugar by 62.5%. In contrast, consumption of other foods remained below the recommended standards; dairy products, vegetables and fruit intake were more than 40% below the recommended intake (Table 2.19).

Komi Republic

A nutrition survey of the general adult population in Komi Republic was conducted between 2001 and 2015. Results indicate that fat consumption exceeded the recommended WHO intake level by 15–30% over the entire 14-year period. Protein intake was consistently lower than the recommended WHO level (on average about 30% lower, and up to 42% lower in 2003). Carbohydrate intake was also consistently lower (up to 25%) than the recommended WHO level (except 2001 and 2004) (Figure 2.8). At present, the diet of the population of Komi Republic is not sufficiently diverse. It is characterized by a narrow range of basic foods, mainly high-calorie foods with a low vitamin and mineral content (white bread, pasta, confectionery products, sugar). The amount of canned food and highly processed foods is increasing, and also contributes to a noticeable lack of vitamins (Bojko, pers. comm.).

Table 2.18 Daily diet of Indigenous children (11–17 years) studying and living in boarding schools in rural settlements, Nenets Okrug, 2012–2013 and 2017–2018 (Shepeleva and Dedkova, pers. comm.).

Food item	Daily diet, g or ml/person/day		Change in five years, %	Standard[a] g or ml/person/day	Difference in consumption 2017–2018 from the standard, %
	2012–2013	2017–2018			
Milk and sour milk	470.3	350.1	-25.6	480	-37.1
Curd and curd products	11.6	19.7	+69.8	60	-77.2
Sour cream	2.9	5	+72.4	10	-50
Cheese	10.7	10.1	-5.6	11.8	-14.4
Butter	33	31.4	-10.8	35	-10.3
Vegetable oil	17.5	21.1	+20.6	18	+17,2
Meat (beef)	90.2	103.5	+14.7	78	+32.7
Sausages	21.6	25.6	+18.5	19.6	+30.6
Chicken	42.4	50.6	+19.3	53	-4.5
Eggs	35.2	34.1	-3.2	40	-14.7
Fish	68.6	57.2	-16.6	77	-25.7
Potatoes	231.3	245.7	+6.2	188	+30.7
Vegetables	301.9	276.7	+8.3	320	-13.5
Fruit	178.8	156.8	-12.3	185	-15.2
Dried fruit	13.7	6.1	-55.5	20	-69.5
Juice	197.3	194	-1.7	200	-3.0
Bread, black	66.4	61.7	-7.1	120	-48.6
Bread, white	148.5	149.9	+0.9	200	-25.0
Cereals, beans	57.8	59,1	+2.2	50	+18.2
Macaroni	22.8	18.8	-17.5	20	-6.0
Biscuits	13.9	21.8	+56.8	15	+45.3
Sugar	46.5	60.8	+30.8	45	+35.1

[a]SanPiN (2008).

Table 2.19 Consumption of foods by the general population of Arkhangelsk Oblast, 1998-2017 (Shepeleva and Degteva, pers. comm.). Consumption data from the Russian Federal State Statistics Service.

Food items	Average consumption, kg/person/year			Change in consumption, 1998–2017, %	Standard (Russian Federation Ministry of Health Care, 2016) kg/person/year	Difference in consumption in 2017 from the standard, %
	1998	2010	2017			
Meat products	29	53	64	+121	73	-12.3
Dairy products	126	158	176	+40	325	-45.8
Eggs	138	253	240	+74	260	-7.7
Vegetable oil	8.5	11.9	13.4	+58	12	+11.7
Potatoes	95	74	69	-27	90	-23.4
Vegetables	57	76	81	+42	140	-42.1
Fruit and berries	18	61	59	+228	100	-41
Bread, macaroni, flour, cereals, beans	107	109	105	0	96	+9.4
Sugar	30	39	39	+30	24	+62.5

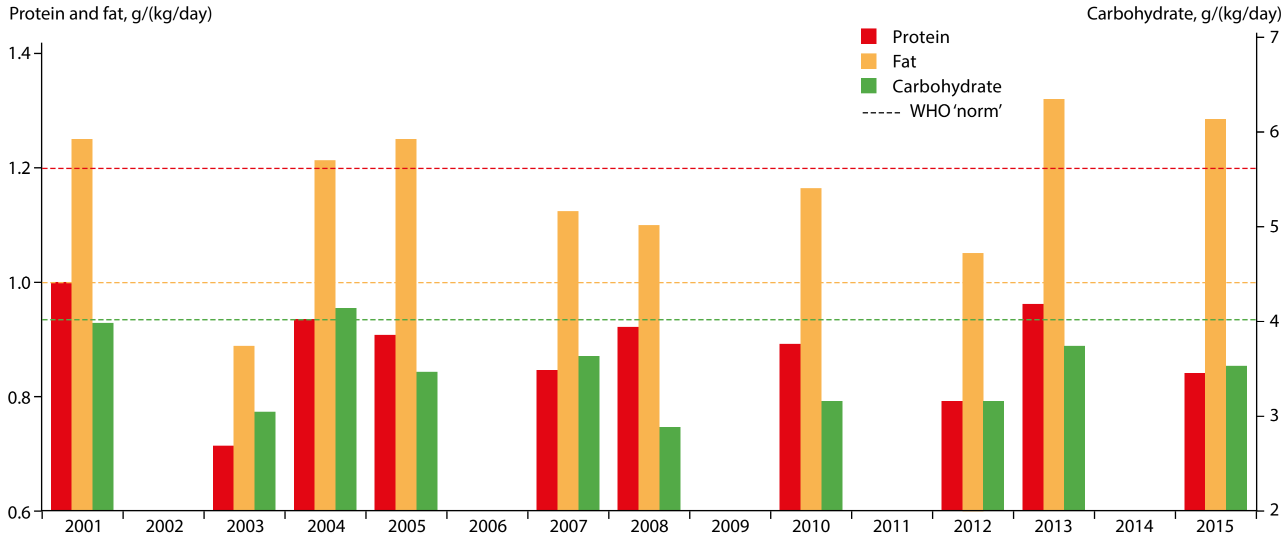

Figure 2.8 Daily intake of protein, fats and carbohydrates in the general population of Komi Republic, 2001–2015 (WHO, 2003; Bojko and Vasilenko, pers. comm.).

2.2.10.3 Consequences of dietary transition

Twenty years of research indicate a pronounced spread of hypovitaminosis (a disorder caused by the deficiency of a vitamin) among residents across the entire European north of Russia (Bojko, pers. comm.). Within Indigenous northern ethnic groups in Russia (Nenets, Komi), those following a more traditional lifestyle have been found to have higher vitamin D status (Kozlov et al., 2014). Increased consumption of processed foods high in starch, fat and sugar and decreased physical activity might lead to an increase in the prevalence of chronic diseases such as diabetes or cardiovascular disease among Indigenous populations in Arctic Russia (Petrenya et al., 2011) and may also be responsible for the observed increase in the prevalence of obesity (Snodgrass et al., 2006; Kozlov, 2019).

2.2.10.4 Gaps in knowledge

There have been very few studies on dietary patterns and dietary transition in the past 10 to 20 years across the vast Russian Arctic, a region inhabited by many different Indigenous ethnic groups. The same is true for studies on the assessment and monitoring of environmental contaminants in traditional foods in Arctic Russia. New studies are needed in the 'unexplored' territories, as well as follow-up studies in previously studied areas, to monitor dietary changes, particularly in relation to the effects of climate change, industrialization and other simultaneously occurring changes in the Arctic.

2.3 Opportunities to support traditional food consumption

2.3.1 Canada

The section gives examples from three Arctic regions that describe efforts to increase food security while also supporting food sovereignty through empowerment and control over food systems and practices.

2.3.1.1 Inuvialuit Settlement Region – training course on country food processing

Responding to priorities concerning regional food security (i.e., high food prices and growing demand for country food) and economic development (i.e., value-added country foods and tourism) in the Inuvialuit Settlement Region (ISR) of the Northwest Territories, the Country Food Development and Value-added Processing Initiative was started by the Inuvialuit Community Economic Development Organization in 2017 (Kenny et al., 2018b). The initiative includes a country food processing training facility fitted with commercial-grade food processing equipment, as well as the Country Food Processing Methods Training Course offered in conjunction with a local college (Aurora College).

The course aims to enhance access to country foods through hands-on teaching, including a variety of flavoring and processing techniques for culturally-valued and less favored parts/species (e.g., beaver bacon) and a range of traditional and contemporary preservation techniques to extend shelf life (e.g., vacuum sealing and canning), with the potential for also making market-ready country-food products. The initiative responds to two regional priorities to support food security, identified during a regional food security engagement process in 2014. These are to promote use of traditional foods to address food security and to build and strengthen capacity within communities through the development of hands-on educational programs, recognizing that education is key to empowering communities (Fillion et al., 2014). The initiative includes specific activities identified by community representatives during the food security engagement, including the development of programs to enhance community capacity to cook traditional food and new food species, and the development of a regional processing plant in Inuvik for muskox and/or reindeer. Furthermore, increasing community capacity to make long-life country-food products may also facilitate sharing of country foods from annual and/or seasonal community hunts both within and between ISR communities – also identified as regional food security priorities (Fillion et al., 2014).

While the ISR initiative is based in Inuvik (Northwest Territories), the administrative center for the western Canadian Arctic, participants from all eight communities of the Beaufort Delta (including Tuktoyaktuk and the four remote Inuvialuit communities) travel to attend the course. The planned construction of community country-food processing and storage facilities is poised to provide participants with the infrastructure necessary to apply their skills in their communities. Community-level facilities will also increase access to the initiative for community members (e.g., single mothers) whose employment-, family-, and community responsibilities otherwise limit or prevent them from travelling to Inuvik for the ten days required to complete the training.

2.3.1.2 Nunavut – development of country food guidelines

Household food insecurity, a measure of income-related problems of food access, increased over time among 3250 Nunavut households, from 33.1% affected households in 2010 to 46.6% in 2014 (St-Germaine, 2019). The Nunavut Food Security Coalition, which includes government departments, Inuit organizations, non-governmental organizations, and the private sector, identified in the 2014-16 Action Plan that access to country food was a priority in achieving food security.

The Qikiqtani Inuit Association of Nunavut describes Inuit food sovereignty as incorporating Inuit knowledge, language, culture, and community self-sufficiency; furthermore, Inuit food sovereignty encompasses not only the right to healthy and nutritious food, but also the right to culturally appropriate food (QIA, 2019). Country food is central to food sovereignty for Inuit in Nunavut.

Recognizing country food as foundational food for the majority of Nunavummiut (people living in Nunavut), the Nunavut Food Security Coalition and the Government of Nunavut Department of Health developed guidelines to support country food availability in publicly funded facilities (such as hospitals, schools) and community-based programs (including prenatal nutrition programs). Development of the guidelines involved over thirty key informant interviews with Inuit organizations in Nunavut, public health specialists, hunters, regional wildlife organizations, wildlife biologists, veterinarians and others, as well as an extensive environmental scan of current literature related to zoonotic disease in country foods of interest.

Guidance on the procurement, handling, storage, and serving of country food has enabled publicly funded facilities (such as schools, hospitals) and community programs to purchase country food from experienced hunters, and to offer country food in a way that is familiar and acceptable to Nunavummiut.

The Guidelines were not created to regulate country food; rather, to provide an evidence-based reference tool to support country food access while people are in the care of the government, or accessing programs. In this way, the 'Serving Country Food' Guidelines (Nunavut Food Security Coalition, 2016) strive to support country food access for the most vulnerable Nunavummiut, including elders, children, and pregnant women.

Following the release of the Guidelines, a pilot project was undertaken to introduce country food to in-patients at the regional hospital in Iqaluit, and to support increased country food access in Kugluktuk community programs. The pilot project included the purchase of equipment (freezers, butchering equipment, food safe packaging), the development of mechanisms for paying hunters, food safety training, and the development of resources to support appropriate use of country food in an institutional setting. Formal evaluation of the pilot project is forthcoming; but perhaps the best summary was provided by an elder who participated in taste-testing seal stew in her hospital room, when she remarked "Yes, this is good. My stomach recognizes this food. Right away it knows what I am eating."

2.3.1.3 Nunatsiavut – food security and a wild food credit program in daycare centers

Nunatsiavut is the Inuit Settlement Region on the north coast of Labrador and comprises five geographically isolated coastal communities: Nain, Hopedale, Postville, Makkovik and Rigolet. Nunatsiavut communities are vibrant, close-knit communities with dynamic food systems where residents rely on a combination of harvested foods (including berries, fish, marine mammals, land mammals, birds) and market foods. This dual food system faces many existing and emerging challenges, which create obstacles for individual, household and community food security.

The most recent Nunatsiavut-specific data show that 60% of households in the region are food insecure, with disparities between communities (Furgal et al., 2017). A 2014 survey found a prevalence of household food insecurity of 79.8% in Nain and 83.1% in Hopedale. In Hopedale, 5.6% of households reported that at some time in the past month children within the household had not eaten for an entire day. In Nain, 13.4% of households reported this situation.

The Nunatsiavut Government Department of Health and Social Development operates daycare centers in all five Nunatsiavut communities with support from the First Nations/Inuit Child Care Initiative. The daycare programs play a fundamental role in community food security by providing healthy meals and snacks to Nunatsiavut communities' most precious resource – its children. The Department of Health and Social Development prioritizes incorporating Inuit culture, values and traditions into program activities and ensures that program components remain culturally relevant. One innovative example of such a program is an informal policy adopted by the daycare centers to allow families to donate harvested traditional food to their daycare center and in return to receive a rebate on their registration fees. The wild food credit program allows the community and the daycare center to mutually support many food security objectives simultaneously: it ensures that children in the daycare centers have access to wild food as part of their daily program and supports families in their ability to prioritize harvesting activities. In developing the program, the Department of Health and Social Development created policies around the preparation and handling of foods that were to be donated to the daycares, including guidelines for cleaning, storing and quality of fish, meats and berries. The foods most commonly received are Arctic char, Canada goose, partridge (including ptarmigan and spruce grouse), seal and berries. The foods shared with the daycare centers are used in the preparation of nutritious meals and snacks, and are also incorporated into cultural programming. For example, when fresh char is received in spring, daycare staff will show the participants how to make *pitsik*, a dried fish treat that is enjoyed by all.

Partnerships, innovative policies and programs grounded in Inuit culture and practices such as the daycare wild food credit, as well as the self-determination that allows the region to implement such initiatives are essential to address gaps and work towards achieving food security and food sovereignty in Inuit communities.

2.3.2 Greenland

Many new initiatives have been undertaken to increase the use of Greenlandic foods in Greenland, such as cooking books with recipes that use the varied Greenlandic foods available, and family food programs on television. All municipalities have an annual food festival with local produce. NERISA – an Arctic Food Cluster (Nerisa, 2020), gives access to a network of people all over Greenland and Denmark (more than 40 companies/ public institutions) interested in Greenlandic food topics. Some members produce foods, some approve foods, some sell foods, some serve foods, and some have a health interest in foods. NERISA provides insight into the opportunities and challenges in the food arena, as well as increased insight into the high demand for Greenlandic foods. NERISA's members are concerned about the barriers experienced by food entrepreneurs when they want to turn an idea into a business. One of these is food legislation, which today makes it difficult to start small-scale food productions or offer food experiences to tourists.

2.4 Conclusions

For several Arctic Indigenous populations, a decrease in fish and marine mammal consumption has resulted in lower intakes of contaminants but unfortunately also in lower intakes of several important nutrients. As well as the lower intake of marine omega-3 fatty acids, intakes of iodine and vitamin D warrant special attention and should be monitored in Arctic populations. The situation concerning vitamin D and iodine and the need for fortification requires studying because there appears to be substantial variation between countries.

An increase in obesity has been found in most Arctic populations, and an increase in metabolic disorders and dental problems in some populations. This is at least partly explained by dietary transitions to increased consumption of processed foods high in starch, fat and sugar. It is important to monitor these health trends in Arctic populations. However, an increase in imported and store-bought foods is not always negative for health. An increase in the consumption of vegetables and fruit has been found in many countries due to the dietary transitions, resulting in a higher intake of some vitamins, minerals and dietary fiber. The goal should be to get the best from both the traditional diet and the imported diet. To achieve this, the consumption of fish low in contaminants should be promoted in the Arctic Indigenous populations as well as in the general populations of Arctic countries. Risk communication is vital for limiting the intake of contaminants without risking deficiency of beneficial nutrients.

Dietary intakes should be continuously monitored in the Arctic populations, using the same methodology to ensure comparability over time. It is important to include traditional foods in such studies. Food frequencies based on modern diets will probably not capture dietary habits in Arctic populations. Food composition databases need to include traditional foods. There is a need for dietary studies in populations in many Arctic countries, especially in Russia, where there is a total lack of dietary studies in many Arctic Indigenous populations.

Food insecurity is an issue in some Arctic Indigenous populations and should be monitored using common methodology. Examples of successful initiatives to increase consumption of traditional foods and improve food security and food sovereignty have been collated in this chapter and are available for countries to learn from each other.

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3. Human biomonitoring and exposure

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Key findings

- *The highest levels of Hg and POPs are in Greenland, Faroe Islands, and Nunavik (Canada), plus coastal Chukotka (Russia) for some POPs only.*
- *PFOS is the predominant PFAS measured in most populations across the Arctic, and concentrations for pregnant women and children measured in the past decade are generally highest in Greenland. PFOA is the second most predominant PFAS in some Arctic regions, however, there are many exceptions: higher levels of PFNA than PFOA on St. Lawrence Island, Alaska (USA) and in the Canadian Arctic (especially in Nunavik) and in pregnant women from Greenland; higher levels of PFHxS than PFOA in children from Sweden; and higher levels of PFOA than PFOS in children from Finland.*
- *Concentrations of most POPs and metals are declining in Arctic regions where time trends data exist, although the declines are neither uniform nor consistent across all regions. The exception is PFASs, with concentrations of some long-chain PFASs such as PFNA increasing in Nunavik, Greenland and Sweden.*
- *Several contaminants previously identified by AMAP as chemicals of emerging Arctic concern have been detected in the Arctic. Baseline levels have been measured in parts of the Canadian Arctic and Greenland, but only in Sweden are there sufficient data to establish time trends.*
- *A comparative study of Hg levels in pregnant women across seven Arctic countries found the highest mean Hg levels to occur in Greenland and Nunavik. A comparison of POPs in pooled samples from five of the original regions found the highest levels of POPs in pregnant women in Nunavik, while levels in Norway, Sweden and Finland were similar and relatively low. Levels of most PFASs in pregnant women were similar between regions, although PFOS, PFNA and PFUnDA levels were higher in Nunavik and PFOA and PFHxS levels were higher in Finland. Levels of many dioxins and furans were below the limits of detection; detected levels were highest in Iceland and Finland.*
- *Levels of Hg, PCB153 and DDE in some Arctic regions are comparable to those in some non-Arctic regions; but for those Arctic regions with the highest levels of these contaminants, concentrations are generally higher than for most non-Arctic regions. Levels of PBDEs are relatively low in the Arctic (except for Alaska), while PFAS concentrations are comparable to those in many non-Arctic regions.*

3.1 Introduction

The harvesting of local plants, berries, mollusks and seaweeds, and the hunting of birds, fish, and terrestrial and marine mammals, has traditionally been an important social, cultural, economic and spiritual part of the lives and wellbeing of Arctic Indigenous populations. Consumption of these 'traditional foods', also commonly known as 'country foods' or 'subsistence foods', has an important impact on the nutrition and food security of Arctic populations (see also Chapter 2). While traditional foods are of significant benefit to the wellbeing of northerners, some traditional foods may contain elevated levels of contaminants. Due to atmospheric and oceanic transport of contaminants to the Arctic, the Arctic has become a 'sink' for many persistent chemicals that bioaccumulate and biomagnify through Arctic food chains. Some species of wildlife, especially certain marine mammals at the top of the Arctic food web, can have elevated levels of particular contaminants (AMAP, 2016). As a result, human consumption of parts of such marine mammals and other traditional foods can lead to elevated exposures to these contaminants. Human biomonitoring and dietary exposure assessment used to investigate levels of contaminants in human populations and the impact of diet on human exposure to these contaminants are critical to the understanding and risk management of contaminants.

This chapter presents human biomonitoring data from all eight circumpolar Arctic countries published since the previous AMAP human health assessment (AMAP, 2015). The aim is to provide an update on the presence of contaminants in human populations living in the Arctic, including the current state of exposure, spatial differences, and temporal trends. Levels of contaminants in Arctic populations are also compared to levels in other populations around the world. The chapter focuses on contaminants that continue to be a priority in Arctic regions, principally persistent organic pollutants (POPs) including organochlorine compounds, brominated flame retardants and per- and polyfluoroalkyl substances (PFASs), as well as metals such as mercury (Hg), lead (Pb), and cadmium (Cd). Biomonitoring data for a number of contaminants of emerging Arctic concern (see AMAP, 2017), such as phthalates, bisphenols and polycyclic aromatic hydrocarbons (PAHs), are also described in this chapter to provide baseline information on the presence of these contaminants in human populations in the Arctic, and temporal trends where data are available. Biomonitoring data are presented for pregnant women, adult men and women, women of childbearing age, children and youth. These data have been collected as part of regional cross-sectional studies or ongoing cohort studies, and contaminant concentrations are primarily reported in blood, which is a commonly used biological matrix for assessing exposure to POPs (plasma/serum) and metals (whole blood). Data are also reported for other media, such as hair or urine, which are relevant biological matrices for assessing human exposure to some metals as well as recent exposure to some chemicals of emerging Arctic concern.

As the traditional diet of Arctic populations, particularly the consumption of marine mammals, is the primary source of exposure to contaminants, this chapter includes a summary of contaminant levels in traditional foods. While general trends of POPs and metals in biota have been reported in other AMAP assessment reports (AMAP, 2011, 2015, 2016), this summary focuses more specifically on key dietary sources of exposure to these contaminants and the food items that most affect human exposure. Discussion of the importance of traditional foods and their impact on nutrition, culture and food security is discussed in Chapter 2.

3.2 Quality assurance / quality control

Persistent organic pollutants and metals can be measured at very low levels in human matrices. In analytical chemistry, low levels of analytes will always be expected to carry higher uncertainties than higher levels, especially when close to the detection limits. Comparison of these low levels therefore necessitates high quality data, which can be compared with confidence. The AMAP Ring Test for POPs was initiated by the experts of the Human Health Assessment Group and began in 2001. Since then, it has been successfully arranged by the Centre de Toxicologie du Québec (CTQ) three times per year. The protocol now involves the analysis of 13 different polychlorinated biphenyl (PCB) congeners, nine pesticides, eight polybrominated diphenyl ethers (PBDEs) and nine PFASs, as well as cholesterol and triglycerides for total lipid calculations. Laboratories submitting data for the AMAP human health assessments are expected to participate on a regular basis. It should therefore be an integral part of each contract between a laboratory and the party requesting the analytical data that any external quality assurance / quality control (QA/QC) participation is mandatory and performance results must be submitted with the data; this will ensure that the laboratory has generated accurate and comparable data.

Laboratories submitting data to this assessment are active participants in different QA/QC programs (Table 3.1), and mere participation in an external QA/QC program has been shown to result in improved performance over time (Ólafsdóttir et al., 2009). In a few cases, data included in this report have come from laboratories which have used rigorous laboratory analytical procedures, but have not participated in external QA/QC programs. While there is no reason to suspect unreliable data from these laboratories, they are strongly encouraged to participate in interlaboratory comparison programs. Variations in measurements between laboratories participating in external QA/QC programs of <20% should not be considered different; however, if comparing data when variations are up to 40% between different laboratories, results should be discussed with care, especially at levels close to limits of detection. This is important in order for AMAP to be able to demonstrate convincingly that spatial and temporal trends in exposure levels are real and not just the incidental results of different laboratories.

The data for POPs presented in this chapter, including organochlorines and PBDEs, are reported on a lipid weight basis (µg/kg plasma lipids) due to their accumulation in lipids; this also enables accurate maternal blood monitoring during pregnancy due to increasing lipid levels during pregnancy and lipid levels adjusting in response to meals. For PFASs, which do not accumulate in lipid tissue but in plasma proteins, data are instead reported on a wet weight basis in plasma or serum (µg/L plasma or serum). Data for metals in blood are also presented on a wet weight basis (µg/L whole blood), while metals in urine are presented on a creatinine-adjusted basis (µg/g creatinine). A number of contaminants of emerging Arctic concern are also presented in this report, such as phthalates, bisphenols and PAHs, and are presented in either blood on a wet weight basis (µg/L serum) or in urine on a creatinine-adjusted basis (µg/g creatinine). Comparisons in this chapter made between populations or contaminants are descriptive, unless specified as statistically significant differences.

3.3 Human biomonitoring: POPs

Persistent organic pollutants can be easily transported to the Arctic via air and water currents, where they persist in the environment and bioaccumulate in the Arctic food web. These chemicals do not easily degrade and, due to their lipophilic nature, tend to accumulate in the fatty tissues of animals. A number of contaminants, such as PCBs, toxaphene, chlordane, and dichlorodiphenyldichloroethylene (DDE), continue to persist in the Arctic even though many of these chemicals and their parent compounds have been banned or their use restricted in many countries around the world (AMAP, 1998, 2003, 2009, 2015). Several have also been targeted by the UNEP Stockholm Convention, due to their persistence, bioaccumulation, toxicity and capacity for long-range transport (26 chemicals listed for elimination under Annex A, two listed for restriction under Annex B, and seven listed for unintentional production under Annex C) (UNEP, 2020a).

Other persistent chemicals particularly PBDEs and PFASs have also been found in the Arctic. PFASs comprise a large group of chemicals which are often grouped as perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkane sulfonic acids (PFSAs). These chemicals also exist at varying carbon chain lengths and are often grouped as either short- or long-chain PFASs. PFCAs with a chain length of less than seven (<C7) and PFSAs with a chain length of less than six (<C6) are referred to as short-chain PFASs. Classifications of short- and long-chain PFASs vary in some countries; for example, in Canada all PFCAs and PFSAs with a chain length of C4–C7 are considered short-chain. The most commonly known examples of PFASs are perfluorooctane sulfonic acid (PFOS, C8) and perfluorooctanoic acid (PFOA, C8), but also include

Table 3.1 Overview of QA/QC participation by laboratories supplying biomonitoring data to the 2021 AMAP Human Health Assessment.

Country	Laboratory	QA/QC Scheme
USA	Institute for Health and the Environment, University at Albany, New York (organochlorines)	New York State Department of Health Proficiency Testing (EPTAVU)
	AXYS Analytical (PBDEs/PFASs)	CALA, NELAP
Canada	CTQ (POPs, PFASs, PCDD/Fs, metals, PAHs, phthalates)	AMAP (POPs, PFASs, PCDD/Fs); QMEQAS (metals); G-EQUAS (metals, POPs, PAHs, phthalates)
	University of Western Ontario (Hg)	QMEQAS (metals)
	University of Montreal (metals)	QMEQAS (metals)
Greenland	University of Erlangen-Nuremberg, Germany (PFASs)	ICI/EQUAS (PFASs)
	Department of Occupational and Environmental Medicine, Lund University, Sweden (phthalates)	ICI/EQUAS (phthalates)
	CTQ (POPs, PFASs)	AMAP (PFASs, metals)
	Institute for Bioscience, Aarhus University, Denmark	AMAP (POPs, PFASs)
	University of Southern Denmark (POPs, PFASs)	QUASIMEME
Iceland	Department of Pharmacology & Toxicology, University of Iceland (POPs)	AMAP (POPs)
	CTQ (Hg)	QMEQAS (Hg)
Faroe Islands	Environmental Medicine, University of Southern Denmark (POPs, metals)	EQUAS, QMEQAS
Norway	University Hospital of North Norway	AMAP (POPs, PFASs)
Sweden	Finnish National Institute for Health and Welfare, Department of Health Security (organochlorines, PBDEs)	G-EQUAS (POPs, PBDEs)
	Department of Environmental Science and Analytical Chemistry, Stockholm University (PFASs)	AMAP (PFASs)
	Division of Occupational and Environmental Medicine, Lund University (metals)	G-EQUAS (metals)
	Division of Occupational and Environmental Medicine, Lund University (phthalates, phenols)	ICI/EQUAS, Erlangen Inter-Laboratory Comparison Program (phthalates, phenols)
	Swedish Food Agency (POPs breastmilk)	QUASIMEME, EURL-POPs
Finland	Jozef Stefan Institute, Department of Environmental Sciences, Slovenia (metals)	PHIME and PHAPAS
Russia	Typhoon, NW Branch, Russia (POPs, metals)	AMAP (POPs), STAMI (metals)
	IDAEA-CSIS Laboratory, Spain	AMAP (POPs)

chemicals such as perfluorohexane sulfonic acid (PFHxS, C6), perfluorononanoic acid (PFNA, C9), perfluorodecanoic acid (PFDA, C10), and perfluoroundecanoate (PFUnDA, C11). Unlike other POPs, PFASs do not typically accumulate in lipids, but instead have a strong affinity for the protein fraction in blood (Martin et al., 2004; Kärrman et al., 2010) and are therefore commonly measured in serum. This section discusses current levels of POPs in different circumpolar Arctic regions, for all available POPs that were measured in Arctic studies.

3.3.1 Alaska

St. Lawrence Island is the largest island in the Bering Sea and home to approximately 1600 Yupik residents between the two villages of Gambell and Savoonga. There are also two formerly used defense sites on the island, one of which is at the Northeast Cape and which has been associated with organochlorine pesticide contamination in soil. Byrne et al. (2015) described exposure to POPs among residents from different regions of the island to better understand potential environmental contamination during site remediation at Northeast Cape (Savoonga is the closest village to Northeast Cape). In 2001, blood samples were obtained from 130 individuals (18+ years old); only 71 samples were analyzed for POPs. Participants were recruited and categorized as residents of the community of Savoonga (n=26), residents of the community of Gambell who spent no time near Northeast Cape (n=21), and residents of Gambell who have historical family ties to Northeast Cape (n=24). Serum samples were analyzed for PCBs, chlordane compounds, DDT compounds and metabolites, Mirex, and hexachlorobenzene (HCB). Serum levels of POPs are reported for all participants in Table 3.2. The highest concentrations observed were for the sum of PCBs, oxychlordane, HCB and DDE+PCB85. As observed in Table 3.2, concentrations of POPs were higher in men than women for all POPs detected. After controlling for age and sex, activities near the Northeast Cape formerly-used defense site were associated with an increase in serum concentrations of HCB compared to residents of Gambell, which was used as the reference group due to it being the furthest village from the site (Byrne et al., 2015).

Later research on St. Lawrence Island in 2013–2014 indicates that residents are also exposed to PBDEs and PFASs (Byrne et al., 2017). Blood serum samples were collected from 85 participants (between the ages of 18 and 45 years) for the measurement of PBDEs and PFASs, along with dust samples from 49 households. Blood and dust samples were collected within a day of each other, during late winter 2013 and early spring 2014. Levels of PFASs and brominated flame retardants in serum are shown in

Table 3.2 Blood concentrations of POPs in Yupik adults from St. Lawrence Island in 2001. POPs data presented as geometric means (range) in serum (µg/kg lipids). Source: Byrne et al. (2015); Byrne (pers. comm. 2019).

	Men		Women	
Year	2001		2001	
Mean age, y (range)	35 (18–48)		32 (18–53)	
Sample size	n=31		n=40	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
Oxychlordane	74.6 (16.1–328)	0	44.5 (<LOD–290)	10
trans-Nonachlor	45.7 (<LOD–147)	10	31.8 (<LOD–139)	10
HCB	86.1 (22.2–195)	0	59.4 (12.8–259)	0
p,p'-DDE + PCB85	355 (152–786)	0	286.1 (53.5–1553)	0
Mirex	27 (<LOD–80.9)	4	9.29 (<LOD–39.3)	25
ΣPCBs	702 (138–1604)	0	460 (124–1565)	0

LOD: Limit of detection.

Table 3.3. PFDA and PFHxS were also measured, but are not shown in Table 3.3 due to the large number of samples being below the limit of detection (61% and 68%, respectively).

Overall, long-chain PFASs were detected more frequently in serum and at higher concentrations than short-chain PFASs. Low levels of PFASs in household dust and the lack of statistically significant correlations between PFASs in household dust and human serum suggest that other sources of human exposure to these compounds exist. Traditional foods are a likely source of exposure as long-chain PFASs accumulate in Arctic wildlife and are very persistent. Serum samples contained higher concentrations of PFOS and PFNA than other PFASs including PFOA, which had concentrations several-fold lower. For PBDEs, a few weakly significant correlations between dust and serum samples were found (r_s=0.33 and p=0.02 for PBDE47 in women), which may suggest dust as a potential source of exposure, although the strength of these correlations was fairly low (Byrne et al., 2017).

When compared to levels of PFASs and PBDEs observed in pregnant Yupik women from the Yukon-Kuskokwim River Delta region of Alaska between 2009 and 2012 (AMAP, 2015), levels of PBDEs and PFOS were higher among Yupik of St. Lawrence Island (19.8, 4.5, 4.6 and 9.5 µg/kg in pregnant women from the Kuskokwim Delta region versus 10.4, 2.02, 2.16, 7.28 µg/kg in women from St. Lawrence Island, for PBDE47, PBDE99, PBDE100, and PBDE153, respectively), although levels of PFOA were lower among women from St. Lawrence Island.

Table 3.3 Blood concentrations of PBDEs and PFASs in Yupik adults. POPs data presented as geometric means (range); PBDEs presented in serum (µg/kg lipids) and PFASs in serum (µg/L serum). Source: Byrne et al. (2017).

	Men		Women	
Year	2013–2014		2013–2014	
Mean age, y (range)	29 (19–45)		28 (18–45)	
Sample size	n=38		n=47	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
PBDE47	9.96 (<LOD–80)	2.63	10.4 (0.85–553.8)	0
PBDE99	2.02 (<LOD–9.5)	10.5	2.02 (<LOD–181.8)	10.6
PBDE100	2.09 (<LOD–16.17)	2.63	2.16 (<LOD–78.7)	2.13
PBDE153	10.72 (3.7–27)	0	7.28 (0.9–54.9)	0
PBDE207	2.4 (0.56–32.4)	0	2.2 (0.37–44.7)	0
PBDE209	3.86 (<LOD–46.6)	2.63	3.28 (0.1–38.57)	0
	µg/L serum	% <LOD	µg/L serum	% <LOD
PFOA	1.45 (0.51–2.9)	0	0.85 (<LOD–1.44)	15
PFNA	2.75 (0.73–10.8)	0	2.07 (<LOD–12.1)	2
PFUnDA	1.04 (<LOD–3.74)	32.0	0.88 (<LOD–1.73)	26.0
PFOS	6.96 (3.07–16)	0	3.29 (<LOD–9.69)	2

LOD: Limit of detection.

3.3.2 Canada

3.3.2.1 Old Crow, Yukon

In 2019, a human biomonitoring survey was completed in the Yukon to help address local concerns regarding high levels of some contaminants in country foods. A total of 77 adult Gwich'in men and women from Old Crow, Yukon participated in the study, which included the collection of blood for analysis of POPs (Drysdale et al., pers. comm. 2020; Drysdale et al., 2021). The predominant organochlorines measured were *p,p'*-DDE, HCB, and PCBs (see Table 3.4). Among the PBDEs, the most commonly detected congeners were PBDE153 and PBDE47, while PBDE99 and PBDE100 were not detected in the majority of samples. In general, the majority of POPs concentrations were low compared to other Canadian Arctic regions and similar to or below the values seen in the general Canadian population. For example, the insecticide dichlorodiphenyltrichloroethane (DDT) and PCB congeners had concentrations below those observed in the general Canadian population as described via the Canadian Health Measures Survey (CHMS) Cycle 1 conducted

Table 3.4 Blood concentrations of POPs in adults in Old Crow, Yukon, Canada. Data presented as geometric means (10th – 95th percentile) in blood plasma (µg/kg lipids). Source: Drysdale et al. (pers. comm. 2020).

	Men		Women	
Year	2019		2019	
Mean age, y (range)	43 (21–75)		39 (20–72)	
Sample size	n=26		n=28	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
Aroclor1260	63 (22–540)	3.8	42 (<14[b]–300)	18
PCB118	<1.4[a] (<1.4[a]–18)	46	<1.4[b] (<1.4[b]–5.2)	54
PCB138	3.8 (<1.4[a]–38)	15	2.7 (<1.4[b]–17)	29
PCB153	7.8 (2.6–66)	3.8	5.2 (<1.4[b]–32)	14
PCB180	5.2 (<1.4[a]–30)	12	3.7 (<1.4[b]–24)	29
PBDE47	5.4 (<4.3[a]–56)	38	<4.2[b] (<4.2[b]–25)	61
PBDE99	<2.9[a] (<2.9[a]–27)	69	<2.8[b] (<2.8[b]–9.8)	79
PBDE100	<2.9[a] (<2.9[a]–11)	77	<2.8[b] (<2.8[b]–12)	89
PBDE153	6.1 (<4.3[a]–35)	31	4.2 (<4.2[b]–32)	50
trans-Nonachlor	5.6 (<1.4[a]–120)	8	2.7 (<1.4[b]–14)	32
β-HCH	<1.4[a] (<1.4[a]–18)	62	<1.4[b] (<1.4[b]–4.7)	57
Hexachlorobenzene	18 (7.0–76)	0	12 (4.0–47)	0
Oxychlordane	2.9 (1.0–50)	3.8	1.6 (<0.7[b]–7.8)	25
p,p′-DDE	46 (19–290)	0	38 (13–220)	0
p,p′-DDT	<29[a]	100	<28[b]	100
Toxaphene, Parlar 26	<0.7[a] (<0.7[a]–12)	65	<0.7[b] (<0.7[b]–2.0)	79
Toxaphene, Parlar 50	1.1 (<0.7[a]–14)	38	<0.7[b] (<0.7[b]–2.7)	61

LOD: Limit of detection; values below the LOD were treated as LOD/2 for calculating the mean; [a]based on the geometric mean (7.0 g/L) of blood lipids observed for male participants; [b]based on the geometric mean (7.1 g/L) of blood lipids observed for female participants.

in 2007–2009 (Health Canada, 2010). In contrast, other POPs such as HCB appeared at levels higher than those observed in the general Canadian population (CHMS Cycle 1, 2007–2009) and First Nations communities across the 10 provinces as listed

Table 3.5 Concentration of blood serum PFASs in adults in Old Crow, Yukon, Canada. Data presented as geometric means (10th – 95th percentile) in blood serum (µg/L). Source: Drysdale et al. (pers. comm. 2020).

	Men		Women	
Year	2019		2019	
Mean age, y (range)	43 (21–75)		39 (20–72)	
Sample size	n=26		n=28	
	µg/L	% <LOD	µg/L	% <LOD
PFBA	<0.08 (<0.08–<0.08)	92	<0.08 (<0.08–<0.08)	89
PFDA	0.20 (<0.09–0.57)	13	0.16 (<0.09–0.35)	13
PFHxA	<0.08	100	<0.08	100
PFNA	1.2 (0.46–3.9)	0	0.77 (0.37–2.0)	0
PFOA	1.1 (0.65–1.7)	0	0.76 (0.41–1.7)	0
PFUnDA	0.11 (<0.10–0.45)	46	0.10 (<0.10–0.30)	41
PFBS	<0.07	100	<0.07	100
PFHxS	0.56 (0.28–1.2)	0	0.26 (0.10–1.4)	0
PFOS	1.4 (0.60–3.9)	7.7	0.78 (<0.40–2.4)	14

LOD: Limit of detection.

in the First Nations Biomonitoring Initiative (FNBI) conducted in 2011 (Health Canada, 2010; Assembly of First Nations, 2013). To determine if there were significant differences in levels of POPs between men and women, one-way ANOVA (when log-transformed concentrations were normally distributed) and Mann-Whitney U tests were performed (Drysdale et al., pers. comm. 2020). The majority of POPs showed similar levels between men and women, with the exception of *trans*-nonachlor (p=0.03), HCB (p=0.04) and toxaphene Parlar 50 (p=0.025), which were higher in men.

Blood serum PFAS levels are presented for adult men and women in Table 3.5. Serum PFAS levels were generally lower or similar in Old Crow compared to the Canadian general population from CHMS Cycle 5, 2016–2017 (Health Canada, 2019) and First Nations populations from the FNBI, 2011 (Assembly of First Nations, 2013); however, levels of PFNA were higher than those reported for the general Canadian population. When age groups were compared to those in CHMS Cycle 5, 2016–2017, Old Crow participants over 40 years in age had higher concentrations of PFNA (Health Canada, 2019). Significant differences across age and sex were assessed using Mann-Whitney U tests since log-transformed data were found to be non-normally distributed. This study found differences in PFAS concentrations between sexes, with men having higher levels than women for PFHxS (p=0.001), PFOS (p=0.003) and

Table 3.6 Blood concentrations of POPs in adults across multiple First Nations communities in the Northwest Territories, Canada. Data presented as geometric means (10th – 95th percentile) in blood serum (µg/kg lipids). Source: Laird and Ratelle (pers. comm. 2019).

	Men		Women	
Year(s)	2016–2018		2016–2018	
Mean age, y (range)	47.6 (18–88)		45.6 (18–80)	
Sample size	n=124		n=122	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
Aroclor1260	132 (30–1102)	3.2	101 (12–1290)	9.8
PCB118	2 (<1.6[a]–17)	43.5	2 (<1.6[b]–22)	43.4
PCB138	7 (1–49)	8.9	6 (<1.6[b]–61)	18.9
PCB153	18 (4–165)	2.4	14 (1–187)	5.7
PCB180	14 (<1.6[a]–134)	9.7	9 (<1.6[b]–98)	15.6
PBDE47	5 (<4.9[a]–23)	45.2	6 (<4.8[b]–102)	42.6
PBDE99	nc (<3.3[a]–14)	77.4	nc (<3.2[b]–20)	77.9
PBDE100	nc (<3.3[a]–16)	84.7	nc (<3.2[b]–21)	82
PBDE153	nc (<4.9[a]–20)	59.7	nc (<4.8[b]–20)	71.3
trans-Nonachlor	8 (<1.6[a]–101)	10.5	6 (<1.6[b]–71)	16.4
β-HCH	nc (<1.6[a]–3)	67.7	2 (<1.6[b]–5)	49.2
Hexachlorobenzene	12 (6–48)	4	12 (6–48)	0.8
Oxychlordane	3 (<0.8[a]–30)	13.7	3 (<0.8[b]–28)	19.7
p,p'-DDE	54 (22–214)	0	59 (17–346)	0
p,p'-DDT	<8[a]	100	<8[b]	100
Toxaphene Parlar 26	nc (<0.8[a]–14)	54.8	nc (<0.8[b]–14)	60.7
Toxaphene Parlar 50	1 (<0.8[a]–33)	48.4	nc (<0.8[b]–28)	52.5

LOD: Limit of detection; nc: not calculated due to high number of non-detects; values below the LOD were treated as LOD/2 for calculating the mean; [a]based on the geometric mean (6.1 g/L) of blood lipids observed for male participants; [b]based on the geometric mean (6.3 g/L) of blood lipids observed for female participants.

PFOA (p=0.02). When the data were stratified by age (i.e., those under 40 years in age and those over 40 years in age), PFAS levels were higher among the older participants (Drysdale et al., pers. comm. 2020).

Table 3.7 Concentration of blood plasma PFASs in adults across multiple First Nations communities in the Northwest Territories, Canada. Data presented as geometric means (10th – 95th percentile) in plasma (µg/L). Source: Laird and Ratelle (pers. comm. 2019).

	Men		Women	
Year	2019		2019	
Mean age, y (range)	48 (18–79)		45 (21–71)	
Sample size	n=57		n=55	
	µg/L	% <LOD	µg/L	% <LOD
PFBA	<0.08 (<0.08–0.082)	89	<0.08 (<0.08–<0.08)	98
PFDA	0.22 (<0.09–1.4)	15	0.20 (<0.09–0.90)	11
PFHxA	<0.08	100	<0.08	100
PFNA	1.5 (0.50–11)	0	1.3 (0.46–6.4)	0
PFOA	1.1 (0.61–3.1)	0	0.72 (0.41–2.8)	0
PFUnDA	<0.10 (<0.10–0.54)	60	<0.10 (<0.10–0.48)	60
PFBS	<0.07	100	<0.07	100
PFHxS	0.58 (0.28–1.5)	0	0.23 (0.10–0.55)	1.8
PFOS	2.5 (1.0–12)	0	1.6 (0.74–4.9)	1.8

LOD: Limit of detection.

3.3.2.2 Dehcho and Sahtú regions, NWT

The Mackenzie Valley of the Northwest Territories (NWT) is home to approximately 5000 First Nations and Métis. Several traditional foods, especially moose, caribou, and wild-harvested fish, are integral to the health and food security of the Indigenous communities within the NWT. Previously reported concentrations of POPs and Hg in long-lived predatory fish species in some lakes, and Cd concentrations in the kidney/liver of moose from some regions of the NWT, has led to concern in local communities and resulted in consumption notices from the Government of the NWT Department of Health and Social Services (see Chapter 6). To address this concern, a human biomonitoring study was undertaken to investigate current levels of metals and POPs among participating First Nations communities, which included collection of hair, urine, and blood samples for measuring contaminant concentrations (Hg, metals, and POPs and metals, respectively) (Ratelle et al, 2020a; Garcia-Barrios et al., 2021). Sampling occurred between 2016 and 2018 and involved nine communities from the Dehcho and Sahtú regions of the NWT. Concentrations of POPs in blood samples from these regions are presented in Table 3.6.

Concentrations of POPs measured in adult men and women from participating First Nations communities were similar and generally low. For many of these contaminants, concentrations were below the limit of detection for a large proportion of participants (Ratelle, pers. comm. 2019). Among the PCBs detected, the main congeners were PCB153 and PCB180. Concentrations of other POPs were generally similar or at lower levels, except for *p,p′*-DDE which was detected in all samples and was the most concentrated POP measured at 54 and 59 µg/kg lipid in men and women, respectively (*p,p′*-DDT however was not detected in any samples). Among the brominated flame retardants, several PBDE congeners were measured, but other than PBDE47 relatively few participants had detectable levels of these contaminants.

PFAS concentrations were also measured in samples from Dehcho communities (see Table 3.7). PFOS, PFOA, PFNA and PFHxS were detected in nearly all samples, while the majority of samples had non-detectable levels of PFBA, PFHxA, PFUnDA and PFBS. PFAS levels were lower than or similar to those in the general Canadian population and on reserve First Nations populations for all PFASs, except PFNA (Assembly of First Nations, 2013; Health Canada, 2019). When age-stratified PFAS levels were compared to those from the CHMS Cycle 5, 2016–2017 (Health Canada, 2019), concentrations of PFNA appeared particularly high in Dehcho participants over 40 years of age. Levels between sexes and age groups were compared using Mann-Whitney U tests since log-transformed concentrations were found to be non-normally distributed (Drysdale et al., pers. comm. 2020). The study found differences between sexes in the region, with men having higher PFAS levels than women for PFHxS ($p<0.001$), PFOS ($p=0.002$) and PFOA ($p<0.001$). When stratified according to age, PFAS concentrations generally increased with age.

3.3.2.3 Nunavik

The Qanuilirpitaa? 2017 Inuit Health Survey was conducted in 2017, and was designed as a follow-up to the Qanuippitaa? 2004 Health Survey conducted among Inuit communities in the Nunavik region. In addition to surveying many indicators and determinants of health, the environmental health component of the survey included the measurement of contaminant levels in the blood and urine of Inuit. While the previous Inuit Health Survey in 2004 only recruited adult Inuit (18 years and above), the Qanuilirpitaa? 2017 survey (hereafter referred to as ‘Q2017’) also recruited and measured concentrations of metals in the blood of youth (16–17 years of age).

Concentrations of POPs in the blood of Inuit adults from a representative sub-sample of the Q2017 survey (n=500) in Nunavik are presented in Table 3.8, for several organochlorine contaminants and two PBDE congeners. Most of the organochlorines measured, such as several chlordanes, *p,p′*-DDE and PCBs, were detected in the majority of participants, the only exception being *p,p′*-DDT which was detected in 30% of participants. Unlike the organochlorines, PBDEs were only detected in a minority of participants. The predominant POPs measured in both Inuit men and women were *p,p′*-DDE, PCB153, and *trans*-nonachlor. Concentrations of all POPs were very similar between men and women. Concentrations of POPs are further broken down into two age groups, 18–49 years of age and 50+ years of age (Table 3.9). As seen in Table 3.9, there is a clear and large difference in concentration between younger and older adults, for both men and women. Geometric mean concentrations of organochlorines in men 50–82 years of age were approximately two- to six-fold higher than in men 18–49 years of age. This trend was even more pronounced among women, where geometric mean concentrations in women 50–75 years of age were approximately three- to nine-fold higher than in women 18–49 years of age.

Table 3.8 Blood concentrations of POPs in Inuit adult men and women from Nunavik, Canada. Data presented as geometric means (10th – 95th percentile) in blood plasma (µg/kg plasma lipids). Source: Lemire and Blanchette (pers. comm. 2020).

	Men		Women	
Year	2017		2017	
Mean age, y (range)	38.9 (18–86)		38.4 (18–81)	
Sample size	n=251		n=249	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
Oxychlordane	31 (6.1–320)	0	33 (6.7–370)	0.5
trans-Nonachlor	59 (12–540)	0.4	63 (14–540)	0.5
cis-Nonachlor	8.6 (1.8–66)	4.0	9.6 (2.3–76)	4.9
p,p′-DDE	190 (54–1040)	0	200 (48–1080)	11.3
p,p′-DDT	<LOD	77	<LOD	72.6
HCB	32 (10–170)	0	38 (11–180)	0.4
β-HCH	4.2 (<LOD–33)	17.4	4.7 (<LOD–31)	15.9
Mirex	7.0 (<LOD–88)	15.8	5.5 (<LOD–61)	18.9
Toxaphene, Parlar 26	6.0 (0.89–48)	8.5	7.7 (1.6–47)	5.9
Toxaphene, Parlar 50	9.8 (1.7–78)	5.1	12 (2.7–74)	2.3
PCB138	29 (6.4–200)	1.2	29 (6.0–240)	0.2
PCB153	70 (16–660)	0	62 (12–570)	0
PCB180	40 (6.9–470)	0.2	28 (4.9–350)	2.0
PBDE47	nc (<LOD–12)	71.7	nc (<LOD–12)	76.4
PBDE153	nc (<LOD–18)	48.6	nc (<LOD–11)	70.5

LOD: Limit of detection; nc: geometric mean not calculated due to number of samples <LOD.

In addition to the measurement of some POPs in individual samples, thirty pooled plasma samples were established for measurement of additional contaminants such as PFASs. These pooled plasma samples were created by adding equal amounts of plasma from participants grouped according to age, sex, and region of residence (five age groups, two sexes, three regions of residence). The predominant PFASs measured were PFOS, followed by PFNA and then PFOA (Table 3.10); the only exception was among the youngest age group (16–19 years of age), where concentrations of PFNA were greater than for both

Table 3.9 Blood concentrations of POPs in two different age groups of Inuit adult men and women from Nunavik. Data presented as geometric means (10th – 95th percentile) in blood plasma (µg/kg plasma lipids). Source: Lemire and Blanchette (pers. comm. 2020).

	Men		Women	
Year	2017		2017	
Mean age, y (range)	30.7 (18–49)	60.1 (50–82)	31.7 (18–49)	59.4 (50–75)
Sample size	n=174	n=77	n=183	n=66
Oxychlordane	21 (5.5–100)	85 (9.7–610)	21 (5.8–110)	120 (34–600)
trans-Nonachlor	42 (9.7–190)	150 (24–1150)	43 (12–200)	210 (67–950)
cis-Nonachlor	6.3 (1.6–27)	21 (3.6–160)	6.6 (1.7–21)	31 (10–130)
p,p′-DDE	150 (43–590)	380 (97–2150)	140 (45–520)	590 (190–2440)
p,p′-DDT	nc (<LOD–12)	nc (<LOD–41)	nc (<LOD–11)	nc (<LOD–27)
HCB	25 (9.7–89)	62 (15–360)	28 (8.7–100)	89 (33–300)
β-HCH	3.1 (<LOD–15)	10 (2.5–76)	3.4 (<LOD–15)	13 (4.2–56)
Mirex	4.4 (<LOD–26)	27 (5.2–150)	3.4 (<LOD–20)	24 (6.1–96)
Toxaphene Parlar 26	4.5 (0.79–30)	13 (1.7–130)	5.8 (1.3–28)	19 (6.3–80)
Toxaphene Parlar 50	7.5 (1.6–43)	21 (2.8–210)	9.4 (2.3–46)	30 (10–130)
PCB138	21 (5.7–100)	71 (12–450)	20 (5.1–85)	100 (34–390)
PCB153	48 (11–230)	200 (31–1040)	39 (11–180)	260 (81–1130)
PCB180	25 (5.8–140)	160 (36–750)	16 (4.4–84)	150 (45–730)
PBDE47	nc (<LOD–9.7)	nc (<LOD–16)	nc (<LOD–11)	nc (<LOD–13)
PBDE153	nc (<LOD–17)	5.5 (<LOD–30)	nc (<LOD–9.8)	nc (<LOD–14)

LOD: Limit of detection; nc: geometric mean not calculated due to number of samples <LOD.

PFOS and PFOA. Concentrations of other PFASs were lower, and varied among men and women with higher concentrations of PFDA in women, but lower concentrations of PFHxS compared to men. While some samples had detectable concentrations of PFBA, none of the pooled samples had detectable concentrations of PFHxA and PFBS. PFOA and PFHxS levels were similar to those measured in CHMS Cycle 5 (2016–2017), whereas all other PFASs detected were markedly higher in Nunavik, particularly PFNA and PFOS, which were ten- and two-fold higher, respectively, than in the Canadian general population. Except for PFOA, PFAS exposure levels were far higher in Nunavik than elsewhere in the Arctic. Concentrations of PFASs were generally similar between men and women but did vary with age. Concentrations of PFOS, PFNA, PFDA, PFUnDA and PFHxS appeared to increase steadily with age in all five age groups. Concentrations of other PFASs appeared similar among the younger age groups but were still highest in the oldest age groups, with PFBA the only exception.

Thirteen years separated the Q2017 survey and the previous survey in 2004. Data for the 2004 Nunavik Inuit Health Survey were presented in the previous AMAP human health assessment report (AMAP, 2015), and it is clear when comparing concentrations of POPs in men and women between 2017 and 2004 that all concentrations have declined by a large margin (for PFASs, only PFOS was measured in 2004). The range in declines for geometric mean concentrations in men

Table 3.10 Concentrations of PFASs in pooled blood samples of adult Inuit from Nunavik. A total of n=30 pooled samples were established, divided by sex, five age groups, and three regions of Nunavik; data presented here with regions combined. Data presented as means (min–max) in plasma for PFASs (µg/L). Source: Lemire and Blanchette (pers. comm. 2020).

	Men						Women					
Year	2017						2017					
Age, y	16–86 (all)	16–19	20–29	30–39	40–59	60+	16–81 (all)	16–19	20–29	30–39	40–59	60+
Sample size	n=15	n=3	n=3	n=3	n=3	n=3	n=15	n=3	n=3	n=3	n=3	n=3
PFOS	7.2 (3.4–17)	4.3 (3.4–5.3)	5.7 (4.9–6.6)	7.7 (5.7–9.5)	8.7 (7.6–10)	14 (11–17)	6.3 (2.6–24)	3.6 (2.6–4.4)	4.6 (3.5–5.3)	5.3 (3.6–6.3)	8.8 (5.6–11)	17 (12–24)
PFOA	1.4 (1.1–2.7)	1.2 (1.1–1.2)	1.3 (1.2–1.3)	1.4 (1.2–1.4)	1.5 (1.4–1.6)	2.2 (2–2.7)	0.97 (0.57–2.5)	0.82 (0.78–0.9)	0.7 (0.57–0.8)	0.74 (0.65–0.84)	1.3 (1.2–1.4)	2 (1.7–2.5)
PFBA	0.21 (<0.07–11)	1.3 (<0.07–11)	<0.07	0.11 (<0.07–0.25)	0.91 (0.28–2.7)	nc (<0.07–0.07)	nc (<0.07–0.51)	nc (<0.07–0.1)	nc (<0.07–0.51)	nc (<0.07–0.2)	nc (<0.07–0.42)	nc (<0.07–0.1)
PFHxA	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
PFNA	4.7 (2.2–9.9)	5.3 (5.2–5.4)	3.9 (3.8–4.1)	4.3 (2.2–5.2)	4.6 (3.6–5.2)	7.1 (5.5–9.9)	4.5 (2.7–14)	3.9 (3.3–4.2)	3.1 (2.7–3.3)	3.6 (3.1–4.3)	5.9 (4.9–6.8)	10 (5.9–14)
PFDA	0.84 (0.4–2.3)	0.55 (0.4–0.67)	0.68 (0.66–0.78)	0.9 (0.62–1.1)	0.96 (0.84–1.1)	1.6 (1.2–2.3)	0.95 (0.44–3)	0.57 (0.44–0.7)	0.72 (0.61–0.82)	0.84 (0.6–1.1)	1.3 (0.95–1.5)	2.1 (1.4–3)
PFUnDA	0.85 (0.52–2)	0.61 (0.52–0.7)	0.68 (0.62–0.91)	0.87 (0.73–1)	0.96 (0.86–1.1)	1.6 (1.2–2)	1 (0.51–2.8)	0.64 (0.51–0.75)	0.81 (0.66–0.96)	0.91 (0.65–1.1)	1.2 (0.94–1.6)	2.1 (1.5–2.8)
PFBS	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
PFHxS	0.97 (0.52–2.8)	0.57 (0.52–0.63)	0.76 (0.72–0.9)	0.98 (0.86–1)	1.2 (1.1–1.4)	2 (1.6–2.8)	0.62 (0.34–2.2)	0.36 (0.34–0.37)	0.42 (0.38–0.44)	0.47 (0.4–0.56)	0.92 (0.71–1.4)	1.9 (1.7–2.2)

nc: Mean not calculated due to number of samples <LOD.

and women was similar; between approximately 37% (mirex) to 76% (*p,p′*-DDE) for men, and between 22% (mirex) and 77% (*p,p′*-DDE) for women. Excluding mirex, the majority of organochlorines declined by 50–70%, with the *p,p′*-DDE and PCB congeners showing some of the largest declines. The predominant organochlorines in 2004 (*p,p′*-DDE and PCBs) were still the most predominant contaminants measured in 2017, despite these substances showing the largest declines in general, compared to other organochlorines.

Over 4400 Nunavimmiut (the Inuit of Nunavik) have participated in biomonitoring studies over the past 30 years or so, to help better understand exposure to contaminants and their potential effects on Inuit health (Lemire, pers. comm. 2019). The participation of pregnant women in these first studies in the early 1990s revealed elevated levels of exposure to these environmental contaminants (AMAP, 1998, 2003), and this information was critical for supporting the establishment of the Stockholm Convention in 2004. Pregnant women have continued to participate in these studies, and the NQN study in 2016–2017 (Nutaratsaliit Qanuingisiarningit Niqituinnanut – Pregnancy wellness with country foods project) was developed with two main aims. First, to improve understanding of the exposure of pregnant women to contaminants from traditional foods according to season, and second to support the development of local clinical interventions aimed at mitigating Hg exposure while promoting country foods for enhancing the nutritional and food security status of pregnant women and children. This study builds on data produced from previous biomonitoring programs involving pregnant women in the region, and enables substantial time trend analysis of POPs going back as far as 1992 (Table 3.11), while trends for PFOS extend back only to 2004, PFOA to 2007, and long-chain PFASs to 2012 (Table 3.12) (Lemire and Blanchette, pers. comm. 2019). Because a small number of pregnant women were also recruited in the Q2017 survey (n=6 out of 500 for POPs), pregnant women from the Q2017 and NQN studies are combined for the 2017 time point in Tables 3.11 and 3.12. Measurements show that levels of exposure to older POPs among Nunavimmiut have previously been higher than in other regions of the Canadian Arctic, but as shown in Table 3.11, levels among pregnant women in Nunavik are declining. Indeed, levels of POPs in 2017 were between 70% and 87% lower than first observed in 1992. Statistically significant differences over time were observed for all POPs listed in Table 3.11, except for PBDE47. While data are more limited for PFASs, several were measured in pregnant women in 2004, 2007, 2012, and 2017 (Table 3.12). Of these PFASs in 2017, PFOS was the most predominant (geometric mean 3.3 µg/L), followed by PFNA (geometric mean 2.5 µg/L). Geometric means for PFOA and other PFASs were below 1 µg/L. PFBA, PFHxA and PFBS were measured in 2012 and 2017, but are excluded from Table 3.12 because they were not detected in one or both years. Compared to women from the general Canadian population (CHMS Cycle 5, 2016–2017), concentrations of PFOS, PFNA and PFDA in pregnant Nunavik women were 1.8-, 6.3-, and 3.3-fold higher, respectively, while levels of PFOA and PFHxS were lower (Caron-Beaudoin et al., 2020). As a whole, the sum of PFASs in pregnant Nunavik women was twice that of women in CHMS Cycle 5.

Statistically significant declines were observed for PFOS, PFOA and PFHxS (p<0.0001). In contrast to these regulated PFASs, an increase was observed for long-chain PFCAs such

Table 3.11 Blood concentrations of POPs in pregnant Inuit women from Nunavik, Canada. Organochlorine and PBDE data presented as geometric means (range) in µg/kg plasma or serum lipids. Results presented only for contaminants with 60% and more of data detected. Source: AMAP (2015); Lemire and Blanchette (pers. comm. 2020).

Year	1992	1996	1997	1998	1999	2000
Mean age, y (range)	24 (18–35)	24 (16–33)	24 (15–40)	24 (14–37)	25 (17–35)	26 (16–39)
Sample size	n=11	n=25	n=53	n=46	n=26	n=36
Oxychlordane	78 (32–240)	40 (6.1–180)	49 (8.6–390)	33 (7.0–340)	45 (15–140)	41 (7.5–210)
trans-Nonachlor	110 (49–320)	65 (15–250)	75 (14–330)	53 (12–580)	59 (21–170)	61 (13–300)
cis-Nonachlor	28 (11–84)	14 (5.8–40)	16 (<LOD–60)	9.3 (<LOD–110)	12 (5.1–31)	14 (<LOD–66)
p,p'-DDE	660 (290–1570)	290 (71–1020)	370 (59–1440)	260 (67–2270)	280 (140–900)	280 (64–1330)
p,p'–DDT	26 (9.5–96)	17 (4.2–63)	18 (<LOD–86)	13 (<LOD–130)	8.4 (<LOD–46)	11 (<LOD–68)
HCB	97 (47–220)	41 (15–120)	51 (9.2–190)	35 (6.7–350)	36 (14–100)	37 (12–110)
β-HCH	13 (2.3–30)	4.7 (<LOD–14)	6.5 (<LOD–24)	5.2 (<LOD–31)	5.2 (<LOD–11)	5.6 (<LOD–16)
Mirex	13 (5.6–29)	10 (2.3–36)	10 (<LOD–60)	6.2 (<LOD–32)	9.1 (<LOD–39)	8.9 (<LOD–47)
PCB138	110 (45–220)	57 (10–210)	69 (12–320)	45 (13–390)	60 (17–220)	56 (9.7–300)
PCB153	170 (71–290)	100 (19–410)	130 (23–610)	80 (27–710)	110 (29–470)	98 (15–500)
PCB180	90 (34–150)	43 (7.6–190)	51 (11–220)	34 (12–280)	51 (13–380)	42 (5.0–260)
Toxaphene Parlar 26	na	na	na	na	na	na
Toxaphene Parlar 50	na	na	na	na	na	na
PBDE47	na	na	na	na	na	na
PBDE153	na	na	na	na	na	na

LOD: Limit of detection; for statistical purposes, values <LOD were replaced by LOD/2; nc: geometric mean not calculated due to less than 60% of samples >LOD; na: not available; [a]*p*-value based on orthogonal polynomial contrast for linear trend, using regression adjusted for age, smoking status (smoker vs. non-smoker) and multiparous woman (yes vs. no); [b]n=99; [c]n=95.

Table 3.12 Blood concentrations of PFASs and pentachlorophenol (PCP) in pregnant Inuit women from Nunavik, Canada. Data presented as geometric means (range) in µg/L plasma or serum. Results presented only for contaminants with 60% and more of data detected. Source: AMAP (2015); Lemire and Blanchette (pers. comm. 2020).

Year	2004	2007	2012	2017	*p*-value[a]
Mean age, y (range)	27 (19–37)	23 (17–37)	24 (18–39)	24 (15–37)	
Sample size	n=25	n=40	n=111	n=91	
PFOS	9.8 (3.1–20)	5.4 (1.5–15)	3.9 (0.70–23)	3.3 (0.70–19)	<0.0001
PFOA	na	0.86 (0.40–1.9)	0.69 (0.20–2.4)	0.55 (0.19–1.4)	<0.0001
PFNA	na	na	2.1 (0.80–12)	2.5 (0.75–10)	0.0358
PFDA	na	na	0.49 (<LOD–4.0)[b]	0.52 (0.10–3.1)[c]	0.6396
PFUnDA	na	na	0.53 (<LOD–4.5)[d]	0.60 (0.090–3.8)	0.3788
PFHxS	na	0.44 (<LOD–7.0)	0.35 (<LOD–1.5)[e]	0.26 (0.060–1.2)	<0.0001
PCP	0.60 (0.21–1.5)[f]	0.37 (0.15–1.1)	0.29 (<LOD–1.8)[g]	0.15 (<LOD–0.64)[h]	<0.0001

Note: PFBA, PFHxA and PFBS are not presented because 0% of detection for one or both years (measured in 2012 and 2017 only).
LOD: Limit of detection; for statistical purposes, values <LOD were replaced by LOD/2; na: not available; [a]*p*-value based on orthogonal polynomial contrast for linear trend, using regression adjusted for age, smoking status (smoker vs. non-smoker) and multiparous woman (yes vs. no); [b]n=106; [c]n=90; [d]n=110; [e]n=107; [f]n=20; [g]n=112; [h]n=41.

Table 3.11 Continued

2001	2004	2007	2012	2013	2017	*p*-value[a]
27 (17–39) n=20	26 (19–35) n=22	23 (17–37) n=39	24 (18–39) n=112	24 (18–41) n=95	24 (15–38) n=97	
33 (8.2–130)	35 (11–100)	23 (1.8–180)	20 (<LOD–120)	22 (0.91–130)	17 (1.8–120)	<0.0001
49 (11–200)	65 (19–200)	47 (2.5–250)	37 (<LOD–220)	42 (2.0–220)	34 (2.8–230)	<0.0001
8.9 (<LOD–35)	9.9 (3.1–30)	7.5 (<LOD–42)	5.4 (<LOD–41)	5.8 (<LOD–29)	4.7 (<LOD–32)	<0.0001
210 (54–1690)	230 (63–720)	160 (30–720)	120 (11–520)	130 (22–480)	100 (17–490)	<0.0001
6.1 (<LOD–38)	8.6 (3.4–26)	6.0 (<LOD–50)	nc (<LOD–33)	nc (<LOD–15)	nc (<LOD–11)	<0.0001
32 (11–140)	34 (8.9–92)	24 (5.1–83)	18 (<LOD–110)	20 (2.0–92)	19 (<LOD–110)	<0.0001
nc (<LOD–16)	4.3 (<LOD–11)	3.9 (1.1–26)	2.4 (<LOD–16)[b]	2.4 (<LOD–19)	2.1 (<LOD–17)	<0.0001
6.4 (<LOD–30)	3.6 (<LOD–13)	2.2 (<LOD–15)	3.1 (<LOD–19)	3.0 (<LOD–24)	2.9 (<LOD–18)	<0.0001
49 (11–170)	38 (12–120)	23 (3.0–91)	17 (<LOD–77)	19 (2.0–120)	14 (1.3–91)	<0.0001
76 (16–420)	73 (22–240)	43 (4.5–220)	39 (2.4–230)	40 (3.5–320)	30 (3.1–190)	<0.0001
40 (7.5–240)	30 (8.1–120)	18 (2.0–95)	17 (<LOD–160)	16 (1.7–200)	13 (1.8–100)	<0.0001
na	8.7 (2.3–33)	6.9 (<LOD–51)	4.5 (<LOD–49)	5.6 (<LOD–47)	3.9 (<LOD–31)	0.0004
na	15 (3.9–57)	12 (<LOD–89)	7.1 (<LOD–65)	8.9 (<LOD–63)	6.4 (<LOD–48)	<0.0001
na	7.0 (<LOD–33)	6.2 (<LOD–49)	nc (<LOD–29)[c]	nc (<LOD–210)	nc (<LOD–24)	0.6106
na	2.0 (<LOD–12)	2.6 (<LOD–23)	2.9 (<LOD–15)[c]	nc (<LOD–13)	nc (<LOD–19)	0.0392

as PFNA, PFDA, and PFUnDA from 2012 onwards (when they were first measured), with respective increases of 19%, 13% and 21%; however, only the increase in PFNA was statistically significant (Caron-Beaudoin et al., 2020). Among pregnant Nunavik women, strong positive associations were found between several PFAS congeners (PFHxS, PFOS, PFNA, PFDA, PFUnDA) and the omega-3/omega-6 polyunsaturated fatty acid (PUFA) ratio, indicating a positive association with consumption of marine country foods (Caron-Beaudoin et al., 2020). The ratios of PFNA:PFOA, PFNA:PFOS, PFNA:PFHxS and PFUnDA:PFDA serum concentrations were higher in pregnant women from Nunavik compared to CHMS Cycle 5, 2016–2017. While short-chain PFASs such as PFOS and PFOA are often associated with exposure though consumer goods (Xie et al., 2013), the bioaccumulation potential of PFAS congeners is higher in the C9–C14 congeners than in the shorter congeners (e.g., PFHxS, PFOA) (Haukås et al., 2007; Xu et al., 2014), and the higher ratios in pregnant women from Nunavik may indicate an exposure to these compounds occurring through their bioaccumulation in marine country foods (Caron-Beaudoin et al., 2020). Moreover, currently-used fluorotelomer alcohols are known to be transported to the Arctic and degraded into a number of PFASs (i.e., PFOA, PFNA, PFDA, PFUnDA), but compared to PFOA, long-chain PFASs (C9-C14) have greater bioaccumulation potential which could lead to higher accumulation in Arctic wildlife (Caron-Beaudoin et al., 2020).

3.3.2.4 Canadian Arctic comparisons

In the Canadian Arctic, geometric mean concentrations of all POPs were highest in the Nunavik region, particularly PFOS and PFNA, with the exception of PBDEs which were uniformly low across the Canadian Arctic with concentrations in the majority of samples below the limit of detection. POPs concentrations were generally similar in the Yukon and NWT, although most were slightly higher in the NWT, with the exception of HCB in men in the Yukon for which levels were higher than in the NWT. In contrast, concentrations in Nunavik were between two- and ten-fold higher for some contaminants. The largest differences observed between the eastern and western Canadian Arctic were for PFOS, long-chain PFASs, chlordanes such as oxychlordane and *trans*-nonachlor, as well as some of the PCB congeners, while some of the smallest differences observed were for PFOA, PFHxS, HCB and *p,p′*-DDE.

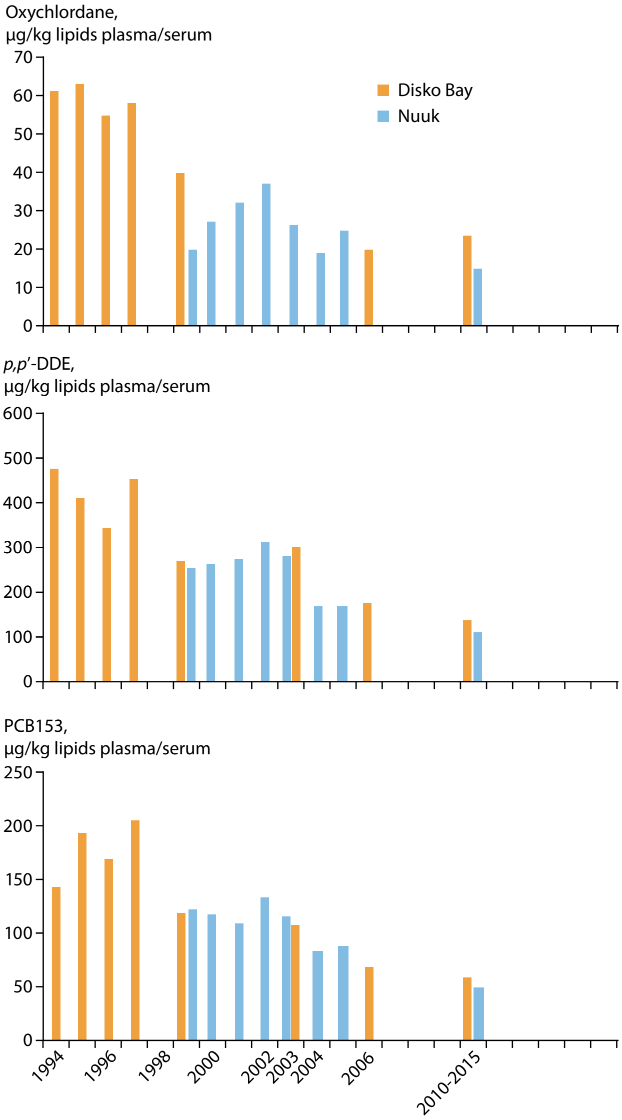
3.3.3 Greenland

The mother-child birth cohort ACCEPT (Adaptation to Climate Change, Environmental Pollution, and dietary Transition) was established in 2010–2015 (see Chapter 1 for cohort descriptions). Blood samples of 504 pregnant Greenlandic women were collected (median age 27 years) (Hjermitslev et al., 2020). Blood serum levels of lipophilic POPs including 14 PCB congeners and 11 organochlorine pesticides, 10 PBDEs, and 16 PFASs were measured in up to 499 samples from pregnant Inuit women. Concentrations are presented in Tables 3.13 and 3.14 for those contaminants that were detected in the majority of samples. Most PCBs were detected in a majority of the samples, with PCB138, PCB153 and PCB180 detected in all samples. The dioxin-like PCB105, PCB118 and PCB156 were detected in 44.4%, 98.6%, and 80.4% of samples, respectively, while non-dioxin-like PCB28, PCB52, PCB101 and PCB128 were detected in a small minority of samples (PCB28 was detected in less than 5% of samples). Seven organochlorine pesticides were detectable in a majority of samples, while aldrin, α-chlordane and γ-chlordane were detected in less than 1.5% of samples. PBDEs were only detected in less than 4% of samples. There were significant regional differences for PCBs and organochlorine pesticides ($p<0.0001$), with higher levels observed in eastern and northern Greenland (Table 3.13). The exposure levels of PCBs and organochlorine pesticides in pregnant Greenlandic Inuit women between 2010 and 2015 were lower than previously reported (Bjerregaard et al., 2013), when comparing to previous levels in Disko Bay and Nuuk (Figure 3.1).

Table 3.13 Blood concentrations of PCBs and organochlorine pesticides in pregnant Greenlandic Inuit women in ACCEPT cohort 2010–2015. Data presented as geometric means (range) in blood plasma (µg/kg lipid). Source: Bonefeld-Jørgensen and Long (pers. comm. 2019); Hjermitslev et al. (2020).

	% <LOQ	North	Disko Bay	West	South	East	*p*-value[a]	All
Mean age, y (range)		28.4 (20–36)	27.1 (18–41)	27.3 (18–42)	28.6 (20–41)	27.4 (19–42)		27.5 (18–42)
Sample size		n=33	n=117	n=280	n=42	n=19		n=491
PCB99	27.5	13.2 (2.00–37.0)	8.71 (2.00–37.0)	6.17 (1.50–120)	7.14 (2.00–23.0)	60.1 (9.00–350)	<0.0001	7.79 (1.5–350)
PCB105	55.6	2.67 (0.50–13.0)	1.7 (0.40–6.70)	1.29 (0.45–15.0)	1.23 (0.50–4.40)	8.97 (2.10–38.0)	<0.0001	1.55 (0.40–38.0)
PCB118	1.4	13.6 (2.40–63.0)	10.1 (2.20–38.0)	7.37 (0.50–74.0)	7.59 (1.80–40.0)	47.9 (9.10–260)	<0.0001	8.92 (0.50–260)
PCB138	0	38.9 (4.80–180)	27.6 (4.30–110)	23 (2.40–410)	28.6 (6.20–82.0)	200 (22.0–1300)	<0.0001	27.6 (2.4–1300)
PCB153	0	82.5 (8.90–950)	57.3 (8.40–210)	47.8 (5.10–910)	60.3 (12.0–180)	414.5 (43.0–2700)	<0.0001	57.4 (5.10–2700)
PCB156	19.6	3.95 (0.50–75.0)	2.85 (0.50–13.0)	2.78 (0.50–27.0)	3.02 (0.50–11.0)	11.4 (1.40–54.0)	<0.0001	3.05 (0.50–75.0)
PCB170	1	13.7 (2.00–390)	8.54 (1.00–35.0)	8.27 (1.30–130)	10.4 (2.50–27.0)	66.5 (7.90–330)	<0.0001	9.53 (1.00–390)
PCB180	0	39.5 (6.60–810)	25.3 (3.90–110)	24.1 (3.80–370)	30.5 (7.30–82.0)	186 (23.0–1100)	<0.0001	27.8 (3.80–1100)
PCB183	17.9	4.7 (0.50–20.0)	3.1 (0.50–12.0)	2.69 (0.50–75.0)	3.62 (0.50–11.0)	27.1 (3.30–200)	<0.0001	3.24 (0.50–200)
PCB187	1.7	18.7 (3.40–100)	12.7 (1.00–45.0)	11 (1.00–230)	14 (2.90–35.0)	85.2 (14.0–610)	<0.0001	13.2 (1.00–610)
cis-Nonachlor	5.6	14 (1.90–61.0)	9.47 (1.40–43.0)	6.64 (0.45–100)	7.73 (0.83–21.0)	40.7 (9.20–200)	<0.0001	8.3 (0.45–200)
Hexachlorobenzene	0.3	35.9 (5.80–130)	31.5 (9.60–100)	23.1 (2.50–170)	22.9 (8.90–56.0)	68.4 (25.0–240)	<0.0001	26.7 (2.50–240)
Mirex	29.4	4.78 (1.00–54.0)	2.64 (0.50–12.0)	2.22 (0.45–47.0)	3.1 (0.50–11.0)	19.5 (4.60–120)	<0.0001	2.72 (0.45–120)
Oxychlordane	1.7	33.8 (2.00–470)	22.7 (2.60–110)	13.6 (0.25–260)	16.8 (1.00–55.0)	134 (18.0–920)	<0.0001	18.1 (0.25–920)
p,p′-DDE	0.7	208 (18.0–990)	135 (22.0–540)	104 (5.00–2500)	127 (26.0–430)	1037 (110–8800)	<0.0001	129 (5.00–8800)
β-HCH	9	5.01 (0.50–34.0)	3.98 (0.50–18.0)	3 (0.50–28.0)	3.36 (0.50–9.2)	13.9 (3.50–64.0)	<0.0001	3.56 (0.50–64.0)
trans-Nonachlor	1.9	75.2 (7.60–320)	50.3 (7.60–220)	32.9 (1.00–580)	38.9 (3.20–110)	264 (47.0–1600)	<0.0001	42.3 (1.00–1600)

LOQ: limit of quantification; [a]difference among regions was tested by one-way ANOVA analysis.



Among 16 PFASs measured, PFOS, PFHxS, PFHpS, PFOA, PFNA, PFDA and PFUnDA were detected in more than 74.7% of samples (Table 3.14), while PFHpA, PFDoDA, PFTrA were detected in less than 50% of samples. PFBS, PFDS, PFOSA, PFPeA, PFHxA and PFTeA were non-detectable. Thus, the data presented are for PFAS congeners detected in more than 50% of samples (Table 3.14). Similar to the pattern of lipophilic POPs, significant regional differences in PFAS congeners were observed, with the highest levels seen in eastern Greenland (Table 3.14). Compared to data reported in 2002–2004 (AMAP, 2015), PFOS and PFOA levels in pregnant Greenlandic women were lower in the ACCEPT study, indicating a declining trend in these compounds which were the two most predominant PFAS congeners measured (Figure 3.2).

The INUENDO birth cohort (Biopersistent organochlorines in diet and human fertility) was established in 2002–2004 and involved around 1400 pregnant women from Greenland, Poland and Ukraine (Lindh et al., 2012; Lenters et al., 2015, 2016). Levels of several organochlorines as well as PFOS and PFOA in pregnant women and their male partners from this study were previously reported by AMAP (2015); however, additional data for PFASs in mothers' serum are now available and presented in Table 3.15, as well as PFAS data for a subset of their male partners. Analysis of blood samples for PFASs, included PFHxS, PFNA, PFDA, PFUnDA, and PFDoDA. Geometric mean concentrations of different PFASs measured were relatively similar, except for PFOS in 2002–2004 for which concentrations were over ten-fold higher than for other PFASs detected (20.6 and 47.4 µg/L serum for pregnant women and men). Geometric mean concentrations of other PFASs were below 2 µg/L in pregnant women and below

Figure 3.1 Trends in plasma concentrations of oxychlordane, *p,p′*-DDE and PCB153 for pregnant women from Disko Bay and Nuuk, Greenland since the early 1990s.

Table 3.14 Blood concentrations of PFASs in pregnant Greenlandic Inuit women in ACCEPT cohort 2010–2015. Data presented as geometric means (range) in serum (µg/L). Source: Hjermitslev et al. (2020).

	% <LOQ	North	Disko Bay	West	South	East	*p*-value[a]	All
Mean age, y (range)		28.4 (20–36)	27.1 (18–41)	27.3 (18–42)	28.6 (20–41)	27.4 (19–42)		27.5 (18–42)
Sample size		n=32	n=122	n=283	n=43	n=19		n=499
PFOS	0	12.2 (2.04–50.7)	10.4 (2.35–43.6)	8.17 (1.45–61.3)	7.12 (3.20–18.0)	18.3 (5.35–42.5)	<0.0001	9.06 (1.45–61.3)
PFHxS	0.2	0.67 (0.10–4.48)	0.49 (0.13–2.52)	0.49 (0.04–2.57)	0.42 (0.17–1.37)	1.49 (0.23–4.34)	<0.0001	0.52 (0.04–4.48)
PFHpS	25.3	0.22 (0.06–1.44)	0.18 (0.06–0.96)	0.14 (0.06–1.15)	0.11 (0.06–0.34)	0.35 (0.06–0.92)	<0.0001	0.15 (0.06–1.44)
PFOA	0.2	0.97 (0.23–2.27)	1.1 (0.24–7.26)	1.04 (0.10–6.33)	0.91 (0.30–2.42)	1.12 (0.33–2.31)	0.3	1.04 (0.10–7.26)
PFNA	0	1.42 (0.34–7.34)	1.3 (0.39–7.87)	1.1 (0.21–7.71)	0.94 (0.43–3.35)	2.52 (0.75–5.93)	<0.0001	1.19 (0.21–7.87)
PFDA	0.1	0.98 (0.22–3.30)	0.88 (0.21–3.92)	0.67 (0.12–7.84)	0.55 (0.19–1.62)	1.51 (0.43–4.35)	<0.0001	0.74 (0.12–7.84)
PFUnDA	0.7	1.91 (0.28–12.1)	1.77 (0.21–16.3)	1.25 (0.08–14.9)	1.01 (0.16–5.36)	3.4 (0.64–18.2)	<0.0001	1.42 (0.08–18.2)

LOQ: limit of quantification; [a]difference among regions was tested by one-way ANOVA analysis. PFHpA, PFDoDA, PFTrA were detected in <50% of samples; PFBS, PFDS, PFOSA, PFPeA, PFHxA, and PFTeA were not detectable.

Table 3.15 Concentrations of PFASs in pregnant Greenlandic women and their male partners from the INUENDO study. Data presented as geometric means (range), in µg/L serum. Source: Lindh et al. (2012); Lenters et al. (2016); Toft (pers. comm. 2019).

	Pregnant women		Men	
Year(s)	2002–2004		2002–2004	
Mean age, y (range)	27 (18–44)		30 (20–43)	
Sample size	n=513		n=196	
	µg/L serum	% <LOD	µg/L serum	% <LOD
PFOS	20.6 (4.10–87.3)	0	47.4 (12.3–161)	0
PFOA	1.78 (0.50–5.13)	0	4.60 (1.52–13.7)	0
PFHxS	1.79 (0.30–12.9)	0	2.39 (0.91–20.5)	0
PFNA	0.73 (0.17–5.71)	0	1.85 (0.53–11.6)	0
PFDA	0.42 (0.10–4.02)	0	0.87 (<LOD–5.92)	1
PFUnDA	0.69 (<LOD–9.40)	2	1.24 (<LOD–13.4)	6
PFDoDA	0.13 (<LOD–1.51)	28	0.14 (<LOD–1.68)	19
PFHpA	0.05 (<LOD–0.42)	18	na	na

LOD: Limit of detection; na: not available.

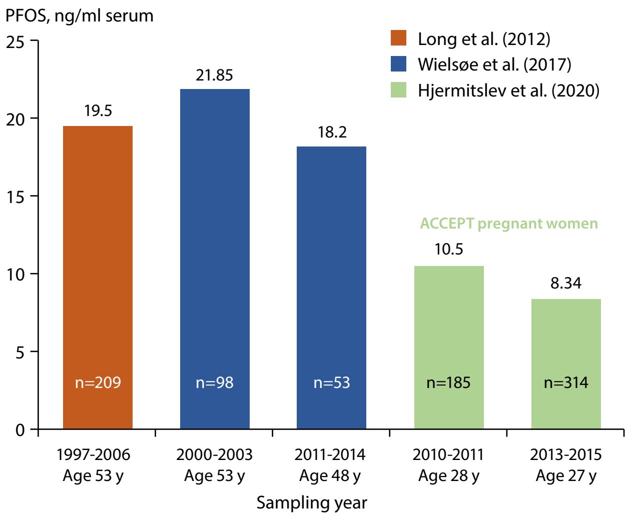


Figure 3.2 Trends in serum concentrations of PFOS for Greenlandic women between 1997 and 2015. Data presented as median concentrations and median age (Long et al., 2012; Wielsøe et al., 2017; Hjermitslev et al., 2020).

5 µg/L in men. Geometric mean concentrations of PFASs in men were much higher than for pregnant women, often twice as high or more (for PFOS, PFOA, PFNA, PFDA) (Lindh et al., 2012; Lenters et al., 2016).

The OCEANS study involved the recruitment of Greenlandic children whose mothers had participated in the INUENDO cohort study (n=598) and/or the IVAAQ cohort study (n=270) during pregnancy (Timmermann et al., 2019). Pregnant women were recruited between 2002 and 2005 and their children participated in the study during 2012–2015. The OCEANS study included participants from one community on the east coast of

Table 3.16 Blood concentrations of contaminants in Greenlandic children. Data presented as geometric means (range); PCBs in lipid-adjusted serum (µg/kg plasma lipids) and PFASs in serum (µg/L). Source: Timmermann et al. (2019); Timmermann (pers. comm. 2019).

	Boys		Girls	
Years(s)	2012–2015		2012–2015	
Mean age, y (range)	9.8 (7.3–12.1)		9.7 (7.1–11.5)	
Sample size	n=176		n=162	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
PCBs				
PCB28	3 (<3–21)	61	4 (<3–398)	49
PCB52	2 (<3–10)	95	2 (<3–29)	90
PCB101	2 (<3–10)	89	2 (<3–30)	81
PCB105	1.7 (<3–11)	90	2 (<3–18)	81
PCB118	5 (<3–50)	41	8 (<3–120)	23
PCB138	40 (<3–453)	1	47 (<3–1137)	2
PCB153	62 (<3–776)	2	70 (<3–1532)	1
PCB156	3 (<3–56)	68	3 (<3–44)	65
PCB180	30 (<3–413)	2	29 (<3–834)	5
ΣPCBs[a]	270 (<3–3155)		298 (18–6600)	
PFASs	µg/L serum	n=176	µg/L serum	n=162
PFHxS	0.717 (0.234–5.28)	0	0.747 (0.303–5.83)	0
PFHxA	0.017 (<0.03–0.575)	95	0.017 (<0.03–0.974)	94
PFHpS	0.277 (0.065–3.00)	0	0.310 (0.079–1.61)	0
PFHpA	0.975 (<0.03–1.25)	23	0.086 (<0.03–2.17)	21
PFOS	8.48 (2.05–38.4)	0	9.37 (2.91–53.1)	0
PFOA	2.36 (1.05–6.33)	0	2.29 (0.824–5.25)	0
PFNA	1.41 (0.434–5.10)	0	1.55 (0.551–8.04)	0
PFDA	0.424 (0.085–2.00)	0	0.457 (0.078–3.64)	0
PFUnDA	0.369 (<0.03–2.35)	2	0.466 (<0.03–5.99)	1

LOD: Limit of detection; values below the LOD were treated as LOD/2 for calculating the mean. [a]Sum of PCBs was calculated as 2x(PCB138 + PCB153 + PCB180) because those three PCBs account for approximately half of the total PCB concentration.

Table 3.17 Regional comparisons of blood concentrations of contaminants in Greenlandic children between 2012–2015. Data presented as geometric means (range); PFASs in serum (μg/L), PCBs in lipid-adjusted serum (μg/kg plasma lipids). Source: Timmermann et al. (2019); Timmermann (pers. comm. 2019).

Region	Greenland (all)	Nuuk	Disko Bay[a]	West[b]	East[c]	p-value[d]
Mean age, y (range)	9.8 (7.1–12.1)	9.3 (7.3–11.0)	9.5 (7.1–11.5)	10.4 (8.1–11.6)	10.5 (9.1–12.1)	
Sample size	n=338	n=84	n=130	n=100	n=24	
PCBs						
PCB28	3 (<3–398)	3 (<3–22)	2 (<3–398)	6 (<3 –21)	3 (<3 –7)	<0.001
PCB52	2 (<3 –29)	2 (<3 –9)	2 (<3 –10)	2 (<3 –9)	4 (<3 –29)	<0.001
PCB101	2 (<3 –30)	2 (<3 –3)	2 (<3 –12)	2 (<3 –11)	5 (<3 –30)	<0.001
PCB105	2 (<3 –18)	2 (<3 –5)	2 (<3 –11)	2 (<3 –12)	4 (<3 –18)	<0.001
PCB118	6 (<3 –120)	3 (<3 –34)	7 (<3 –45)	6 (<3 –37)	30 (<3 –120)	<0.001
PCB138	43 (<3 –1137)	24 (<3 –230)	45 (<3 –1137)	45 (<3 –235)	223 (<3 –997)	<0.001
PCB153	66 (<3 –1532)	39 (<3 –363)	66 (<3 –504)	68 (<3 –454)	351 (<3 –1532)	<0.001
PCB156	3 (<3 –56)	2 (<3 –19)	3 (<3 –56)	3 (<3 –24)	7 (<3 –44)	<0.001
PCB180	29 (<3 –834)	16 (<3 –198)	31 (<3 –413)	29 (<3 –342)	165 (<3 –834)	<0.001
ΣPCBs	283 (<3 –6600)	162 (9–1436)	292 (18–2677)	290 (49–2062)	1484 (289–6600)	<0.001
PFASs						
PFHxS	0.730 (0.234–5.83)	0.636 (0.234–1.43)	0.699 (0.260–1.80)	0.676 (0.291–1.70)	2.11 (0.675–5.83)	<0.001
PFHxA	0.017 (<0.03–0.974)	0.021 (<0.03–0.974)	0.015 (<0.03–0.077)	0.015 (<0.03–0.079)	0.016 (<0.03–0.051)	0.34
PFHpS	0.292 (0.065–3.00)	0.211 (0.085–0.686)	0.263 (0.065–3.00)	0.383 (0.079–1.05)	0.525 (0.114–1.33)	<0.001
PFHpA	0.080 (<0.03–2.17)	0.036 (<0.03–0.454)	0.144 (<0.03–2.17)	0.066 (<0.03–0.432)	0.129 (<0.03–0.414)	<0.001
PFOS	8.89 (2.05–53.1)	6.97 (2.05–18.3)	9.84 (3.23–32.1)	8.08 (2.90–25.1)	18.0 (5.11–53.1)	<0.001
PFOA	2.33 (0.824–6.33)	2.18 (1.05–4.35)	2.70 (1.23–6.33)	1.22 (0.824–5.25)	2.37 (1.60–3.70)	<0.001
PFNA	1.48 (0.434–8.04)	1.23 (0.434–2.93)	1.59 (0.613–5.10)	1.37 (0.459–2.93)	2.60 (0.865–8.04)	<0.001
PFDA	0.440 (0.078–3.64)	0.436 (0.106–1.07)	0.565 (0.083–1.63)	0.258 (0.078–2.41)	1.07 (0.339–3.64)	<0.001
PFUnDA	0.413 (<0.03–5.99)	0.244 (<0.03–1.22)	0.532 (0.068–2.74)	0.357 (<0.03–2.92)	1.20 (0.234–5.99)	<0.001

For statistical purposes, values <LOD were replaced by LOD/2; [a]Qeqertarsuaq, Aasiaat, and Ilulissat; [b]Sisimiut and Maniitsoq; [c]Tasiilaq; [d]differences between areas were tested using Kruskal Wallis test.

Greenland, three communities in the Disko Bay area, Nuuk, and two communities on the west coast (Timmermann et al., 2019). Blood samples from 338 children (between the ages of approximately 7 and 12 years) were analyzed for PCBs and PFASs. Concentrations of many PCB congeners were low among boys and girls, with a large percentage of non-detects measured among the children. Concentrations of PFHxA were below the limits of detection for most (94%) children, while concentrations of other PFASs were detected in almost all children, except for PFHpA which was below the limit of detection for 23% and 21% of boys and girls, respectively. The main PCB congeners detected in the majority of samples were PCB138, PCB153 and PCB180. Concentrations of these congeners were similar between boys and girls, although girls appeared to have slightly higher concentrations (Table 3.16). The predominant PFASs measured in serum was PFOS,

Table 3.18 Trends of POPs in pregnant Icelandic women in their third trimester. Data presented as geometric means (range) for POPs (μg/kg plasma lipid) and for PFOS and PFOA (μg/L plasma). Lipid normalization of data in 1999 and 2004 based on average lipid concentrations from 1995. Source: AMAP (2015); Ólafsdóttir (pers. comm. 2019).

	Reykjavik	All Iceland		Reykjavik	
Year	1995	1999	2004	2009	2015
Mean age, y (range)	30 (18–41)	28.7 (20–42)	30.3 (20–40)	30.4 (21–43)	31.6 (22–43)
Sample size; mean parity	n=40; p=1.9	n=39; p=1.9	n=40; p=1.8	n=33; p=1.7	n=50; p=2.0
Oxychlordane	6.7 (2.6–30)	4.7 (1.3–22)	6.5 (1.3–22)	3.5 (1.3–8.9)	1.6 (<0.5–4.0)
trans-Nonachlor	12 (3.8–50)	15 (6.4–47)	7.1 (1.3–29)	6.7 (3.6–15.5)	4.6 (1.5–12)
p,p′-DDT	na	na	na	1.4 (<1.3–5.7)	0.85 (<0.5–4.2)
p,p′-DDE	113 (42–514)	100 (33–306)	54 (19–226)	36 (12.1–139)	21 (6.0–67)
HCB	41 (17–147)	49 (23–96)	27 (13–51)	20 (12–35)	11 (5.3–17)
β-HCH	32 (11–142)	24 (10–71)	9.0 (2.5–20)	7.1 (3.0–28)	3.3 (0.81–9.9)
Toxaphene Parlar 26	na	na	1.6 (1.3–6.4)	1.3 (<1.3–4.6)	1.2 (<0.5–2.8)
Toxaphene Parlar 50	na	na	2.8 (1.3–10)	2.9 (<1.3–8.0)	2.8 (0.87–7.5)
PCB99	na	na	na	3.7 (<1.3–11)	3.3 (1.4–7.7)
PCB118	16 (7.7–37)	14 (3.8–38)	11 (5.1–24)	8.4 (4.7–18)	4.3 (2.4–8.5)
PCB138	46 (18–99)	40 (17–90)	23 (11–57)	15 (6.0–60)	8.7 (3.4–20)
PCB153	68 (26–158)	60 (24–143)	40 (19–98)	34 (18–108)	16 (6.1–37)
PCB180	34 (14–106)	35 (14–98)	22 (6.4–60)	16 (6.1–79)	8.0 (2.6–17)
ΣPCBs[a]	297 (115–132)	266 (114–662)	172 (78.7–429)	114 (53.4–273)	65.5 (26.3–141)
PBDE47	na	na	na	1.7 (<1.3–21)	1.9 (0.59–11)
PBDE99	na	na	na	<1.3 (<1.3–3.7)	0.85 (<0.5–3.6)
PBDE100	na	na	na	<1.3 (<1.3–5.0)	<0.5 (<0.5–2.5)
PBDE153	na	na	na	<1.3 (<1.3–3.9)	na
PFOS	na	na	na	6.2 (4.2–13)[b]	na
PFOA	na	na	na	4.8 (1.4–40)[b]	na

na: Not analyzed; values below the LOD were treated as LOD/2 for calculating the mean; [a]ΣPCB= 2x(PCB138+PCB153+PCB180); [b]n=10.

with concentrations approximately four-fold higher than for PFOA, the next most predominant PFAS. The only PFASs with geometric mean concentrations above 1 μg/L serum were PFOS, PFOA and PFNA.

Area of residence was significantly associated with contaminant levels, and comparisons between the different Greenlandic regions, as shown in Table 3.17, showed statistically significant differences in PCB and PFAS concentrations in children (Timmermann et al., 2019). The lowest geometric mean concentrations of PCBs were observed in Nuuk (Table 3.17), while the highest were observed in Tasiilaq (eastern Greenland). While statistically significant differences were observed for all

PFASs measured, except PFHxA, regional trends were more varied. The lowest mean concentrations of PFOA and PFDA were observed in western Greenland (Sisimiut and Maniitsoq), while PFOS was lowest in Nuuk. Similar to PCBs, most PFASs were observed at higher concentrations in eastern Greenland. While increased consumption of traditional Greenlandic food was associated with higher levels of all contaminants, levels of PFOA were not as strongly associated with food consumption, which may suggest other sources of exposure (Timmermann et al., 2019).

3.3.4 Iceland

Levels of POPs in maternal plasma have been monitored at approximate five-year intervals since 1995. Maternal blood sampling took place either at birth (1995), or during the third trimester in Reykjavik (1995, 2009, 2015) and other locations in Iceland (1999, 2004). Iceland has a socially and culturally homogeneous population, and results from maternal sampling in 1999 and 2004 across Iceland have indicated that observed exposures and contaminant concentrations are similar (AMAP, 2009). The mean age and parity of mothers remained similar across the five time points shown in Table 3.18.

The time series show a clear downward trend in levels of most POPs, especially from 2004 to 2015. Levels observed in 2015 are roughly 20–30% of those recorded in 1995. In contrast to other POPs, levels of toxaphenes have hardly changed since they were first analyzed in 2004 (Table 3.18). Parlar 50 in particular has remained effectively the same over the entire sampling period (2.8, 2.9, and 2.8 µg/kg plasma lipids in 2004, 2009 and 2015, respectively), which could be due to continued exposure or to its long half-life which would result in a negligible decline over each five-year period. In terms of the potential for continued exposure, toxaphene is banned for use in Europe and North America; but it is still used in some parts of the world which may provide further inputs to global circulation and bioaccumulation of toxaphenes in aquatic food chains. Toxaphenes are known to bioaccumulate in the tissues of fish, shellfish and marine mammals and Parlar 50 is the dominant organochlorine found in cod liver in the marine environment around Iceland (Sturludottir et al., 2014). PBDEs were analyzed in 2009 and 2015 (although PBDE153 was not measured in 2015) and levels appear similar at these two time points. While PBDE47 continues to be the predominant congener, concentrations of PBDEs are low and close to the limit of detection; 26% and 36% of samples in 2015 were below the limit of detection for PBDE99 and PBDE100.

A dietary transition from a high marine fish diet in the 1900s to a much smaller intake of fish in 1990 (73 g/day), 2002 (40 g/day) and 2011 (46 g/day) has been recorded among Icelandic people. This reduction in marine fish intake is probably responsible for the decline in levels of POPs (Steingrimsdottir et al., 2003; Adalsteinsdottir et al., 2020). The reduction in fish consumption was strongest among young women, and only half the population followed the recommended intake of two fish meals per week (Þorgeirsdottir et al., 2011).

3.3.5 Faroe Islands

Several cohorts have been initiated in the Faroe Islands since the late 1980s to investigate Faroese exposure to Hg and POPs due to concerns associated with pilot whale consumption. Pregnant women and children have been followed-up over time, with continued participation of children from the first cohort who are now adults. The following sections include newly available data for participants from Faroe Islands Cohorts 1, 3, and 5, which build on previously reported cohort data (AMAP, 2015).

3.3.5.1 Faroe Islands Cohort 1

The first birth cohort in the Faroe Islands involved maternal blood samples collected in 1986–1987 to assess methylmercury (MeHg) exposure and health impacts among newborns. The most recent samples collected from this cohort (28-year-olds in 2013–2016) were analyzed for a large suite of POPs which also included several PFASs (Table 3.19). Results show levels of most POPs were lower than those observed in cord blood and during early childhood at ages 7 and 14 years, but do not appear to have decreased since last measured as 22-year-olds in 2008–2009, and for some such as *p,p′*-DDE and several PCB congeners, levels actually increased slightly in the 28-year-olds measured in 2013–2016.

3.3.5.2 Faroe Islands Cohort 3

The third birth cohort in the Faroe Islands (initial sampling 1998–2000) also comprised mother-child pairs, and concentrations of PFASs in mothers and children are presented in Table 3.20. Serum concentrations of PFASs were similar among children at ages 5 and 7.5 years; however, a large decline in levels of PFOS and PFOA was observed in children at age 13 years. PFASs including PFHxS, PFNA, and PFDA showed no clear upward or downward trend among children between the ages of 5 and 13 years.

Mogensen et al. (2015) evaluated the time-dependent impact of breastmilk as an exposure pathway for PFASs. Serum concentrations of five major PFASs (PFHxS, PFOA, PFOS, PFNA, PFDA) were measured in maternal blood and serum from children followed-up at ages 11, 18, and 60 months. Duration of exclusive breastfeeding was associated with increases in most PFASs measured in children (by up to 30% per month), with lower increases observed with partial breastfeeding. In contrast to this main pattern, PFHxS was not affected by breastfeeding. After breastfeeding ended, all serum concentrations decreased. This finding supports the evidence of breastfeeding being an important exposure pathway to some PFASs in infants.

3.3.5.3 Faroe Islands Cohort 5

The fifth birth cohort in the Faroe Islands was initiated between 2007 and 2009, and comprised 501 mother-child pairs. In addition to previously reported levels of POPs in maternal blood and child serum at 18 months of age, data are available for PCBs, organochlorine pesticides and PFASs in children at 5 years of age (n=347), as shown in Table 3.21. Concentrations of PCBs, *p,p′*-DDE, and HCB declined in Faroese children from 18 months of age in 2009–2011 to 9 years of age in 2016–2018.

Table 3.19 Time series of blood POPs concentrations from the Faroe Islands Cohort 1. All participants are Faroese children born in 1986–1987. Data presented as geometric means (range), POPs in µg/kg plasma lipid, PFASs in µg/L plasma. Source: AMAP (2015); Petersen (pers. comm. 2019).

Year(s)	1986–1987	1993–1994	2000–2001	2008–2009	2013–2016
Mean age, y	Cord blood	6.9	13.8	22.1	28
Sample size	n=1022	n=922	n=792	n=849	n=703
p,p'-DDE	270 (4.2–4487)	na	468 (25.4–8050)	122 (5.4–3257)	189 (6.5–4501)
HCB	45.9 (3.4–1469)	na	94.3 (22.1–858)	18.9 (3.1–164)	16.3 (0.4–243)
PCB118	na	na	na	11.8 (0.1–282)	10.6 (1.5–226)
PCB138	83 (0.3–1068)	na	na	64.6 (0.1–790)	65.7 (1.5–798)
PCB153	130 (0.3–1127)	na	na	93 (8.2–1006)	101 (4.8–1227)
PCB180	72 (0.3–889)	na	na	60.8 (3.4–673)	74.4 (8.3–792)
ΣPCBs[a]	604 (17–5606)	1525 (210–7040)	708 (4.2–4941)	443 (36–4940)	489 (35.4–5479)
PFOS	na	31.1 (7.2–96.9)	na	na	6.27 (0.554–28.7)
PFOA	na	5.4 (1.3–17.3)	na	na	1.226 (0.108–13.2)
PFHpA	na	na	na	na	0.02 (0.015–1.52)
PFHxS	na	na	na	na	0.383 (0.015–4.06)
PFNA	na	na	na	na	0.941 (0.157–4.17)
PFHpS	na	na	na	na	0.077 (0.015–0.412)
PFDA	na	na	na	na	0.328 (0.034–2.61)
PFUnDA	na	na	na	na	0.375 (0.015–3.10)

na: not available; [a]Sum of PCBs = 2×(PCB138+PCB153+PCB180).

Table 3.20 Time series of blood PFAS concentrations in Faroese women and their children from Faroe Islands Cohort 3 (1998–2000). Data presented as geometric means (range). PFASs in µg/L. Source: Petersen (pers. comm. 2019).

	Mothers	Children		
Year(s)	1998–2000	2002–2005	2005–2007	2011–2012
Mean age, y (range)	30 (16–43)	5.0 (4.8–5.2)	7.5 (7.0–7.9)	13.2 (12.6–14.3)
Sample size	n=618	n=545	n=500	n=526
PFOS	27.4 (9.4–68.8)	16.7 (3.3–48.2)	15.3 (5.6–35.5)	6.6 (1.0–16.6)
PFOA	3.2 (0.8–8.4)	4.1 (0.8–15.4)	4.5 (1.7–19.2)	2.0 (0.6–6.1)
PFHxS	4.4 (0.6–26.5)	0.6 (0.02–19.5)	0.5 (0.1–8.9)	0.4 (0.07–4.1)
PFNA	0.6 (0.1–2.5)	0.6 (0.02–19.5)	0.5 (0.5–9.5)	0.7 (0.2–2.1)
PFDA	0.3 (0.03–1.2)	0.3 (0.05–1.2)	0.4 (0.07–2.2)	0.3 (0.09–1.2)

A decline in PFASs was also observed for children between 5 and 9 years of age, and PFOS continues to be the highest of the PFASs. Concentrations of several PFASs were also measured in a subset of mothers and children at 18 months and 5 years of age (Oulhote et al., 2017). While concentrations of PFOS and PFOA appear to have declined (lower among children at 5 years of age than 18 months of age), concentrations of other PFASs appeared higher among children at 5 years of age.

3.3.5.4 Cohort trends

In an effort to better understand changes in exposure sources to PFASs in Faroese communities, child data from three different cohorts between 1993 and 2012 (Faroe Islands Cohorts 1, 3, and 5) were analyzed for 19 PFASs (Dassuncao et al., 2018). Analysis of time trend data revealed that exposure in Faroese children peaked in 2000 at just under 50 µg/L, and that PFASs (total sum) have decreased by 14.4% per year since 2000. The majority of this decrease is attributed to a rapid decrease in levels of PFOA and PFOS, which aligns temporally with the voluntary withdrawal of PFOS from

Table 3.21 Time series of blood organochlorines and PFASs in Faroese women and their children from Faroe Islands Cohort 5 (2007–2009). Data presented as geometric means (range) in blood serum (µg/kg lipid) for organochlorines, and in whole blood (µg/L blood) for PFASs. Source: AMAP (2015); Petersen (pers. comm. 2019).

	Mothers	Children		
Year(s)	2007–2009	2009–2011	2012–2014	2016–2018
Mean age, y (range)	30.7 (17.2–49.4)	1.5 (1.4–1.7)	5	9
Sample size	n=500	n=363	n=347	n=381
PCB118	14.8 (1.0–134)	29.7 (15–224)	10.3 (2–109)	3.3 (1.5–95.9)
PCB138	53.7 (3.0–383)	80.1 (15–796)	60.2 (2–526)	33.3 (1.5–636.5)
PCB153	91.2 (1.0–694)	105 (15–1214)	84.8 (2–739)	54.9 (1.5–1033.6)
PCB180	60.1 (3.0–496)	61 (3.0–872)	49.9 (2–724)	30.1 (1.5–943.9)
ΣPCBs[a]	420 (16–2965)	500 (70–5760)	397.8 (10–3470)	249.4 (9–5228)
p,p-DDE	131 (6.0–1517)	180 (15–4414)	185.2 (13–2575)	90.8 (1.5–1051.5)
HCB	17.3 (3.0–116)	26.5 (15–144)	23.9 (7–85)	11.6 (1.5–68.5)
PFHpA	na	na	0.07 (0.015–1.58)	0.05 (0.015–0.273)
PFOA	na	2.9 (0.5–22.5)	2.22 (0.682–13.34)	1.44 (0.672–2.983)
PFHxS	na	na	0.34 (0.077–3.252)	0.27 (0.1–1.751)
PFNA	na	na	1.12 (0.124–5.745)	0.65 (0.147–3.404)
PFHpS	na	na	0.1 (0.015–0.392)	0.03 (0.015–0.15)
PFDA	na	na	0.33 (0.015–1.715)	0.24 (0.045–0.828)
ΣPFOS[b]	na	6.5 (1.4–28.3)	4.68 (1.066–16.275)	3.27 (0.652–11.654)
PFUnDA	na	na	0.17 (0.015–1.773)	0.17 (0.015–0.93)

na: not available; [a]ΣPCBs = 2x(PCB138+PCB153+PCB180); [b]ΣPFOS is a sum of linear and branched PFOS.

markets in 2000. In addition, principal component analysis allowed the differentiation of seafood from other possible sources of PFASs. Pilot whale consumption was an ongoing source of exposure, but was not the driving factor behind the observed changes in PFAS levels. Modeling work however, indicated that consumption of pilot whale was still a significant source of PFNA and other new generation PFASs. The marine environment may take longer to reflect changes in emissions, and the rapid decreases observed in levels of PFASs were not wholly explained by seafood consumption. Use of and exposure to PFASs from consumer products may have a greater role in explaining the observed rapid declines in PFAS levels in the Faroese population.

3.3.6 Norway

In a longitudinal study by Nøst et al. (2013) described in the previous AMAP human health assessment report (AMAP, 2015), repeated measurements in older men from Tromsø across five time points between 1979 and 2007 revealed that earlier-born cohorts had higher concentrations of POPs than later-born cohorts. To build on this work and to determine the relevance of age-period-cohort effects by including a younger age group and keeping age constant among the participants, a new study was designed for individual measurements in repeated cross-sectional samples of 30-year-olds in the same Tromsø population surveys as in the previous longitudinal study (Nøst et al., 2019). This made it possible to track changing levels of POPs in 30-year-old adults (reproductive age) from population surveys (n=45 per survey) over a 22-year period (1986, 1994, 2001, 2007). Concentrations of a sum of 14 POPs (eight PCB congeners, HCB, *p,p′*-DDE, *p,p′*-DDT, β-HCH, oxychlordane, *trans*-nonachlor) decreased among 30-year-olds between 1986 and 2007, with median decreases (relative to 1986) in 1994, 2001 and 2007 of 71%, 81%, and 86%, respectively among women, and 65%, 77% and 87%, respectively among men (Nøst et al., 2019). Median concentrations of POPs were higher among men in 1986, 1994 and 2001, although no differences between men and women were observed in 2007, except for β-HCH which was slightly higher in women (Table 3.22). Median concentrations of PCB153 were lower in 30-year-olds, compared to older men at the same time points (1986, 1994, 2001, 2007) as part of the previous longitudinal study. In addition, the observed relative decreases in 30-year-olds over time were greater than the decreases in older men. These decreases are similar to those found by Thomsen et al. (2007), which instead repeated cross-sectional samples among Norwegian men between 40 and 50 years old. Decreasing concentrations over time were observed for all POPs measured, with the strongest declines seen for HCB and β-HCH. The declines in the periods studied since the 1970s in Norway are considerable and convincingly follow national and international action to regulate the production and use of these compounds (Nøst et al., 2017). By comparing the biomonitoring results using two different designs (Nøst et al., 2013, 2017), it was seen that time trends differed between age groups and were stronger in the younger age group and that regardless of age group the declining trends were evident for POPs.

The Tromsø study, Fit Future 1, was initiated to investigate the effects of lifestyle, diet and social network on the health of adolescents in the Arctic. Due to concerns about bioaccumulation of PFASs in the Norwegian Arctic, a sub-project was developed to measure serum concentrations of 18 different PFASs and to investigate associations with dietary and lifestyle variables (Averina et al., 2018). This study involved over 900 youth, and approximately 99% of participants had measurable concentrations of six different PFASs. Linear and branched species were also quantified for PFHxS, PFHpS, PFOS, PFNS, PFDS and PFOSA (however PFASs in Table 3.23 are presented as a sum value, Σ). The most abundant PFASs measured were PFOS, PFOA, PFHxS, PFNA and PFDA. The PFASs with the highest concentrations were PFOS and PFOA, and concentrations were inversely

Table 3.22 Concentrations of POPs in 30-year-olds from the Tromsø Study. Data presented as medians (range), POPs in serum (μg/kg lipids). Source: Nøst et al. (2019).

	Men	Women	Men	Women	Men	Women	Men	Women
Year	1986		1994		2001		2007	
Age, y	30		30		30		30	
Sample size	n=14	n=31	n=17	n=28	n=21	n=24	n=20	n=25
Oxychlordane	15 (6–23)	9 (4–21)	6 (2–23)	3 (<LOD–6)	5 (2–13)	3 (2–10)	2 (<LOD–5)	2 (<LOD–6)
trans-Nonachlor	38 (11–62)	15 (5–45)	12 (4–66)	7 (<LOD–15)	12 (5–23)	7 (<LOD–20)	6 (<LOD–14)	4 (<LOD–12)
HCB	78 (50–152)	61 (28–140)	16 (9–33)	11 (4–23)	19 (8–46)	16 (9–41)	11 (5–18)	12 (5–23)
p,p′-DDE	438 (106–718)	533 (28–2340)	110 (57–366)	114 (31–295)	73 (32–1650)	67 (19–1180)	39 (16–79)	46 (12–328)
p,p′-DDT	19 (<LOD–53)	23 (<LOD–83)	nc (<LOD–19)	nc (<LOD–16)	nc (<LOD–14)	nc (<LOD–14)	<LOD	nc (<LOD–18)
β-HCH	20 (14–53)	25 (7–58)	4 (<LOD–8)	4 (<LOD–14)	4 (<LOD–32)	5 (<LOD–12)	nc (<LOD–5)	3 (<LOD–18)
PCB118	31 (15–62)	31 (9–604)	16 (7–27)	9 (2–20)	9 (6–28)	9 (4–23)	4 (2–11)	5 (<LOD–17)
PCB138	121 (68–200)	101 (9–291)	52 (30–209)	40 (11–68)	35 (20–102)	21 (10–116)	18 (8–35)	18 (5–88)
PCB153	218 (119–338)	165 (30–425)	99 (61–348)	65 (23–120)	60 (38–171)	43 (19–204)	35 (19–66)	30 (10–183)
PCB156	24 (16–37)	14 (7–35)	8 (5–26)	4 (<LOD–9)	6 (2–12)	4 (<LOD–18)	2 (<LOD–7)	3 (<LOD–12)
PCB170	58 (32–79)	35 (19–85)	23 (16–68)	14 (6–31)	13 (9–31)	9 (4–43)	9 (4–18)	7 (3–39)
PCB180	164 (95–226)	94 (49–235)	71 (46–226)	46 (21–89)	39 (24–98)	25 (14–128)	24 (13–50)	19 (8–134)

LOD: limit of detection; nc: not calculated.

associated with age. Girls had statistically significantly higher PFHpA, PFOA, PFNA, PFDA and PFUnDA concentrations than boys, while boys had significantly higher ΣPFHxS and ΣPFOS concentrations than girls (Averina et al., 2018). ΣPFOS, PFOA, PFNA and PFDA were positively associated with reindeer consumption, while PFNA was also positively associated with 'junk food' consumption. Fatty fish (salmon, trout, mackerel, herring) consumption was positively associated with the concentrations of ΣPFHxS, linear PFHxS, ΣPFHpS, PFHpA, PFOA, ΣPFOS, linear PFOS, PFNA and PFDA. Only PFUnDA concentrations were positively associated with the consumption of both fatty and lean fish (cod, haddock, saithe).

In an exposure assessment of adult men and women from Oslo, Norway, between the ages of 20 and 66 and recruited in 2013–2014, concentrations of PFASs were measured in multiple different blood matrices to better assess the presence and distribution of PFASs in whole blood, plasma and serum (Poothong et al., 2017) as shown in Table 3.24. A total of 25 PFASs were measured, including linear and branched PFASs. Strong positive correlations were made among all matrices for PFSAs and PFCAs. PFHpS, PFOS, PFOA, PFHxPA and PFNA were detected in all three matrices; only PFHxA was detected in all whole blood samples but none of the serum or plasma samples. This suggests that many past biomonitoring studies investigating PFASs in serum or plasma could have missed detecting the presence of this compound in humans. In this sample of Norwegian men and women, the predominant PFASs measured in whole blood were in decreasing order: PFOS, PFOA, PFHxA, PFHxS, PFNA, PFDA, PFUnDA. Whole blood concentrations of PFHxS, PFHpS, and PFOS were significantly lower in women than men. In addition, concentrations of several PFASs were significantly higher in older adults compared to other age groups (<36, 36–45, >45 years old).

As part of a sample of 100 women recruited in the Norwegian Mother and Child Cohort study (MoBa) between 2003 and 2009, concentrations of PFASs were measured in plasma across two consecutive pregnancies to investigate determinants of change across pregnancies (Papadopoulou et al., 2015). Concentrations of 10 PFASs were measured (PFHxS, PFHpS, PFOS, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA) in blood plasma of pregnant women during two pregnancies, which were approximately 18 months apart

Table 3.23 PFASs in in children from the Tromsø Fit study, Norway. Data collected from 2010–2011 and presented as geometric means (range) in blood serum (μg/L serum). Source: Averina et al. (2018).

	Girls		Boys	
Year(s)	2010–2011		2010–2011	
Mean age, y (range)	16.5 (15–19)		16.3 (15–19)	
Sample size	n=445		n=495	
	μg/L serum	% <LOD	μg/L serum	% <LOD
PFOS	5.71 (1.28–99.2)	0	6.52 (1.33–19.44)	0
PFOA	2.14 (<0.3–13.97)	0	1.86 (0.51–5.44)	0
PFHxS	0.8 (0.19–84.72)	0	0.95 (0.18–44.18)	0
PFNA	0.61 (0.15–5.35)	0	0.48 (0.12–1.91)	0
PFDA	0.27 (0.05–1.89)	0	0.19 (<0.03–0.801)	0
PFNS	0.22 (<0.02–1.24)	84	0.22 (<0.02–1.24)	89
PFUnDA	0.17 (<0.03–0.85)	3	0.14 (<0.03–0.64)	6
PFHpS	0.13 (<0.01–7.62)	5	0.16 (<0.01–0.49)	3
PFHpA	0.126 (<0.07–1.47)	21	0.091 (<0.07–0.37)	29
PFHxA	0.093 (<0.04–1.34)	79	0.083 (<0.04–0.34)	77
PFDoDA	0.058 (<0.02–0.24)	91	0.032 (<0.02–0.16)	91

LOD: limit of detection.

Table 3.24 PFASs in adults (men and women) from Oslo, Norway. PFASs presented as means (range) in whole blood (μg/L). Source: Poothong et al. (2017).

	Adults (all)
Year(s)	2013–2014
Mean age, y (range)	41 (20–66)
Sample size	n=58
PFOS	3.57 (0.74–11.03)
PFOA	1.19 (0.20–11.83)
PFNA	0.43 (0.13–0.99)
PFUnDA	0.22 (<LOD–0.94)
PFHxS	0.50 (0.13–1.37)
PFDA	0.24 (0.09–0.55)

LOD: limit of detection.

(median time). Maternal concentrations in the second pregnancy were statistically significantly lower for all PFASs measured, compared to the first pregnancy. For almost all the women, concentrations of PFOS, PFOA and PFHxS were lower in the second pregnancy; however, for 30 women concentrations of PFNA, PFUnDA and PFDA actually increased in the second pregnancy. Timing of sampling proved an important factor for concentrations of some PFASs, particularly PFNA and PFDA where there was a statistically significant 31% and 75% increase for every additional year between pregnancies. Concentrations of PFASs during the first pregnancy were an important determinant of concentrations in the second, and the degree of correlation between the repeated PFAS measurements closely matched the half-lives of the measured compounds. Breastfeeding (negatively associated with PFAS concentration in the second pregnancy), time between pregnancies, and seafood consumption (particularly shellfish) were also important determinants for some PFASs (Papadopoulou et al., 2015).

3.3.7 Sweden

In a case-control cohort within the Västerbotten Intervention Programme (VIP), plasma concentrations of PCBs, DDE, HCB, and PFASs were measured in adults in the county of Västerbotten in northern Sweden (Donat-Vargas et al., 2018, 2019a,b; Tornevi et al., 2019). Adults participated in the study twice, ten years apart, with the baseline visit occurring between 1990 and 2003 and the follow-up visit between 2000 and 2013. Concentrations of the sum of two dioxin-like PCBs, the sum of eight non-dioxin-like PCBs, HCB and DDE in normotensive and hypertensive pre-diabetics and non-diabetics are presented at baseline and follow-up in Table 3.25. There was a decrease in chlorinated POPs over the 10-year period with relative changes of -27% (sum of dioxin-like PCBs), -25% (sum of non-dioxin-like PCBs), -41% (HCB) and -39% (DDE).

PFASs were measured for 187 of the case-control pairs. Concentrations of six PFASs with measurements above the quantification limit for the 187 controls at baseline and follow-up are presented in Table 3.26. The remaining PFASs (PFDoDA, PFTrA, PFTA, PFHxA, PFHpS, PFHpA, PFDS) were all below this limit (Donat-Vargas et al., 2019b). PFOA and PFOS decreased by 15% (interquartile range -33% to 11%) and 29% (IQR -42% to -8 %), respectively, from baseline to follow-up. For PFNA and PFHxS there was instead an increase of 53% (IQR 23% to 94%) and 13% (IQR -15% to 37%), respectively.

The cross-sectional national dietary survey Riksmaten Adolescents 2016–2017 was undertaken by the Swedish Food Agency during the 2016–2017 school year (Moraeus et al., 2018). The survey was school-based and students in grades 5, 8 and 11 (mean ages 12, 15 and 18 years) were recruited from representative Swedish schools. A total of 3477 respondents participated in the dietary study. Forty percent of the schools were randomly selected, and 1305 of the 2377 invited students participated in the blood and urine sampling component of the survey. Complete dietary information and valid blood and urine samples were available for 1105 of those students. A selection of POPs measured in the study is shown in

Table 3.25 Concentrations of POPs data from the VIP are presented as medians (±SD) in blood plasma (μg/kg in lipids). Source: Donat-Vargas et al. (2018).

	Baseline 1990–2003		Follow-up 2000–2013	
Characteristics	Normotensive	Hypertensive	Normotensive	Hypertensive
Sample size	n=351	n=330	n=291	n=539
Dioxin-like PCBs[a]				
Pre-diabetics	42±25	44±22	33±17	35±21
Non-diabetics	38±20	42±20	28±15	32±16
Non-dioxin-like PCBs[b]				
Pre-diabetics	494±203	500±232	445±235	426±198
Non-diabetics	479±200	487±210	361±160	392±175
HCB				
Pre-diabetics	36±13	38±16	25±10	24±11
Non-diabetics	35±14	34±14	21±8	22±10
DDE				
Pre-diabetics	324±204	371±263	241±198	252±206
Non-diabetics	268±195	313±252	157±139	188±149

[a]Sum of PCBs (PCB118+PCB156); [b]sum of PCBs (PCB74+PCB99+PCB138+PCB153+PCB170+PCB180+PCB183+PCB187).

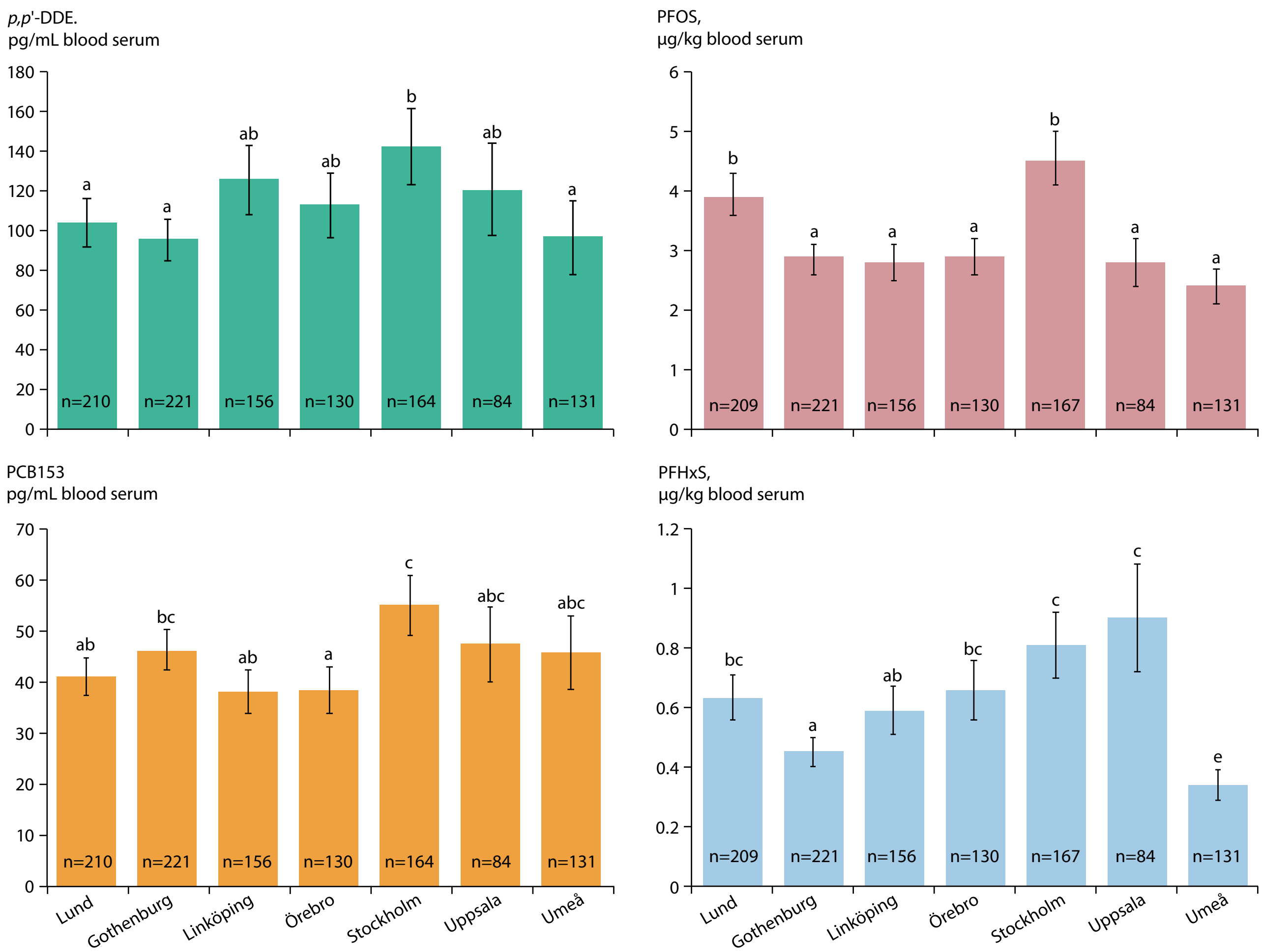


Figure 3.3 Concentrations of *p,p'*-DDE, PCB153, PFOS and PFHxS in blood serum samples from Swedish adolescents per region adjusted for grade and gender, and interactions between all factors (back-transformed least squares means with 95% confidence intervals from the analysis of log values). Different letters indicate significant differences between regions ($p<0.05$) according to Tukey's multiple comparison test. The number of observations per region is shown at the base of each bar.

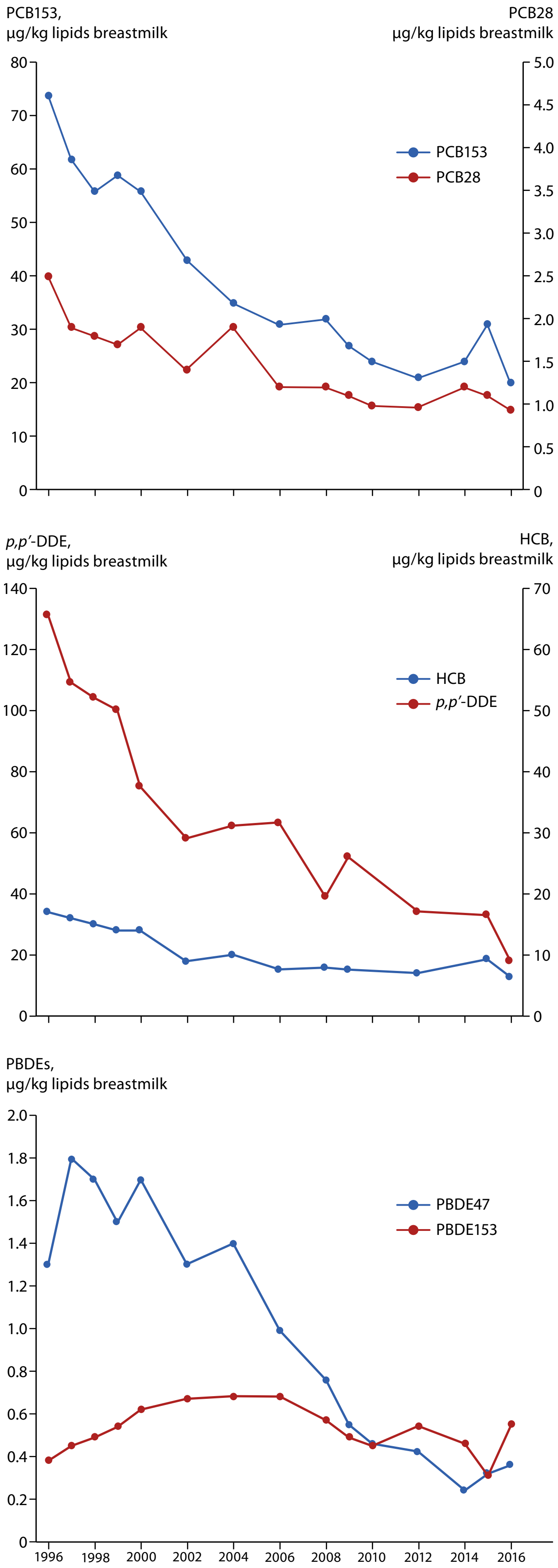


Figure 3.4 Trends in PCB, *p,p′*-DDE, HCB and PBDE concentrations in breastmilk samples from Swedish first-time mothers. Samples collected three weeks after delivery. Data presented as median concentrations (Gyllenhammar et al., 2017).

Table 3.26 Concentrations of PFASs in participants free of diabetes at baseline and follow-up. Data presented as median concentrations (interquartile range) in blood plasma (µg/L). Source: Donat-Vargas et al. (2019b).

	Baseline 1990–2003	Follow-up 2000–2013
Sample size	n=187	n=187
PFOA	2.9 (2.2–4.2)	2.7 (1.9–3.6)
PFOS	20 (15–26)	15 (9.7–21)
PFNA	0.53 (0.42–0.74)	0.83 (0.64–1.1)
PFHxS	1.0 (0.74–1.4)	1.2 (0.82–1.5)
PFDA	0.23 (0.08–0.31)	0.33 (0.25–0.45)
PFUnDA	0.19 (0.08–0.28)	0.22 (0.08–0.37)

Table 3.27 for all participants (lipids were not measured, so POPs are presented per volume or wet weight). Levels of HCB, *p,p′*-DDE, PCB138, PCB153, PCB170, PCB180, PCB187, PFNA, PFHxS and PFOS were significantly higher in boys than girls (Livsmedelsverket and Naturvårdsverket, 2020). This suggests possible gender-related differences in dietary habit or elimination. Consumption of fish, an important contributor to PCB and PFAS exposure, was for example higher in male than female participants (Warensjö Lemming et al., 2018). For PFASs, regular blood loss during menstruation may increase the elimination of PFASs in females (Wong et al., 2014). The concentrations of PCBs and chlorinated pesticides tended to increase with increasing age/grade, significantly for PCB153, PCB170, PCB180 and *p,p′*-DDE (Livsmedelsverket and Naturvårdsverket, 2020). The lack of significant associations with age for some PCBs is probably due to the small differences in age between participants and/or the increase in body weight during adolescence.

In contrast, the concentrations of PFOA, PFHxS and PFOS tended to be higher in individuals in grade 5 than grades 8 and 11 (Livsmedelsverket and Naturvårdsverket, 2020). An age-associated decrease in the levels of PFASs might be explained by differences in dietary habit between age groups or by growth dilution from grade 5 to grade 11. The brominated flame retardants PBDE47, PBDE99 and PBDE153 were below the quantification limit in almost all individuals.

Levels of *p,p′*-DDE, PCB153, PFOS and PFHxS per region and adjusted for grade and gender are shown in Figure 3.3. The different letters in the figures indicate significant differences between regions (p<0.05) according to Tukey's multiple comparison test. Umeå is the region that represents the northern part of Sweden and had significantly lower levels of *p,p′*-DDE, PFOS and PFHxS than the other regions.

A time series of POPs concentrations in breastmilk samples from 1996 to 2016 in Swedish first-time mothers in Uppsala (Figure 3.4) shows a decline for many POPs, such as PCBs, *p,p′*-DDE and HCB. Trends for PBDEs are also downward, with PBDE153 showing a slower decline than PBDE47 after

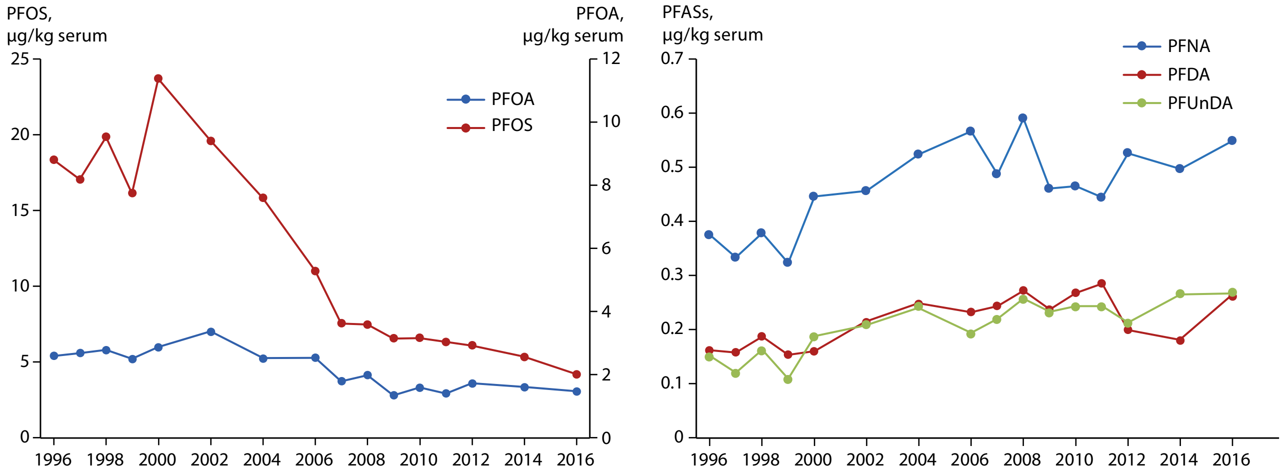


Figure 3.5 Trends in PFAS concentrations in serum samples from Swedish first-time mothers. Samples collected three weeks after delivery. Data presented as median concentrations (Glynn et al., 2017).

Table 3.27 Blood serum concentrations of POPs in adolescents in Sweden. POPs data presented as arithmetic means (5th – 95th percentile); chlorinated and brominated POPs presented per volume in blood serum (ng/L); PFAS data presented in blood serum in wet weight (µg/kg). Source: Livsmedelsverket and Naturvårdsverket (2020).

Year(s)	2016–2017	
Mean age, y (range)	14.7 (10–21)	
Sample size	n=1096	
	ng/L	% <LOQ
PeCB	<LOQ (<LOQ–<LOQ)	99.8
HCB	52 (22–75)	0.0
α-HCH	<LOQ (<LOQ–<LOQ)	100.0
β-HCH	<LOQ (<LOQ–15)	94.7
γ-HCH	<LOQ (<LOQ–<LOQ)	99.5
Oxychlordane	<LOQ (<LOQ–<LOQ)	99.8
trans-Nonachlor	5 (<LOQ–10)	76.9
p,p'-DDT	<LOQ (<LOQ–<LOQ)	96.8
p,p'-DDE	191 (<LOQ–575)	7.1
PCB74	6 (<LOQ–10)	75.5
PCB99	5 (<LOQ–11)	67.7
PCB118	8 (<LOQ–17)	29.9
PCB138	32 (6–76)	0.8
PCB153	53 (13–129)	0.1
PCB156	6 (<LOQ–15)	60.0
PCB170	16 (<LOQ–42)	16.3
PCB180	32 (5–87)	3.8
PCB183	<LOQ (<LOQ–6)	91.3
PCB187	8 (<LOQ–19)	45.8
PBDE47	<LOQ (<LOQ–<LOQ)	98.0
PBDE99	<LOQ (<LOQ–<LOQ)	99.3
PBDE153	<LOQ (<LOQ–<LOQ)	99.5
	µg/kg	% <LOQ
PFOS[a]	4.6 (1.2–9.7)	0.0
PFNA[a]	0.4 (<LOQ–0.9)	7.2
PFDA[a]	0.2 (<LOQ–0.4)	37.5
PFOA	1.4 (0.6–2.5)	0.2
PFHxS[a]	1.8 (0.2–2.7)	7.8

LOQ: limit of quantification; values below the LOQ were treated as LOQ/√2 for calculating the mean; [a]n=1098.

levels peaked around 2006. Trends for PFASs in serum samples are less consistent (Figure 3.5), with PFOS and PFOA showing a declining trend and levels of PFNA, PFDA and PFUnDA increasing.

3.3.8 Finland

Breastmilk samples from the Finnish Mother Child Cohort on Reproductive Health (1997–2002) were collected between one and three months postnatally (Antignac et al., 2016). Breastmilk samples from a total of 22 Finnish mothers were analyzed for concentrations of organochlorines, dioxins and PBDEs (see Table 3.28). The prominent PCB congeners measured were PCB105, PCB118, PCB156 and PCB167, for which concentrations were several orders of magnitude higher than for other PCB congeners. Concentrations of PBDE congeners were very low, with the predominant congener PBDE47 having a geometric mean of 2.77 ng/kg lipid. Dioxins and furans were also present at detectable concentrations; concentrations were highest in the dioxins 1,2,3,6,7,8-HxCDD and 1,2,3,4,6,7,8-HpCDD with geometric means of 15.39 and 18.37 ng/kg lipid, respectively, which was several orders of magnitude higher than for other dioxins detected.

In eastern Finland, a group of 54 children born in 2004–2005 to mothers recruited in the birth cohort study (LUKAS2), were followed-up at ages 1, 6, and 10.5 years between 2005/2006 and 2014/2015. Between 2005 and 2015, serum concentrations of PFASs decreased significantly (except PFHxS, which declined but was not statistically significant, p=0.16), as presented in Table 3.29 (Koponen et al., 2018). Comparing time trends between boys and girls, no differences were observed except for PFNA (where statistical declines were not observed in boys between 6 and 10.5 years of age). Concentrations between boys and girls were not significantly different with the exception of PFOA in children at 10.5 years of age (p<0.01, boys were higher). The predominant PFASs measured were PFOA followed closely by PFOS, which together accounted for 73–80% of median concentrations. Significant increases in estimated body burdens of PFNA and PFHxS were observed between children at 1 and 6 years of age and between 1 and 10.5 years of age (except for PFHxS in girls between 1 and 10.5 years of age) (Koponen et al., 2018).

Table 3.28 Concentrations of POPs in breastmilk samples from Finnish women. Data presented as geometric means (range), in ng/kg lipid. Source: Antignac et al. (2016).

Year(s)	1997–2002	Year(s)	1997–2002
Mean age, y (range)	32.1 (23.8–44.7)	Mean age, y (range)	32.1 (23.8–44.7)
Sample size	n=22	Sample size	n=22
2,3,7,8-TCDD	0.84 (0.34–2.39)	PCB105	1780 (725–3500)
1,2,3,7,8-PeCDD	2.62 (0.77–6.75)	PCB114	422 (204–838)
1,2,3,4,7,8-HxCDD	0.66 (0.03–6.04)	PCB118	7540 (3140–13,900)
1,2,3,6,7,8 -HxCDD	15.4 (8.08–27.6)	PCB123	108 (45.5–242)
1,2,3,7,8,9-HxCDD	1.82 (0.54–4.50)	PCB156	4180 (1820–9550)
1,2,3,4,6,7,8-HpCDD	18.4 (7.74–42.0)	PCB157	759 (320–1460)
OCDD	94.3 (36.47–277.21)	PCB167	1080 (452–2200)
ΣPCDDs	137 (55.1–305.68)	PCB189	429 (166–1140)
2,3,7,8-TCDF	0.66 (0.21–1.72)	ΣPCBs (non-coplanar)	16,500 (7300–31,000)
1,2,3,7,8-PeCDF	0.29 (0.05–0.99)	PCB28	1.73 (0.76–5.55)
2,3,4,7,8-PeCDF	8.55 (2.44–20.8)	PCB52	0.22 (0.07–0.58)
1,2,3,4,7,8-HxCDF	1.98 (0.75–5.56)	PCB101	0.55 (0.18–1.48)
1,2,3,6,7,8-HxCDF	1.77 (0.71–5.21)	PCB138	25.2 (12.0–45.5)
1,2,3,7,8,9-HxCDF	0.14 (0.06–0.47)	PCB153	42.9 (20.1–86.8)
2,3,4,6,7,8-HxCDF	0.46 (0.11–1.13)	PCB180	24.4 (10.1–56.7)
1,2,3,4,6,7,8-HpCDF	3.47 (1.36–23.9)	PBDE28	0.35 (0.12–1.09)
1,2,3,4,7,8,9-HpCDF	0.12 (0.03–0.36)	PBDE47	2.77 (0.14–13.9)
OCDF	0.33 (0.03–17.7)	PBDE99	0.61 (0.08–3.74)
ΣPCDFs	19.32 (7.11–55.4)	PBDE100	0.50 (0.12–1.70)
PCB77	5.66 (1.57–22.3)	PBDE153	0.75 (0.37–3.09)
PCB81	1.36 (0.45–4.36)	PBDE154	0.05 (0.02–0.17)
PCB126	35.0 (14.9–66.62)	PBDE183	0.03 (0.01–0.10)
PCB169	23.4 (9.64–46.3)	PBDE209	<LOD
ΣPCBs (coplanar)	68.5 (28.4–123)	α-HBCD	0.32 (0.03–2.19)

LOD: limit of detection.

Table 3.29 Median concentrations of PFASs in Finnish children, boys and girls, at 1, 6, and 10.5 years of age. Data presented as median (range) concentrations in μg/L serum. Source: Koponen et al. (2018).

	All	Boys	Girls	All	Boys	Girls	All	Boys	Girls
Year(s)		2005/2006			2010/2011			2014/2015	
Mean age, y (range)		1 (0.97–1.06)			6 (5.71–6.32)			10.5 (9.90–10.95)	
Sample size	n=54	n=26	n=28	n=54	n=26	n=28	n=54	n=26	n=28
PFOA	6.6	5.6 (1.4–15)	7.1 (2.0–13)	2.7	2.8 (1.4–5.7)	2.7 (1.9–3.4)	1.5	1.6 (0.80–2.5)	1.4 (0.96–2.1)
PFOS	5.5	4.6 (2.0–40)	6.3 (1.7–16)	2.1	2.1 (0.98–4.5)	2.3 (1.3–3.3)	1.5	1.5 (0.63–3.4)	1.6 (0.62–3.4)
PFNA	0.8	0.69 (0.22–2.1)	0.84 (0.29–1.8)	0.54	0.5 (0.25–1.2)	0.56 (<LOQ–0.90)	0.36	0.37 (0.23–1.2)	0.35 (<LOQ–0.67)
PFHxS	0.47	0.42 (<LOQ–1.5)	0.49 (<LOQ–1.2)	0.42	0.4 (<LOQ–0.94)	0.43 (<LOQ–0.84)	0.21	0.23 (<LOQ–0.56)	0.2 (<LOQ–0.37)

LOQ: limit of quantification.

Table 3.30 POPs in the population of the Pechenga district of Murmansk Oblast, Russia. Data presented as geometric means (range) in blood serum (µg/kg lipids). Source: Dudarev et al. (2016a).

	Men		Women		Pregnant women	
Year(s)	2013		2013		2013–2014	
Mean age, y (range)	39.9 (27–54)		45.2 (26–65)		29.2 (20–42)	
Sample size	n=18		n=32		n=50	
	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD	µg/kg lipids	% <LOD
HCB	42.4 (10.9–189)	6	32.31 (12.8–74.4)	0	18.2 (5.3–251.6)	0
β-HCH	49.1 (27.9–111.9)	22	54.5 (17.6–157.1)	9	8.5 (0.8–145.8)	0
α-HCH	<LOD	94	<LOD	72	<LOD	98
γ-HCH	<LOD	94	<LOD	50	<LOD	78
4,4'-DDE	169.8 (51.6–940)	0	139.3 (39.4–537.7)	0	101.9 (16–1220.8)	0
4,4'-DDT	41.8 (11.6–131.9)	6	17.7 (6.5–123.9)	19	11.4 (1.3–376.4)	0
2,4'-DDE	<LOD	94	<LOD	84	<LOD	90
4,4'-DDD	<LOD	100	<LOD	97	<LOD	78
2,4'-DDT	<LOD	100	<LOD	97	<LOD	94
PCB28	29.5 (18–59)	33	18.8 (7.9–37)	19	17.8 (7.6–58.5)	60
PCB52	45.6 (19.7–113)	22	28.8 (5.9–86.9)	6	16.8 (5.6–81.8)	44
PCB99	19.7 (11.8–45.1)	39	14.5 (6.3–72.2)	25	13.8 (4.8–49.9)	32
PCB101	24.4 (10.2–55.5)	11	19.7 (7.7–59.6)	6	11.6 (5.5–39)	20
PCB105	23.2 (9.4–48.6)	17	12.7 (5.1–52.9)	22	14.1 (6–66.6)	48
PCB118	48.3 (9.9–133.9)	11	34.5 (12.1–94.2)	0	26.1 (9.4–119.3)	0
PCB156	<LOD	94	<LOD	87	<LOD	100
PCB128	<LOD	100	<LOD	81	<LOD	100
PCB138	45.5 (14.8–106.4)	11	27.2 (6.4–74.9)	6	9.2 (1–48.2)	0
PCB153	48.5 (21.7–141.3)	11	26.8 (8.5–61)	3	12.2 (1.3–56.7)	0
PCB170	21 (13.7–37.8)	72	10.9 (4–24)	91	13.6 (9.6–19.4)	92
PCB180	27.4 (14.5–106.2)	33	17.3 (8.4–56.5)	44	15.7 (5–46.8)	70
PCB183	<LOD	100	<LOD	100	<LOD	100
PCB187	<LOD	94	<LOD	84	<LOD	84
ΣPCBs[a]	242.8 (102–707.8)	33	142.6 (46.6–384.8)	44	74.2 (14.6–303.4)	70
$\Sigma PCBs_{15}$[b]	284.4 (125–753)	0	200.2 (69.7–456)	0	105.5 (40.7–368.8)	0

LOD: limit of detection; [a]ΣPCBs = 2x(PCB138+PCB153+PCB180); [b]$\Sigma PCBs_{15}$ = sum of fifteen PCB congeners: PCB28, PCB31, PCB52, PCB99, PCB101, PCB105, PCB118, PCB128, PCB138, PCB153, PCB156, PCB170, PCB180, PCB183, PCB187.

3.3.9 Russia

3.3.9.1 Pechenga district of the Murmansk Oblast

The trilateral KolArctic project was an international study conducted in regions bordering Norway, Finland, and Russia. In Russia, the KolArctic project was focused on individuals living in the Pechenga district of Murmansk Oblast (primarily a point source of exposure to a wide range of contaminants arising from the Pechenganickel enterprise; a copper-nickel ore smelter in Nickel and a concentrating plant and roasting shop in Zapolyarny).

The Pechenga district of Murmansk Oblast includes the 'capital' Pechenga with satellites (about 7000 people), Nickel (about 11,000), Zapolyarny (about 14,500), Luostary (about 2200), as well as a dozen other inhabited settlements with far smaller populations. The settlements are all located in the vicinity of the main point sources of pollution (Nickel and Zapolyarny).

The KolArctic project included 50 adult residents of Nickel in 2013 (18 men, 32 women), who had lived there for at least 20 years, as well as 50 pregnant women living in the Pechenga district of Murmansk Oblast, who were recruited (from different towns and settlements of the district) between 2013 and 2014 in the delivery department of Nickel hospital (the only delivery department for the whole Pechenga district) (Dudarev et al., 2016a). The population of the Pechenga district of Murmansk Oblast is non-Indigenous (Russians). Their point source exposure is not reflective of Indigenous People (Saami) living in the Lovozersky district of Murmansk Oblast, located far from the Pechenga district.

A broad suite of POPs was measured in blood samples, with many of these POPs below the limit of detection for a majority of the samples (Table 3.30). Among the hexachlorocyclohexane (HCH) isomers, β-HCH was detected in all pregnant women, but α-HCH and γ-HCH were only detected in 2% and 22% of pregnant women, respectively. Because HCH was not detected in local foods, it was suggested that these exposures may be due to other sources of exposure to HCH. For DDT isomers and related metabolites (DDE and DDD), 2,4'-DDE, 4,4'-DDD, and 2,4'-DDT were only detected in 10%, 22% and 6% of pregnant women, respectively, while 4,4'-DDE and 4,4'-DDT were detected in all pregnant women. Several PCB congeners were detected in a minority of samples only, while the predominant congeners measured were PCB118, PCB138, and PCB153. Concentrations of POPs were generally higher in men than women (except for β-HCH), and concentrations in women were generally higher than in pregnant women, although it should be noted that the pregnant women sampled were younger (average age 29.2 years) than the sample of women (average age 45.2 years).

3.3.9.2 Chukotka Autonomous Okrug

In the Chukotka Autonomous Okrug in the far northeast of the Russian Federation, previous studies have identified high levels of organochlorine compounds in women from coastal eastern Chukotka (Sandanger et al., 2003; Anda et al., 2007). To further investigate serum levels of POPs in pregnant women living in the coastal and inland areas of Chukotka, maternal blood sampling was conducted in 2014–2015 along with a maternal questionnaire (Bravo et al., 2019). Geometric mean concentrations of many organochlorines were below the limits of detection; however, detectable concentrations for most women were measured for HCB, α-HCH and β-HCH, 4,4'-DDE, 4,4'-DDT, and PCB118, PCB138, PCB153 and PCB180 (Table 3.31). POPs concentrations were also compared between the different coastal and inland sites, and statistically significant differences were observed for HCB, β-HCH, PCB118, PCB138, PCB153, PCB180, mirex, and 4,4'-DDE (Bravo et al., 2019). Pregnant women from coastal eastern Chukotka communities had higher concentrations of POPs than pregnant women in other districts, with the strongest differences observed for PCBs (3.3- to 4.2-fold higher than the geometric mean for the whole study population). Comparisons in other districts showed coastal communities generally had higher levels of POPs than inland communities. This is thought to reflect dietary factors, as mothers from these coastal communities have a diet that includes whale, walrus, and seal blubber. Linear multivariate analysis showed residence to be an important factor in explaining POPs exposure, particularly for PCBs, β-HCH and mirex.

Table 3.31 POPs in pregnant women from the Chukotka Autonomous Okrug (both inland and coastal settlements), Russia. Data presented as geometric means (range) in blood serum (μg/kg lipids). Source: Bravo et al. (2019).

Year(s)	2014–2015	
Mean age, y (range)	27.8 (15–44)	
Sample size	n=246	
	μg/kg lipids	%<LOD
HCB	35 (<LOD–850)	1
α-HCH	3.2 (<LOD–100)	6
β-HCH	35 (<LOD–660)	3
γ-HCH	<0.02 (<LOD–13)	62
4,4'-DDE	120 (<LOD–1100)	1
4,4'-DDT	9 (2–67)	0
2,4'-DDE	<LOD (<LOD–9.7)	93
4,4'-DDD	<0.004 (<LOD–53)	73
2,4'-DDT	<0.008 (<LOD–74)	64
Mirex	<LOD (<LOD–46)	57
PCB28	<LOD (<LOD–36)	73
PCB52	<LOD (<LOD–750)	82
PCB101	<LOD (<LOD–8)	91
PCB118	10 (<LOD–1100)	2
PCB138	17 (1.3–440)	0
PCB153	31 (3.9–880)	0
PCB180	5.4 (<LOD–230)	22

LOD: limit of detection.

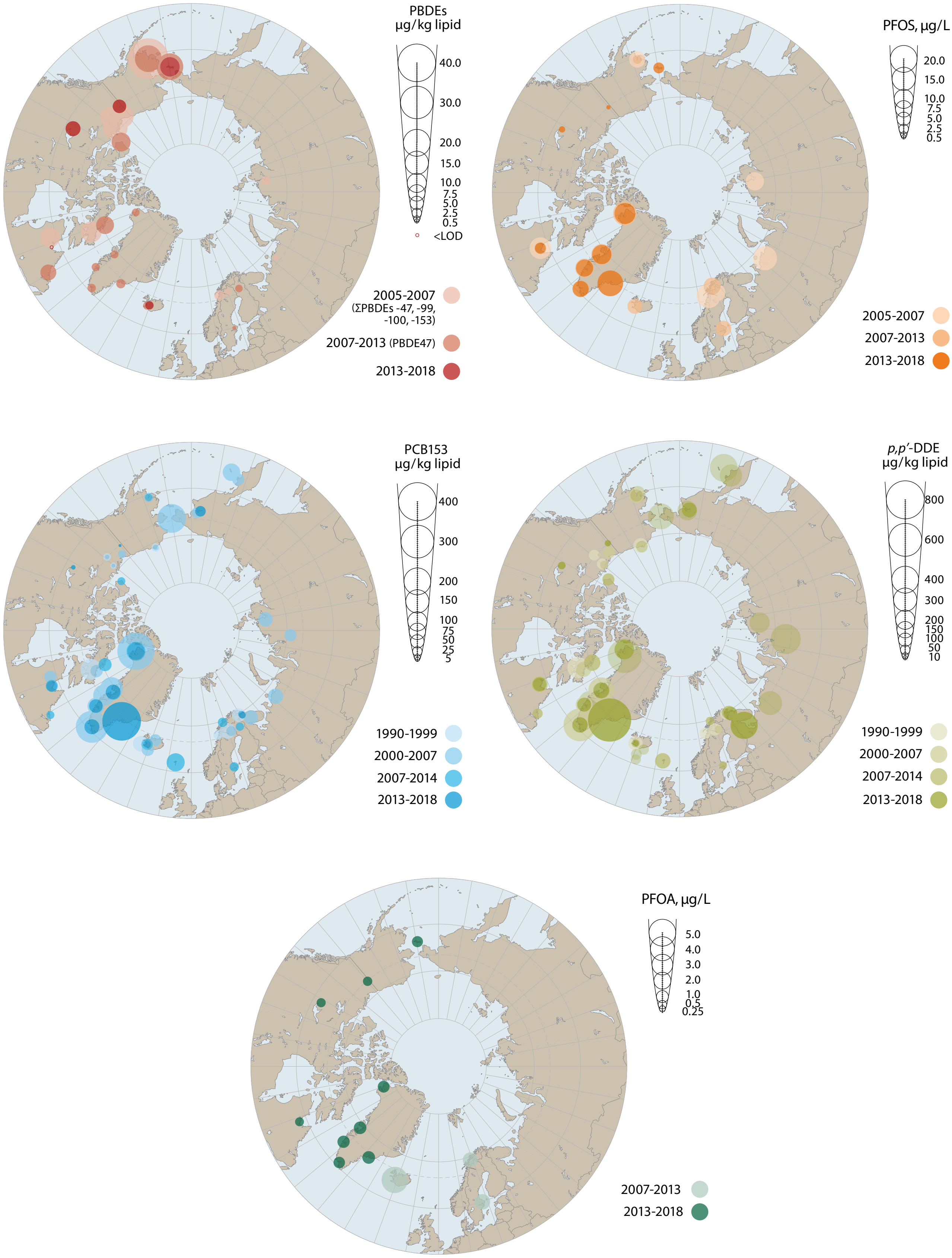


Figure 3.6 Circumpolar concentrations of PBDEs, PFOS, PCB153, *p,p′*-DDE and PFOA. Unless otherwise indicated, POPs and PBDEs presented in µg/kg plasma lipid; PFASs presented in µg/L. Data from women of childbearing age (Yukon, Dehcho/Sahtú region, Inuvialuit Settlement Region, Nunavut and Nunatsiavut [Canada]), maternal blood (Alaska, Faroe Islands, Sweden, and coastal Chukotka [Russia]), blood of pregnant women (Nunavik [Canada], Greenland, Iceland, Norway, Sweden, Pechenga district of Murmansk Oblast, and Chukotka [Russia]), and from breastmilk (Sweden, Finland).

When comparing geometric mean concentrations of POPs in pregnant women from the Pechenga district of Murmansk Oblast (2013) with the coastal eastern Chukotsky district of Chukotka Okrug (2014–2015), concentrations appear much higher in coastal Chukotka for many POPs including HCB (18 vs 110 μg/kg lipids, respectively), β-HCH (8.5 vs 92 μg/kg lipids), DDE (102 vs 140 μg/kg lipids), and PCB153 (12.2 vs 130 μg/kg lipids). These results support previous studies that found high levels of POPs in coastal Chukotka (Sandanger et al., 2003; Anda et al., 2007; Dudarev et al., 2010, 2012a,b).

3.3.10 Summary discussion

Over the past three decades, AMAP has reported on levels of contaminants in populations across the Arctic, with a focus on pregnant women due to the vulnerability of the fetus to prenatal exposure. This has resulted in strong time trend information for several POPs, while time trend information is being built for various new POPs including several PFASs. Time trends for some POPs go back as far as the 1990s for most Arctic countries, and even the late 1980s for some (Faroe Islands). Figure 3.6 shows mean concentrations of some of the most predominant organochlorines, PBDE congeners, and PFASs among women of childbearing age and pregnant women from across the circumpolar Arctic over multiple time periods (1990–1999, 2000–2007, 2007–2013, 2013–2018).

Although time trends vary by contaminant and region, in general, concentrations of POPs such as PCBs and *p,p′*-DDE continue to decline in many of the Arctic regions where time series data are available. Other POPs such as PBDEs and PFOS show a less clear time trend while levels of more persistent long-chain PFASs appear to be increasing. As seen in Figure 3.6, in the Kuskokwim region of Alaska, concentrations of some POPs appear to have declined among mothers, while levels of PFASs such as PFOS and PFOA appear to have increased slightly. In Nunavik, extensive time trend series for pregnant women (starting in the early 1990s) show continued declines of many POPs, while the limited time points available for PBDEs and PFOS show a decline since 2004, although this is less pronounced between 2012 and 2016/2017, and an increasing trend for PFNA since 2012. In pregnant Greenlandic women, the most recent data from the ACCEPT study show that levels of POPs such as PCB153 and *p,p′*-DDE have continued to decline across Greenland, with the exception of eastern Greenland. Time trends of POPs in Disko Bay extend back to the mid-1990s, and late 1990s for Nuuk. Levels of oxychlordane, *p,p′*-DDE and PCB153 declined substantially over this period in both areas; this is also shown in finer detail in Figure 3.1. Levels of PFOS in Greenlandic women have also been recorded since the late 1990s, and appear to decline between 1997 and 2015 (see also Figure 3.2); however, it should be noted that the age of participants from these time points varies widely with the most recent time points representing much younger populations (median ages of 53, 53, 48, 28, and 27 years, respectively). Levels of POPs in Iceland and Scandinavian countries continue to decline based on available time points. In the Faroe Islands, time series data show POPs levels are continuing to decline among children, including PFASs in Cohort 3 children (between 2002 and 2012) and organochlorines in Cohort 5 children (between 2009 and 2018). The exception is children from Cohort 1, who are now 28 years old. Previous levels reported in this cohort showed declines in organochlorine concentrations between children at 7, 14 and 22 years of age; however, the most recent levels among cohort participants (age 28 years) appear to have plateaued and even slightly increased for some contaminants (*p,p′*-DDE, PCBs). Levels of PFOS and PFOA appear to have decreased between 1993–1994 and 2013–2016.

While levels of many POPs are declining, concentrations vary across the Arctic and when comparing Arctic regions, some geographical trends are clear. Similar to past AMAP assessment reports, the highest levels of many POPs continue to be seen in Greenland (particularly eastern Greenland). The next highest levels (Figure 3.6) are found in the Faroe Islands, Nunavik, the Chukotsky district of the Chukotka Autonomous Okrug and the Pechenga district of Murmansk Oblast (Russia). The lowest levels were observed in Iceland and the Dehcho and Sahtú regions of the NWT in Canada. In the Canadian Arctic, levels of POPs range widely among pregnant women and women of childbearing age from different regions. Women of childbearing age in First Nations communities from the NWT appear to have the lowest concentrations in the Canadian Arctic, and when compared to Inuit Health Survey data for the Inuvialuit Settlement region, Nunavut and Nunatsiavut (AMAP, 2015), levels were roughly 4- to 5-fold lower than levels in the Nunatsiavut region. A different trend has been observed for PBDEs and older PFASs. The highest levels of PBDEs are found in Alaska (St. Lawrence Islands and the Kuskokwim region), and are roughly an order of magnitude higher than levels in some Arctic European countries. Similar to many PCBs and organochlorine pesticides, levels of PFOS were highest in Greenland, particularly northern and eastern Greenland, although levels of PFOA were fairly similar across the Arctic. In Alaska, levels of PFASs among Yupik women from St. Lawrence Island appear similar to levels in mothers from the Kuskokwim region of Alaska.

Compared to past AMAP human health assessments, there are now substantial data available for numerous PFASs, not just PFOS and PFOA. Several of these substances have recently been added to the Annexes to the Stockholm Convention that list prohibited or restricted POPs (e.g., PFOA and its salts) or are being evaluated for possible inclusion in the Annexes. The human levels reported here represent some of the first measurements of these substances in the Arctic, and so will establish a baseline for future measurements across the Arctic. Data from several Arctic cohorts and cross-sectional studies have included PFASs among the adult population (men and women, including pregnant women) as well as children, and comparisons between these populations in Figures 3.7 and 3.8, respectively, are shown for the following PFASs: PFHxS, PFOS, PFOA, PFNA, and PFDA. In most Arctic regions the most predominant PFASs were PFOS followed by PFOA, with a few exceptions including adult men and women from Alaska, the Canadian Arctic (including the Yukon, the NWT, and Nunavik), and pregnant women from Nunavik and Greenland where levels of PFNA were higher than PFOA (in Nunavik especially), although not as high as PFOS. In Figure 3.7, the highest levels of PFOS were observed in pregnant women from Greenland.

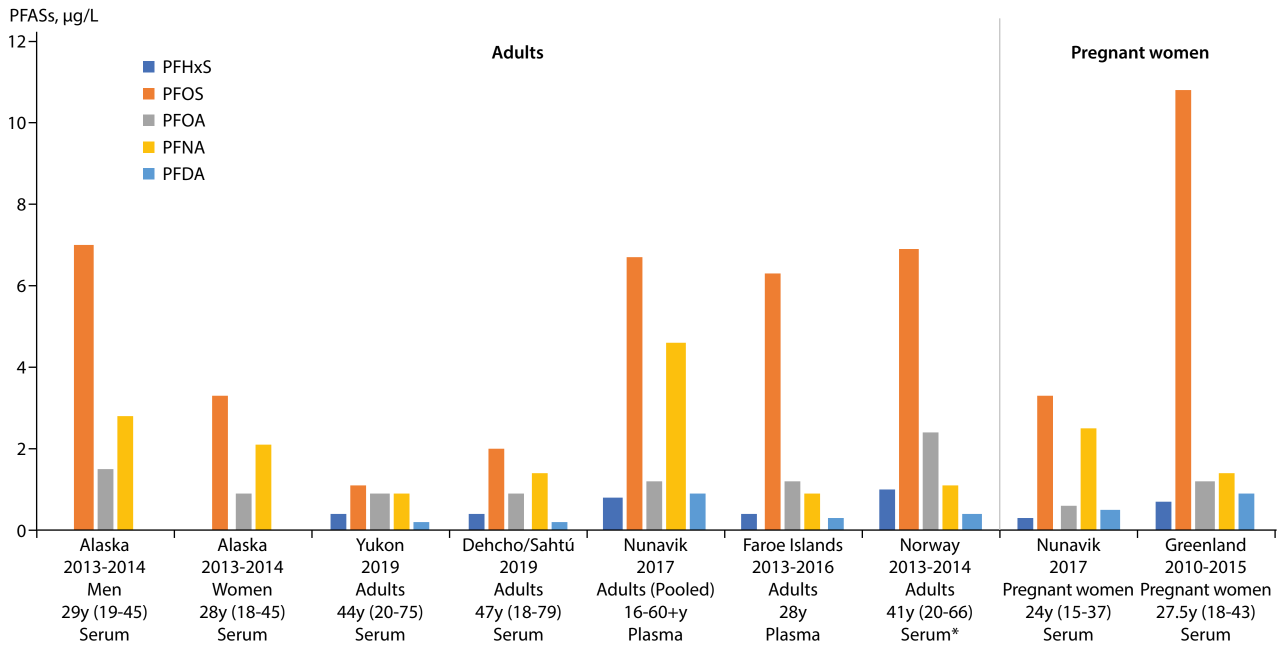


Figure 3.7 Blood concentrations of PFASs across Arctic countries. Data presented as geometric/arithmetic* means in adults and pregnant women (Byrne et al., 2017; Poothong et al., 2017; Bonefeld-Jørgensen and Long, pers. comm. 2019; Petersen et al., pers. comm. 2019; Ratelle and Laird, pers. comm. 2019; Laird et al., pers. comm. 2020; Lemire et al., pers. comm. 2020).

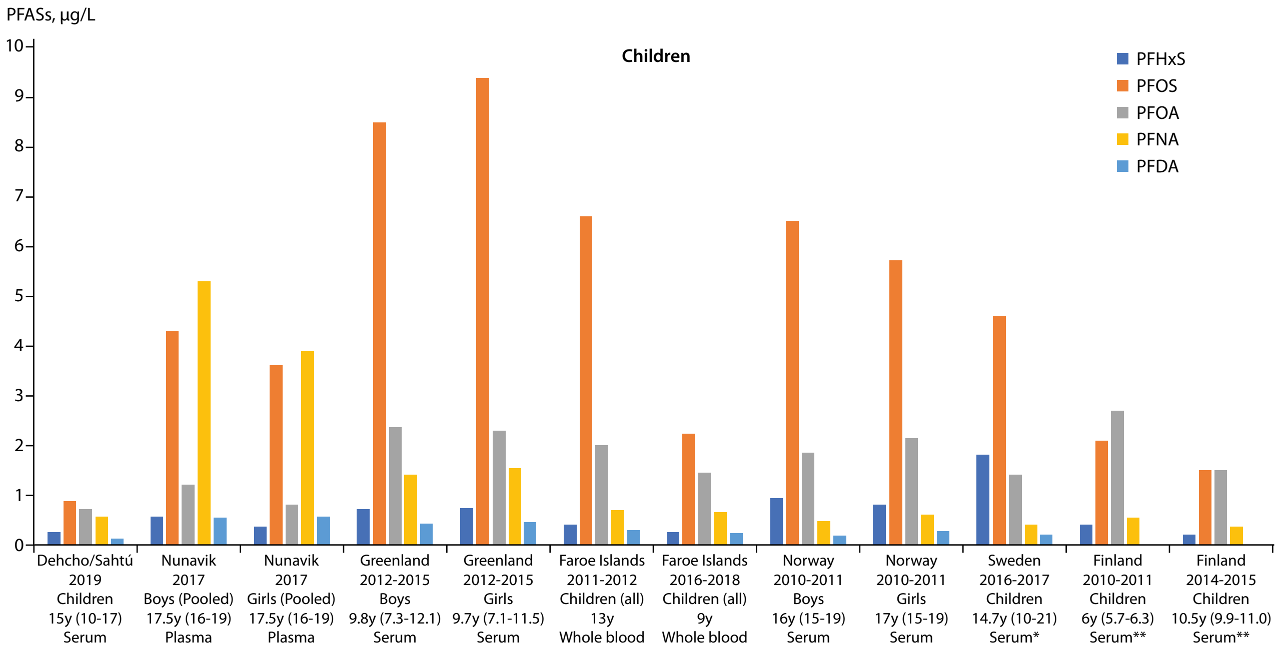


Figure 3.8 Blood concentrations of PFASs across Arctic countries. Data presented as geometric/arithmetic means* or medians** in children (Koponen et al., 2018; Averina, pers. comm. 2019; Petersen et al., pers. comm. 2019; Timmermann, pers. comm. 2019; Laird et al., pers. comm. 2020; Lemire et al., pers. comm 2020; Livsmedelsverket and Naturvårdsverket, 2020).

Similar to adults, the most predominant PFASs in children were PFOS and PFOA, with a few exceptions including: adolescents in Nunavik (ages 16–19 years) where levels of PFNA were substantially higher than PFOA and PFOS; children in Sweden with higher levels of PFHxS than PFOA (these were also the highest levels of PFHxS seen in children across the Arctic); and children in Finland who had similar or higher levels of PFOA than PFOS. In general, the highest levels of PFNA in children are in Nunavik and Greenland.

Levels of PFASs were mostly similar in boys and girls, across several regions of the Arctic. It is interesting to note the changes over time in PFAS levels measured in several of the Faroese cohorts at different time points. For example, levels of PFOS and PFOA were much higher in 13-year old Faroese children from 2011–2012 than in 9-year old Faroese children in 2016–2018. In contrast to PFOS and PFOA, levels of other PFASs such as PFNA and PFDA did not substantially change.

3.4 Human biomonitoring: metals and trace elements

3.4.1 Canada

3.4.1.1 Old Crow, Yukon

Owing to concerns over high levels of some contaminants in country foods, adult Gwich'in men (aged 21 to 75 years) and women (aged 20 to 72 years) from Old Crow, Yukon were recruited in 2019 as part of a biomonitoring project to investigate exposure. Participants provided blood, hair and urine samples which were analyzed for metals (Drysdale et al., pers. comm. 2020), as presented in Tables 3.32 and 3.33 for concentrations in blood and urine.

Urine and blood levels in Old Crow were compared to those observed in the First Nations Biomonitoring Initiative (FNBI) (Assembly of First Nations, 2013) and the Canadian Health Measures Survey (Health Canada, 2010, 2013, 2017, 2019). Levels of the majority of metals and trace nutrients in urine and blood were similar (with some exceptions) to those observed in the general population and First Nations on reserve populations in Canada. For example, Pb and Cd in both blood and urine in Old Crow were elevated compared to corresponding measurements in other parts of Canada.

Table 3.32 Urine concentrations of heavy metals in adults in Old Crow, Yukon, Canada. Data presented as geometric means (10th – 95th percentile) in urine adjusted for creatinine (µg/g creatinine). Source: Drysdale et al., pers. comm. (2020).

	Men		Women	
Year	2019		2019	
Mean age, y (range)	47 (21–75)		38 (20–72)	
Sample size	n=22		n=25	
	µg/g creatinine	% <LOD	µg/g creatinine	% <LOD
Arsenic	9.8 (6.1–18)	0	15 (8.2–110)	0
Cadmium	0.34 (0.14–1.2)	0	0.30 (0.078–1.3)	3.8
Lead	0.75 (0.20–3.1)	0	0.58 (0.22–14)	0
Mercury	<0.15[a] (<0.15[a]–0.56)	50	<0.23[b] (<0.23[b]–0.77)	83
Selenium	52 (29–90)	0	56 (39–130)	0

LOD: Limit of detection; values below the LOD were treated as LOD/2 for calculating the mean; [a]based on the geometric mean (1.3 g/L) of urine creatinine observed for male participants; [b]based on the geometric mean (0.87 g/L) of urine creatinine observed for female participants.

3.4.1.2 Dehcho and Sahtú regions, NWT

In addition to the POPs described in Section 3.3.2.2, blood and urine samples were collected for measurement of metals, and hair samples were collected for measurement of Hg (Ratelle et al., 2020a). Hair samples were collected from children (n=74) and adult men and women (n=190 and n=179, respectively) for analysis and measurement of Hg concentrations. Levels measured in hair reflect the cumulative Hg exposure of each participant from the two months prior to hair sampling. Mercury was detected in 99% of hair samples and concentrations were generally low, with a geometric mean of 0.47 µg/g hair for all participants (Ratelle and Laird, pers. comm., 2019). Hg concentrations in all children and women of childbearing age were below the 2 µg/g hair guidance value used to identify the need for follow-up testing. Few participants had Hg concentrations above 5 µg/g in hair (i.e., within the 'increasing risk' threshold range of 5–25 µg/g in hair; described further in Chapter 5). Notably, hair Hg levels among participants were approximately two-fold higher than those observed in CHMS Cycle 5 (2016–2017) (geometric mean 0.19 µg/g), and were higher in the Sahtú region than the Dehcho region. Differences in hair Hg concentration for bi-monthly periods were tested using a repeated measures ANOVA with a Greenhouse-Geisser correction. Of the 443 participants across the nine participating communities who provided hair samples, only 170 provided samples that were long enough to measure hair Hg over the 12-month period preceding sample collection and had detectable Hg concentrations in each analyzed segment. Of the 170 participants included in the retrospective hair Hg analysis, 94% were female and the mean±SD age was 38±19 years. Segmental hair analysis showed significant differences among time periods, with the highest mean hair Hg levels occurring between July and October. For the majority of participants, Hg exposures remained consistently below health-based guidance values in the months leading up to biological sample collection (Laird, pers. comm. 2019).

Table 3.33 Blood concentrations of heavy metals in adults in Old Crow, Yukon, Canada. Data presented as geometric means (10th – 95th percentile) in whole blood (µg/L). Source: Drysdale et al., pers. comm. (2020).

	Men		Women	
Year	2019		2019	
Mean age, y (range)	43 (21–75)		39 (20–72)	
Sample size	n=26		n=28	
	µg/L	% <LOD	µg/L	% <LOD
Arsenic	0.53 (0.14–2.3)	0	0.56 (0.21–6.7)	0
Cadmium	0.85 (0.10–4.7)	0	0.85 (0.19–4.3)	0
Lead	30 (12–110)	0	19 (6.4–110)	0
Mercury	0.90 (0.11–6.2)	3.8	0.66 (0.10–3.2)	7.1
Selenium	170 (150–280)	0	170 (150–220)	0

LOD: Limit of detection.

Table 3.34 Urine concentrations of heavy metals in adults across multiple First Nations communities in the Northwest Territories, Canada. Data presented as geometric means (10th – 95th percentile) in urine adjusted for creatinine (µg/g creatinine). Source: Laird and Ratelle (2019).

	Men		Women	
Year(s)	2016–2018		2016–2018	
Mean age, y (range)	50.9 (18–88)		49.8 (18–80)	
Sample size	n=92		n=88	
	µg/g creatinine	% <LOD	µg/g creatinine	% <LOD
Arsenic	1.15 (2.51–20.9)	0	7.16 (3.29–34.2)	0
Cadmium	0.33 (0.147–1.03)	0	0.497 (0.167–1.92)	0
Lead	0.689 (0.208–2.91)	0	0.746 (0.269–6.60)	0
Mercury	0.423 (<0.4[a]–1.51)	40.9	0.536 (<0.6[b]–2.17)	40.2
Selenium	56.2 (33.3–112)	0	66.5 (34.4–147)	0

LOD: Limit of detection; values below the LOD were treated as LOD/2 for calculating the mean; [a]based on the geometric mean (1.0 g/L) of urine creatinine observed for male participants; [b]based on the geometric mean (0.67 g/L) of urine creatinine observed for female participants.

Table 3.35 Blood concentrations of heavy metals in adults across multiple First Nations communities in the Northwest Territories, Canada. Data presented as geometric means (10th – 95th percentile) in whole blood (µg/L). Source: Laird and Ratelle (2019).

	Men		Women	
Year(s)	2016–2018		2016–2018	
Mean age, y (range)	47.3 (18–88)		45.6 (18–80)	
Sample size	n=128		n=122	
	µg/L whole blood	% <LOD	µg/L whole blood	% <LOD
Cadmium	0.373 (<0.006–3.58)	9.8	0.404 (<0.006–3.15)	10.2
Lead	21.0 (8.42–74.4)	0	14.8 (5.36–73.6)	0
Mercury	nc (<0.03–7.68)	63.1	nc (<0.03–3.89)	55.5
Selenium	170.1 (136–225)	0	171 (140–229)	0

LOD: Limit of detection; nc: not calculated as number of non-detects greater than 50%.

Urine samples were also collected from adult men (n=92) and adult women (n=88) and analyzed for metals including Cd, Pb, Hg, and selenium (Se). The creatinine-adjusted results are presented in Table 3.34. Concentrations of Hg were low and only detected in approximately 60% of samples. Concentrations of Hg and Cd were similar to or slightly lower than concentrations reported among the general Canadian population from CHMS Cycle 2, 2009–2011 (Health Canada, 2013). In contrast, several other metals were, on average, higher than observed in the general population of Canada (CHMS Cycle 2, 2009–2011) including Pb and Se. Lead and Se were also elevated at the upper percentiles of exposure. Notably, urinary biomarker levels of these metals remained higher than typically observed after creatinine adjustment. Interestingly, Hg levels in urine were higher in the Sahtú region than the Dehcho. In contrast, several essential trace elements such as Se were higher in the Dehcho.

Blood samples were also collected from adult men (n=128) and adult women (n=122), and concentrations of metals in blood are shown in Table 3.35. Analyses showed blood Pb levels in the Dehcho and Sahtú region of the NWT were substantially higher than those observed in the general population. For example, the geometric mean and 95th percentile of blood Pb in study participants were 1.7- and 2.8-fold higher than observed in the general Canadian population (CHMS Cycle 5, 2016-2017), respectively. Cd was also observed to have a higher geometric mean relative to the CHMS and/or FNBI. Lead was also elevated relative to the CHMS and FNBI at both the geometric mean and 95th percentile. In contrast, Se was elevated at the 95th percentile but not the geometric mean. Blood Pb was also higher in the Sahtú region than the Dehcho region, while blood Cd and Hg levels were higher in the Dehcho. Hg levels in blood were generally low in adult men and women, with a majority of participants having concentrations below the limit of detection. Blood and hair Hg were significantly and positively correlated (Spearman, R=0.55, $p<0.001$) (Drysdale et al., pers. comm. 2020).

In addition, the Hg hair-to-blood ratio (calculated from the slope of simple linear regression of complete cases) was observed to be 450 (Tang, 2019). However, participation followed an opt-in framework that allowed each individual who took part in the study to decide which types of biological sample (e.g., hair only, blood only, blood and hair) they would provide. It should be noted that due in part to the relative invasiveness of blood sampling, participants were most likely to provide a hair sample. In addition, Hg levels were more likely to be below the limit of detection for blood (0.05 µg/L) than hair (0.01 µg/g). Therefore, multiple imputation (MI) methods were used to better calculate the relationships between hair and blood Hg (and hair-to-blood Hg ratio) by drawing on information from partially observed cases. These analyses showed that the slopes and intercepts defining the relationship between hair and blood Hg differed among communities. As such, the MI methods used to explore the Hg hair-to-blood ratio (after accounting for biases implicit to the complete cases) were stratified by community. These analyses showed the Hg hair-to-blood ratio to range from 260 to 1100 among communities. This finding shows that the typically-assumed ratio of 250:1 may not be applicable for all Dene/Metis communities of the NWT. Also, for communities with particularly high hair-to-blood ratios, hair Hg levels may overestimate Hg risks. These observations, therefore, underline the importance of understanding site-specific hair-to-blood ratios when interpreting hair Hg results (Laird and Packull-McCormick, pers. comm. 2019).

3.4.1.3 Nunavik

The Qanuilirpitaa? 2017 Inuit Health Survey included the measurement of contaminant levels in the blood and urine of Inuit. While the previous Inuit Health Survey in 2004 recruited only adult Inuit (18+ years), the Q2017 survey also recruited and measured concentrations of metals in the blood of youth (16–17 years of age).

Concentrations of metals in the blood of Inuit adults from Nunavik are presented in Table 3.36, for Hg, Pb, Cd, and Se. Geometric mean Hg concentrations were slightly higher in women than men (10 and 8.1 µg/L, respectively), as were concentrations of Se (330 and 280 µg/L, respectively). Concentrations of Pb and Cd were comparable for men and women. Concentrations of metals are further broken down by age in Table 3.37, where data are presented for youth (16–17 years), adults (18–49 years), and older adults (50+ years). For most of the metals measured, concentrations appeared to increase with age with the highest geometric mean concentrations observed in the oldest age group (50+ years) for both men and women. This was particularly evident for Hg where the mean concentrations in the oldest age group (50+) were almost double those of the younger age group (18–49), and three-fold higher than the youngest age group (16–17) of men. It is also noted that mean Hg concentrations of women at 16–17 years of age were approximately double those of men in the same age range. Unlike Hg, Pb, and Se, geometric mean concentrations of Cd were lowest in the oldest age group for both men (0.97 µg/L) and women (1.5 µg/L). While concentrations of Cd in men were highest in the 18–49 year-old age group (1.8 µg/L), the highest concentrations of Cd in women occurred in the youngest at 16–17 years old (2.1 µg/L). In Nunavik, Cd has been associated with smoking rather than country food consumption (Fontaine et al., 2008).

The Q2017 survey was designed as a follow-up to the 2004 Nunavik Inuit Health Survey, and comparison of concentrations to the 2004 data presented in the last AMAP human health assessment (AMAP, 2015) show concentrations of Hg and Pb have decreased in Nunavik Inuit of a similar age range (18–74 years old). A decline between 2004 and 2017 was noted for Pb and to a lesser extent for Hg in men, with mean Pb and Hg concentrations in men from 2017 of 28 and 8.1 µg/L, respectively, compared to 46 and 9.2 µg/L, respectively, in men from 2004. A decline, although less pronounced for Hg, is also observed for women, with mean concentrations of 24 and 10 µg/L for Pb and Hg, respectively, in 2017, compared to 34 and 12 µg/L, respectively, in 2004. Mean concentrations of Se, however, have increased in women since 2004, rising from 300 to 330 µg/L in 2017, while mean concentrations in men have remained stable at 280 µg/L.

The NQN study was developed to improve understanding of pregnant women's exposure to contaminants from country foods according to year and season, and to support the development of local interventions aimed at mitigating Hg exposure while promoting country food consumption and enhancing nutritional and food security status for pregnant women and children. With additional blood metal data from pregnant women in the NQN study, time trend data span approximately 25 years for Hg and Pb and 20 years for Se

Table 3.36 Blood concentrations of metals in Inuit adults (18 years old and older) from Nunavik, Canada. Data presented as geometric means (10th – 95th percentile) in whole blood (µg/L). Source: Lemire and Blanchette (pers. comm. 2020).

	Men		Women	
Year	2017		2017	
Mean age, y (range)	38.9 (18–86)		38.4 (18–81)	
Sample size	n=407		n=791	
	µg/L whole blood	% <LOD	µg/L whole blood	% <LOD
Mercury	8.1 (1.9–36)	0	10 (2.6–42)	0
Lead	28 (11–93)	0	24 (9.3–98)	0
Cadmium	1.6 (0.25–5.6)	0	1.7 (0.32–5.1)	0
Selenium	280 (160–670)	0	330 (170–820)	0

LOD: Limit of detection.

Table 3.37 Blood concentrations of metals in three different age groups of Inuit from Nunavik. Data presented as geometric means (10th – 95th percentile) in whole blood (µg/L). Source: Lemire and Blanchette (pers. comm. 2020).

	Men			Women		
Year	2017			2017		
Mean age, y (range)	16.6 (16–17)	31.4 (18–49)	60.0 (50-86)	16.6 (16–17)	31.1 (18–49)	58.7 (50-81)
Sample size	n=45	n=268	n=139	n=82	n=558	n=233
Mercury	3.5 (0.3–18)	7.1 (1.8–29)	12 (3–54)	7.2 (2.1–23)	8.7 (2.3–38)	15 (5.4–51)
Lead	18 (8.2–60)	26 (11–81)	38 (14–110)	14 (6.9–54)	21 (8.5–68)	39 (17–110)
Cadmium	1.6 (0.12–4.8)	1.8 (0.25–5.8)	0.97 (0.24–3.7)	2.1 (0.24–6.1)	1.8 (0.28–5.2)	1.5 (0.33–4.9)
Selenium	210 (120–390)	270 (150–620)	320 (160–750)	260 (160–550)	320 (160–790)	370 (190–950)

Table 3.38 Trends in metals concentrations in pregnant Inuit women from Nunavik, Canada. Data presented as geometric means (range) in µg/L whole blood. Results presented only for contaminants with 60% and more of data detected. Source: AMAP (2015); Lemire and Blanchette (pers. comm. 2020).

Year	1992	1996	1997	1998	1999	2000
Mean age, y (range)	24 (18–35)	24 (16–33)	24 (15–40)	24 (14–33)	24 (17–35)	25 (16–35)
Sample size	n=11	n=25	n=53	n=27	n=16	n=29
Total mercury	11 (3.6–33)	13 (4.2–29)	11 (3.8–44)	6.9 (3.2–27)	8.8 (2.6–31)	8.6 (1.8–38)
Lead	42 (8.3–170)	48 (17–140)	56 (10–260)	53 (27–130)	54 (19–110)	43 (10–140)
Cadmium	2.8 (0.36–7.5)	na	na	na	na	na
Selenium	na	360 (190–620)	320 (190–980)	290 (180–460)	300 (150–570)	330 (190–1230)

Note: weighted estimates for 2017 (Hg, Pb, Se). LOD: Limit of detection; for statistical purposes, values <LOD were replaced by LOD/2; na: not available; [a]*p*-value based on orthogonal polynomial contrast for linear trend, using regression adjusted for age, smoking status (smoker vs. non-smoker) and multiparous woman (yes vs. no); [b]n=32.

Table 3.39 Concentrations of total whole-blood Hg and Se, total plasma Hg and Se, plasma Se proteins and plasma Hg associated with selenoproteins, in Inuit adults of Nunavik (men and women) from the 2004 Nunavik Inuit Health Survey. Data presented as mean values (range) in whole blood and plasma, Se and Hg compounds in µg/L. Source: Achouba et al. (2016).

Year	2004	% <LOD
Age, y	18+	
Sample size	n=852	
Total selenium (whole blood)	350 (119–3550)	0
Total selenium (plasma)	140 (84.5–229)	0
GPx3	35.6 (19.6–90.7)	0
SelP	72.4 (45.9–110)	0
SeAlb	32.6 (19.2–75.6)	0
	n=845	
Total mercury (whole blood)	17.9 (0.10–241)	0
Total mercury (plasma)	2.59 (<LOD–24.5)	0.1
Hg-GPx3	0.55 (<LOD–6.47)	7.7
Hg-SelP	1.46 (<LOD–11.7)	0.5
Hg-SeAlb	0.70 (<LOD–5.74)	2.4

LOD: Limit of detection; GPx3: glutathione peroxidase 3; SelP: selenoprotein P; SeAlb: selenoalbumin.

(Table 3.38). As some pregnant women were also recruited in the Q2017 survey (n=33 for metals), pregnant women from the Q2017 and NQN studies are combined for the 2017 time point in Table 3.38. However, as the NQN sampling occurred from January to March (2016–2017), while sampling in the Q2017 survey took place from August to October (2017), the samples were weighted to get a better representation on an annual basis.

Statistically significant differences were observed for Hg, Pb, Cd and Se between 1992 and 2017 (Table 3.38). Concentrations of Hg have declined since 1992, although this decline has not been continuous over the last 25 years, with geometric mean concentrations briefly rising at the turn of the century before decreasing again in 2004 and finally plateauing from 2007 onwards (with only small changes observed during this time). Exceedances of Canadian blood guidelines also declined over this period (see Chapter 5). When studying retrospective monthly hair Hg levels as part of the NQN survey, prenatal exposure was significantly higher in the summer months and in the Hudson Strait region, when and where most of the beluga hunt takes place in Nunavik. Beluga meat and *nikku* (air-dried meat) were identified as the most important dietary source of MeHg exposure for pregnant women, as well as adult Inuit (Lemire et al., 2015; Pontual et al., 2021).

Exposure of pregnant women to Pb has steadily declined since the late 1990s which coincides with a voluntary ban on Pb pellets for hunting, although concentrations appear to have reached a plateau in 2012 with only slight fluctuations observed since then. Unlike Hg and Pb, concentrations of Se have not shown a significant decline. Country foods from the sea, and particularly beluga *mattaaq*, an Inuit delicacy made of whale skin and blubber, are particularly rich in Se. While concentrations appear to have declined throughout the 1990s and mid-2000s, this decline was followed by a brief increase in 2012 and 2013 before declining again in 2017. These fluctuations may be due to time of blood sampling as well as the seasonality of marine mammal consumption by pregnant women.

As Se is of interest from a health effects perspective (i.e., its potential for mitigating Hg), studies have been conducted to explore the form of Se found in blood and interactions with Hg. Based on archived samples from the 2004 Nunavik Inuit Health Survey, adult plasma from 852 participants (men and women over 18 years of age) was analyzed for Hg and Se-containing proteins (Achouba et al., 2016). Glutathione peroxidase 3 (GPx3), selenoprotein P (SelP) and selenoalbumin (SeAlb) represented 25%, 52% and 23% of the total plasma Se concentrations, respectively. In addition, 50% of the Hg measured was found to be bound to SelP (Table 3.39). Conversely, a non-linear relation was observed between whole blood and plasma concentrations of Se, which contrasts with other studies that looked at populations in the Brazilian Amazon that consume Brazil nuts which are

Table 3.38 Continued

2001	2004	2007	2012	2013	2017	*p*-value[a]
26 (17–39) n=18	27 (19–37) n=25	23 (17–37) n=42	24 (18–39) n=111	24 (18–41) n=95	24 (15–38) n=123	
9.5 (1.6–33)	7.4 (1.3–30)	4.3 (0.68–24)	5.1 (0.18–40)	5.1 (0.28–32)	5.4 (0.70–40)	<0.0001
35 (10–130)	17 (5.8–85)	17 (6.6–77)	13 (2.7–230)	14 (4.2–62)	13 (4.1–230)	<0.0001
na	2.8 (0.36–8.0)	2.0 (0.22–7.6)	na	na	1.5 (0.079–4.4)[b]	0.0046
250 (200–390)	260 (130–700)	230 (130–710)	320 (120–2990)	300 (130–1420)	250 (120–670)	0.0033

rich in Se, mainly present as selenomethionine. A recent study showed that this difference is due to a different selenocompound named selenoneine found in Nunavik Inuit blood, which accumulates in the blood cellular fraction of Inuit and is associated with the consumption of beluga *mattaaq*. Indeed, selenoneine was found to be the major form of Se in beluga *mattaaq*, which is known to be exceptionally high in Se (Achouba et al., 2019; Little et al., 2019).

3.4.1.4 Canadian Arctic comparisons

The Canadian Arctic is geographically vast, and levels of contaminants can vary among the different populations living in the Canadian Arctic, as seen from the studies reported above in the Yukon, NWT, and Nunavik. Geometric mean levels of Hg, Se and Cd in Nunavik were much higher than those observed in the western Arctic between 2016 and 2019 (Yukon and NWT). Concentrations of blood Hg were highest in Nunavik, with geometric means of 8.1 and 10 µg/L in men and women, respectively, compared to those observed in the Yukon (geometric means of 0.90 and 0.66 µg/L) and NWT (majority of NWT participants had Hg concentrations <LOD of 0.03 µg/L). Concentrations of Pb were more comparable across the Canadian Arctic and did not follow the same regional trends as Hg, since Pb exposure is more likely to reflect the type of ammunition used than dietary characteristics. Concentrations of Pb were higher in Nunavik Inuit (geometric means of 28 and 24 µg/L in men and women, respectively) than in First Nations from the NWT (21.0 and 14.8 µg/L in men and women, respectively), and Gwich'in from the Yukon had slightly higher mean concentrations of Pb in men and women (30 and 19 µg/L, respectively) than First Nations from the NWT. Concentrations of Pb in all three regions were noticeably higher in men than women. Concentrations of Cd were lowest in the NWT, while concentrations in the Yukon were approximately twice as high as in the NWT. Nunavik had the highest concentrations of Cd, which were approximately twice as high as in the Yukon (and about four-fold higher than in the NWT). Mean concentrations of Se in Inuit men and women from Nunavik (280 and 330 µg/L, respectively) were almost twice those observed in the NWT and Yukon, which were almost identical at around 170–171 µg/L for men and women in both regions, and which probably reflects higher marine mammal consumption in Nunavik (notably due to high levels of Se and selenoneine in beluga *mattaaq*, see Section 3.4.1.2.2).

3.4.2 Greenland

In the birth cohort ACCEPT study (2010–2015), thirteen metals and elements were measured in blood samples from 497 pregnant Greenlandic Inuit women (median age 27 years). Clear regional differences were observed of statistical significance for several metals (Table 3.40), and the highest geometric mean concentrations of Hg, Pb and Cd were observed in eastern Greenland. In contrast, geometric mean concentrations of iron (Fe) and zinc (Zn) were lowest in eastern

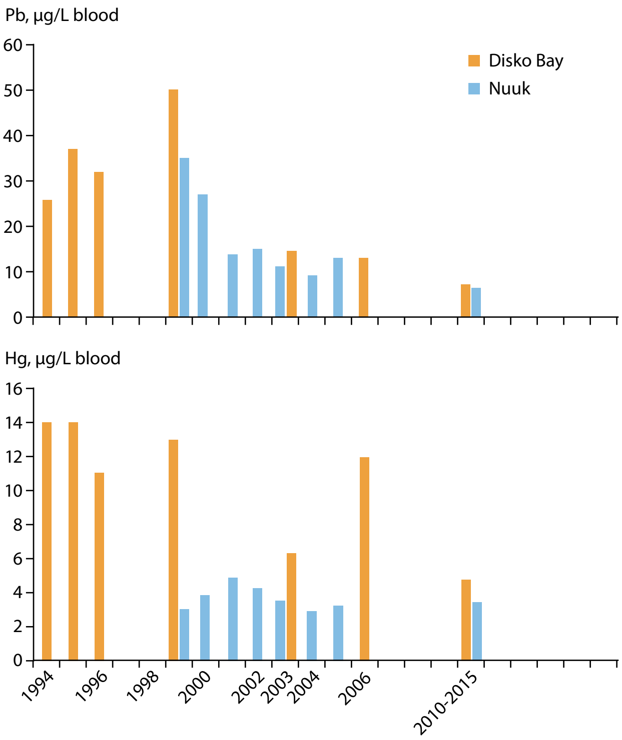


Figure 3.9 Trends in lead and mercury in whole blood from pregnant women in Disko Bay and Nuuk, Greenland.

Table 3.40 Blood concentrations of metals in the pregnant Greenlandic Inuit women of the ACCEPT cohort 2010–2015. Data presented as geometric means (range) in whole blood. Source: Bank-Nielsen et al. (2019).

	North	Disko Bay	West	South	East	*p*-value[a]	Total	
Mean age, y (range)	28.4 (20–36)	27.1 (18–41)	27.4 (18–42)	28.6 (20–41)	28.2 (19–43)		27.5 (18–43)	
Sample size	n=32	n=123	n=289	n=44	n=20		n=509	
Metals, μg/L								% <LOQ
Mercury	6.5 (1.28–54.5)	4.48 (0.83–69.3)	3.32 (0.32–73.0)	3.44 (0.83–16.8)	10.2 (2.10–29.3)	<0.001	3.9 (0.32–73.0)	21.6
Lead	7.67 (4.32–26.3)	6.54 (1.58–31.5)	7.12 (1.58–64.1)	7.14 (2.72–48.4)	9.76 (4.30–58.4)	0.069	7.1 (1.58–64.1)	37.8
Arsenic	5.03 (1.05–26.3)	5.9 (0.03–58.8)	5.39 (1.05–29.7)	4.86 (1.05–18.9)	3.62 (2.10–10.4)	0.022	5.35 (0.03–58.8)	64.3
Cadmium	0.87 (0.17–3.98)	1.09 (0.11–10.8)	0.92 (0.11–7.79)	0.85 (0.11–4.75)	1.61 (1.05–3.68)	0.011	0.97 (0.11–10.8)	65
Chromium	12.9 (3.68–72.5)	21.7 (3.68–128)	16.3 (2.54–402)	19.9 (3.68–144)	14.3 (3.68–82.4)	0.042	17.4 (2.54–402)	66.1
Manganese	16.4 (7.41–33.6)	17.8 (3.39–80.9)	16.9 (3.39–236)	16.2 (3.68–67.2)	19.7 (9.62–81.4)	0.69	17.1 (3.39–236)	3.9
Nickel	11.2 (1.58–74.9)	11.1 (1.58–7308)	10.7 (1.58–4631)	11.6 (1.58–123)	12.8 (2.85–17.9)	0.891	11 (1.58–7308)	92.4
Selenium	164 (59.8–1096)	141 (62.0–2248)	127 (45.4–2795)	118 (74.4–259)	145 (83.0–267)	0.019	132 (45.4–2795)	0
Serum-selenium	76.2 (29.4–157)	69.1 (27.3–153)	69.4 (5.25–177)	71.2 (23.1–145)	71.5 (37.8–105)	0.785	70 (5.25–177)	0.1
Metals, mg/L								
Iron	430 (276–500)	432 (279–929)	439 (215–1069)	476 (351–1092)	390 (256–991)	<0.001	438 (215–1092)	0
Copper	1.33 (0.89–2.02)	1.37 (0.71–2.15)	1.38[b] (0.61–2.69)	1.21 (0.60–2.41)	1.49[c] (0.73–2.25)	0.015	1.36 (0.16–2.69)	0
Zinc	4.84 (3.59–6.00)	4.44 (2.68–8.18)	4.7 (3.15–12.1)	5.07 (3.43–12.9)	4.26 (2.84–9.30)	<0.001	4.66 (2.68–12.9)	0
Magnesium	36.6[d] (32.2–43.8)	36.8[e] (28.7–58.2)	37.9[f] (30.1–58.3)	39.4[g] (31.8–55.0)	41.9[h] (34.7–54.3)	0.007	37.7 (28.7–58.3)	0
Calcium	64.5[d] (57.3–73.2)	62.2[e] (8.19–83.9)	62.5[f] (5.57–95.0)	48.7[g] (5.04–76.6)	47.1[h] (7.77–76.3)	0.003	61 (5.04–95.0)	0

LOQ: limit of quantification; [a]difference among regions was tested by one-way ANOVA analysis; [b]n=281; [c]n=7; [d]n=20; [e]n=92; [f]n=196; [g]n=27; [h]n=6.

Greenland. Selenium geometric means were highest in the north, and arsenic (As) and chromium (Cr) levels highest in Disko Bay.

A positive correlation was found between age and blood level for Pb, Se, As, and Fe, whereas calcium (Ca) was negatively correlated with age. The level of Cd and Ca in blood was positively correlated with smoking, whereas Fe and Zn were negatively correlated with smoking and current smoking biomarker cotinine. Hg, Pb and Ni were positively correlated with marine food intake, whereas Cr and manganese (Mn) were negatively correlated with marine food intake and the omega-3/omega-6 fatty acid ratio (Bank-Nielsen et al., 2019). Hence, lifestyle and diet influence the level of metals and elements in blood.

Trends in blood levels of Hg and Pb in pregnant women since the mid-1990s are presented in Figure 3.9. Multiple time points from Disko Bay and Nuuk show a declining trend for Pb, but there does not appear to be a clear trend for Hg.

The OCEANS study (described in Section 3.3.3) also included Hg analysis of blood samples from 333 children (Timmermann et al., 2019). Mercury was detected in all children, with geometric mean concentrations of 3.12 and 3.76 μg/L blood in boys and

Table 3.41 Blood concentrations of contaminants in Greenlandic children. Data presented as geometric means (range); mercury in whole blood (μg/L). Source: Timmermann et al. (2019); Timmermann (pers. comm. 2019).

	Boys		Girls	
Years(s)	2012–2015		2012–2015	
Mean age, y (range)	9.8 (7.3–12.1)		9.7 (7.1–11.5)	
Sample size	n=175		n=158	
	μg/L blood	% <LOD	μg/L blood	% <LOD
Mercury	3.12 (0.16–37)	0	3.76 (0.29–99)	0

LOD: Limit of detection.

Table 3.42 Regional comparisons of blood concentrations of contaminants in Greenlandic children between 2012–2015. Data presented as geometric means (range); mercury in whole blood (µg/L). Source: Timmermann et al. (2019); Timmermann (pers. comm. 2019).

Region	Greenland (all)	Nuuk	Disko Bay[a]	West[b]	East[c]	*p*-value[d]
Mean age, y (range)	9.8 (7.1–12.1)	9.3 (7.3–11.0)	9.5 (7.1–11.5)	10.4 (8.1–11.6)	10.5 (9.1–12.1)	
Sample size	n=333	n=81	n=128	n=100	n=24	
Mercury	3.41 (0.16–98.9)	2.19 (0.32–8.06)	4.34 (0.29–18.5)	2.86 (0.16–25.7)	8.73 (4.13–98.9)	<0.001

[a]Qeqertarsuaq, Aasiaat, and Ilulissat; [b]Sisimiut and Maniitsoq; [c]Tasiilaq; [d]differences between areas were tested using Kruskal Wallis test.

girls, respectively (Table 3.41). Girls had slightly higher mean concentrations of Hg than boys, and also a wider range of exposures with concentrations ranging from 0.29 to 99 µg/L blood in girls. Comparisons between children recruited from different communities show the lowest mean concentrations occurred in Nuuk and western Greenland (Sisimiut and Maniitsoq), and the highest in eastern Greenland (Tasiilaq) with a geometric mean of 8.73 µg/L in blood (Table 3.42).

3.4.3 Iceland

Limited metals data are available from Iceland; however, a study of archived samples collected in 1995 from pregnant women in Reykjavik involved the measurement of blood levels of Hg and Se (Table 3.43), which represent baseline Hg and Se data for the region. Geometric mean concentrations of Hg (3.1 µg/L) and Se (96.0 µg/L) are relatively low compared to other Arctic regions. In addition to these data, blood samples were collected from pregnant women as part of the MercuNorth project (Adlard et al., 2021) in 2014–2015. Geometric mean Hg concentrations appear to have declined in Reykjavik, falling from 3.1 µg/L in 1995 to 1.29 µg/L in 2014–2015.

Table 3.43 Concentrations of total mercury and selenium in pregnant Icelandic women from Reykjavik. Data collected in 1995 and in 2014–2015 (as part of the MercuNorth study). Data presented as geometric means (range) in whole blood µg/L. Source: Adlard et al. (2020); Ólafsdóttir (pers. comm. 2019).

Year(s)	1995	2014–2015
Mean age, y (range)	29.6 (18–41)	31.3 (22–43)
Sample size	n=40	n=50
Mercury	3.1 (<2–7)	1.29 (0.14–3.61)
Selenium	96.0 (65–140)	na

na: not available

3.4.4 Faroe Islands

In the Faroe Islands, children from several cohorts continue to be followed to measure concentrations of total Hg over time (Table 3.44). Children from the first Faroes Islands Cohort in 1986–1987 have continued to participate in follow-up studies over the past few decades and are now in adulthood (average age 28 years in 2013–2016). Since cord blood samples were first collected in 1986–1987, total Hg concentrations in the blood of these children have decreased from 8.4 µg/L in 1993–1994, to 4.1 µg/L in 2000–2001, to 2.5 µg/L in 2008–2009 when child participants had reached adulthood at age 22 years. Since then however, the trend for Hg has reversed, and in 2013–2016 the mean concentration in 28-year-olds had increased to 3.93 µg/L. Children from Faroe Islands Cohort 5 have also continued to be followed. Concentrations of Hg are much lower in this cohort of children compared to Cohort 1 children of similar age groups. As Cohort 5 is more recent (initiated in 2007–2009), fewer time points are available; however, these time points indicate an increase in Hg between the ages of 1.5 years (1.4 µg/L in 2009–2011) and 5 years (up to 2.52 µg/L in 2012–2014). Further follow-up of Cohort 5 children at age 9 years in 2016–2018 showed concentrations had decreased to 1.4 µg/L. Whether this decline will continue has yet to be seen; however, it will be many years before this cohort is old enough to be compared to adult children from the first Faroe Islands Cohort.

Table 3.44 Time series of blood Hg in children from Faroe Islands Cohort 1 and Faroe Islands Cohort 5. Data presented as geometric means (range) in whole blood (µg/L). Source: AMAP (2015); Petersen (pers. comm. 2019).

	Cohort 1					Cohort 5			
Year(s)	1986–1987	1993–1994	2000–2001	2008–2009	2013–2016	2007–2009	2009–2011	2012–2014	2016–2018
Mean age, y	Cord blood	7	13.8	22.1	28	Cord blood	1.5	5	9
Sample size	n=1022	n=922	n=792	n=849	n=703	n=500	n=363	n=349	n=390
Total mercury	22.3 (0.9–350)	8.4 (0.1–62.8)	4.1 (0.3–39.8)	2.5 (0.1–46.3)	3.93 (0.111–84.4)	4.6 (0.8–44.5)	1.4 (0.1–21.3)	2.52 (0.21–40.9)	1.40 (0.067–41.8)

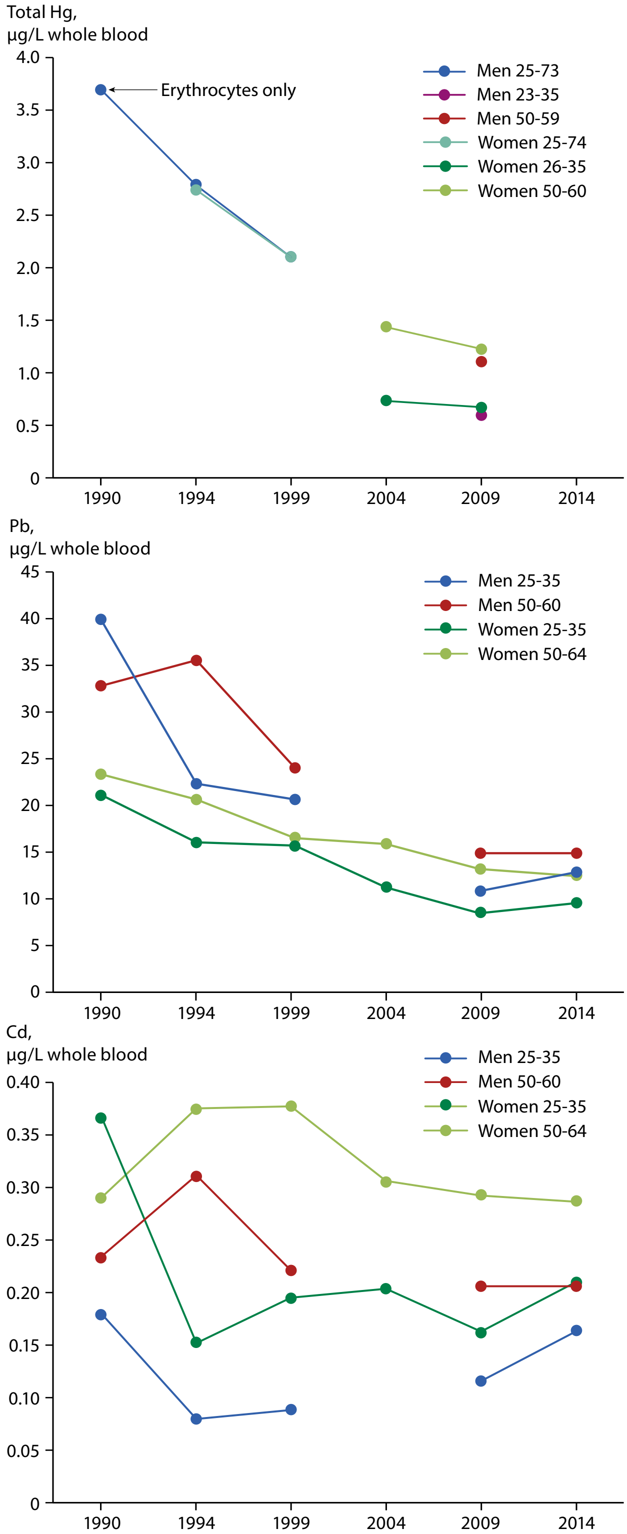


Figure 3.10 Trends in total mercury, lead and cadmium in the adult population of northern Sweden, 1990–2014. Data presented as geometric means in whole blood, except for mercury in 1990, 1994 and 1999 where the data are for erythrocytes. Data sources: mercury (Wennberg et al., 2006; Sundkvist et al., 2011); lead and cadmium (Wennberg et al., 2017).

3.4.5 Sweden

The population-based Northern Sweden Monitoring of Trends and Determinants in Cardiovascular Disease (MONICA) study provides concentrations of several environmental pollutants, including data for time trends in adults going back several decades (1990–2014) for Hg, Pb and Cd (Wennberg et al., 2006, 2017; Sundkvist et al., 2011).

Mercury was measured in erythrocytes from adults in 1990, 1994 and 1999 and a strong decline in Hg levels is clear in men (age 25–73 years) and women (age 25–74 years) (Figure 3.10). For men and women combined, this was a decrease of 5.8% per year (Wennberg et al., 2006). In later years, Hg was measured in whole blood, which cannot be directly compared with concentrations in erythrocytes. In 2004, concentrations of Hg in whole blood were available for women (in two age groups), but not men. Geometric mean concentrations of Hg in women in the younger and older age groups both declined between 2004 and 2009, with the decline slightly stronger in the older women (1.43 to 1.22 µg/L) than the younger women (0.725 to 0.662 µg/L). In 2009, concentrations of Hg in whole blood were measured in two age groups for men. The geometric mean concentrations for Hg in the younger men (0.583 µg/L) was approximately half that of the older men (1.10 µg/L).

Concentrations of Pb in whole blood were measured in men and women, in two different age groups, between 1990 and 2014, except for 2004 when only women were sampled. A strong decline in Pb concentrations is seen in Figure 3.10 in men and women of both age groups, with geometric mean concentrations in 2014 around 32–53% of those measured in 1990; however, changes in Pb concentration were relatively minor after 2000. Between 1990 and 1999, median Pb levels decreased in men (all) and women (all) by 5.6% and 4.4% per year (age-adjusted), respectively (Wennberg et al., 2017). In 2014, geometric mean concentrations of Pb in whole blood were 12.7 and 9.59 µg/L in the young age groups for men and women, respectively. At the same time, in the older age groups, men had a geometric mean concentration of 14.9 µg/L and women, 12.4 µg/L. In both men and women, higher concentrations were observed in the older age groups. In both age groups, men had slightly higher concentrations than women, which was also observed at earlier time points. Higher blood Pb associated with consumption of moose meat was demonstrated in men, but not women, raising the question of whether shooting itself contributes more to Pb exposure than eating moose meat shot with Pb pellets, since hunting and shooting was more common among men than women (Wennberg et al., 2017), and some studies have shown that shooting with Pb pellets can be a significant factor affecting blood Pb levels (Tagne-Fotso et al., 2016; Fustinoni et al., 2017).

Cadmium was also measured in blood from 1990 to 2014 in the same two age groups as Pb. Cd levels in whole blood did not decrease over this period and an analysis of annual median concentration changes in never-smoking women even found an increase of 3% per year (age-adjusted) between 2009 and 2014 (Wennberg et al., 2017). In Figure 3.10, geometric mean concentrations of Cd from 2014 in young men and women were 0.165 and 0.210 µg/L, respectively. Among men and women in the older age group, geometric mean concentrations in 2014 were higher at 0.206 and 0.287 µg/L, respectively. Smoking was confirmed as a major source of Cd in the MONICA study (Wennberg et al., 2017).

Table 3.45 Whole blood concentrations of metals in adolescents in Sweden. Metals data presented as arithmetic means (5th – 95th percentile) in whole blood (µg/L whole blood). Source: Livsmedelsverket and Naturvårdsverket (2020).

Year(s)	2016–2017	
Mean age, y (range)	14.7 (10–21)	
Sample size	n=1099	
	µg/L whole blood	% <LOD
Cadmium	0.16 (0.06–0.35)	2.7
Mercury	0.90 (0.13–2.06)	0.7
Lead	8.35 (3.71–16.32)	0.1

LOD: limit of detection.

Cadmium, Hg and Pb were measured in the Riksmaten Adolescents 2016–2017 study and results are shown in Table 3.45 for all participants. Concentrations of Cd were generally higher in girls than boys. This is probably due to lower iron stores in girls which lead to increased Cd absorption (Vahter et al., 2007). Cadmium concentrations also increased with age. Concentrations of total Hg and Pb were higher in boys than girls (Livsmedelsverket and Naturvårdsverket, 2000). Higher fish consumption in boys may partly explain the observed difference between genders (Warensjö Lemming et al., 2018). There were no significant associations between age and blood levels of Hg and Pb. There were also no regional differences observed.

As part of another study, non-smoking Swedish women (n=192, aged 50–59 years), living in four different regions (including Västerbotten, considered the Arctic part of Sweden), were recruited for Cd measurements in urine in May 2018 (Kippler et al., 2020). There were no differences in Cd concentration in urine between the regions; median Cd concentrations for all Swedish women were 0.24 µg/g creatinine (5–95th percentile 0.10–0.71) or 0.18 µg/L density-adjusted (5–95th percentile 0.07–0.48). The 58 women living in Västerbotten (northern Sweden) had a median Cd concentration of 0.23 µg/g creatinine (5–95th percentile 0.10–0.49) or 0.17 µg/L density-adjusted (5–95th percentile 0.05–0.37) (Kippler et al., 2020).

3.4.6 Finland

The Northern Finland Birth Cohort program (NFBC) was established in 1966 as a prospective longitudinal general population research program. A follow-up of this cohort was conducted in 1997, when the subjects were 31 years of age, and biomonitoring data have been reported for blood As, Cd, Pb, total Hg and Se from 249 NFBC subjects (123 female, 126 male) as shown in Table 3.46. Concentrations of As, Cd and Pb, but not Hg, were lower in this northern Finland population than values reported in other countries.

An analysis of the 1997 data by Abass et al. (2017) investigated associations between blood levels of metals and socio-demographic factors. Arsenic concentrations were not significantly different in men and women and consumers of large amounts of fish did not have significantly higher concentrations of As than non-consumers. Cadmium results indicated significantly higher concentrations in men than women (0.18 vs 0.12 µg/L) and levels in daily smokers were almost ten-fold higher than never-smokers (0.68 vs 0.07 µg/L). Lead concentrations were also higher in men than women (17.06 vs 9.06 µg/L) and daily consumers of reindeer or moose had higher concentrations than non-consumers (17.57 vs 11.17 µg/L) although the difference was not significant. Daily consumers of sweetened drinks had significantly higher concentrations of Pb than non-consumers (17.80 vs 9.66 µg/L). The concentration of Hg was also significantly higher in men than women (2.18 vs 1.85 µg/L) and concentrations in regular consumers of fish (almost every day) were markedly higher than in those consuming fish less than once per month (4.91 vs 0.87 µg/L). Individuals with blood Hg concentrations <3 µg/L had on average 50% organic Hg while those with values >3 µg/L had 50–96% organic Hg.

Table 3.46 Blood concentrations of heavy metals in Finnish adults. Data presented as geometric means (range) in blood (µg/L whole blood). Source: Abass et al. (2017).

	Men	Women	Combined
Year	1997	1997	1997
Mean age, y	31.1	31.1	31.1
Sample size	n=126	n=123	n=249
Arsenic	0.49 (0.08–18.02)	0.44 (0.08–5.92)	0.47 (0.08–18.02)
Cadmium	0.18 (0.05–4.03)	0.12 (0.05–3.37)	0.15 (0.05–4.03)
Lead	17.06 (3.9–145.5)	19.06 (0.8–91.9)	12.44 (0.8–145.5)
Mercury	2.18 (0.32–14.54)	1.85 (0.33–11)	2.02 (0.32–14.54)
Selenium	106.0 (49.5–195.2)	94.34 (30–244.8)	100.0 (30–244.8)

Correlations between concentrations of metals showed significant associations in women between As and Hg, Cd and Pb, Pb and Hg, Pb and Ca, Cd and Se, and Hg and Se. Among men, significant associations were found between Cd and Pb, Cd and Se, and Pb and Hg.

3.4.7 Russia

3.4.7.1 Pechenga District of Murmansk Oblast

As part of the trilateral KolArctic project to investigate metals exposure as a result of emissions from a Ni-Cu smelter in the Pechenga nickel complex on the Russian Kola Peninsula, a biomonitoring study was conducted to assess body burdens through measurement of blood concentrations of Ni, Cu, As, Hg, Pb, Cd, Zn, Mn, and Co (Dudarev et al., 2016b). Sources of exposure to these metals from local foods were also investigated (see Chapter 4). This study included blood results

Table 3.47 Metals in the population of the Pechenga district of Murmansk Oblast, Russia. Data presented as geometric means (range) in blood (µg/L whole blood). Source: Dudarev et al. (2016b).

	Men	Women	Pregnant women
Year(s)	2013	2013	2013–2014
Mean age, y (range)	39.9 (27–54)	45.2 (26–65)	29.2 (20–42)
Sample size	n=18	n=32	n=50
Mercury	3.08 (0.75–25.2)	2.18 (0.45–12.5)	1.08 (0.3–3.99)
Lead	23.06 (12.1–91)	14.39 (4.42–108)	8.21 (3.53–54)
Cadmium	0.97 (0.44–2.4)	0.59 (0.16–2.21)	0.81 (0.24–2)
Arsenic	4.43 (0.74–19.2)	5.19 (0.86–28.7)	1.5 (0.41–19)
Manganese	45.97 (7.9–177)	53.22 (9.7–305)	12.17 (7.3–27.2)
Cobalt	0.77 (0.31–2.1)	0.91 (0.36–2.5)	0.34 (0.2–0.79)
Nickel	6.84 (1.02–85.6)	7.2 (1.71–95.9)	6.39 (4.49–20.4)
Copper	1226 (912–1660)	1436 (1040–2800)	1416 (931–1950)
Zinc	8103 (6590–9970)	7659 (5580–10600)	5369 (3830–6940)

from 50 adult residents (18 men, 32 women) from Nickel, who had resided in the city for at least 20 years, and the blood results from 50 pregnant women residing in the Pechenga district of Murmansk Oblast, who were recruited between 2013 and 2014 in the delivery department of Nickel City hospital. The population of the Pechenga district of Murmansk Oblast is non-Indigenous (Russians), and their point source exposure is not reflective of Indigenous People (Saami) living in the Lovozersky district of Murmansk Oblast, located far from the Pechenga district.

Concentrations of several metals including Pb, Zn, Ni and Hg were notably different among men, women and pregnant women (Table 3.47). While concentrations of most metals were slightly higher among men than women, these sex-based differences were even more noticeable between men and pregnant women. For geometric mean concentrations of Hg and Pb, concentrations were 3.6- and 2.6-fold higher in men than pregnant women. In contrast, men had lower geometric mean blood concentrations of Mn, Co and As compared to women, although pregnant women still had the lowest mean concentrations.

Concentrations of metals also varied widely among participants. In particular, while the geometric mean concentrations of Mn in women was 53.22 µg/L, values ranged between 9.7 and 305 µg/L which is a wider range than for men (7.9–177 µg/L). The highest observed concentrations of Mn, Co, Ni, Cu, Zn, As and Pb were among women, while the highest observed concentrations of Cd and Hg were among men.

The higher geometric mean and individual maximum concentrations of the majority of metals in women could potentially indicate a unique source of exposure, as the women who participated in the study were not employed in local industry, and therefore not exposed directly to any 'occupational' sources of exposure. Exceedances of international recommended blood guideline levels were observed for Hg and Pb and this is explored in Chapter 5.

3.4.8 Summary discussion

Time series for metals such as Hg extend as far back as the early 1990s in some regions of the Arctic, where early biomonitoring studies collected blood from pregnant women. Figure 3.11 shows mean levels among women of childbearing age and pregnant women from across the circumpolar Arctic over several periods (1990–1999, 2000–2007, 2007–2013, 2013–2018). Compared to levels of Hg and Pb first reported in the 1990s, there appears to have been a decline in levels of Hg, while time trends for Pb are less clear.

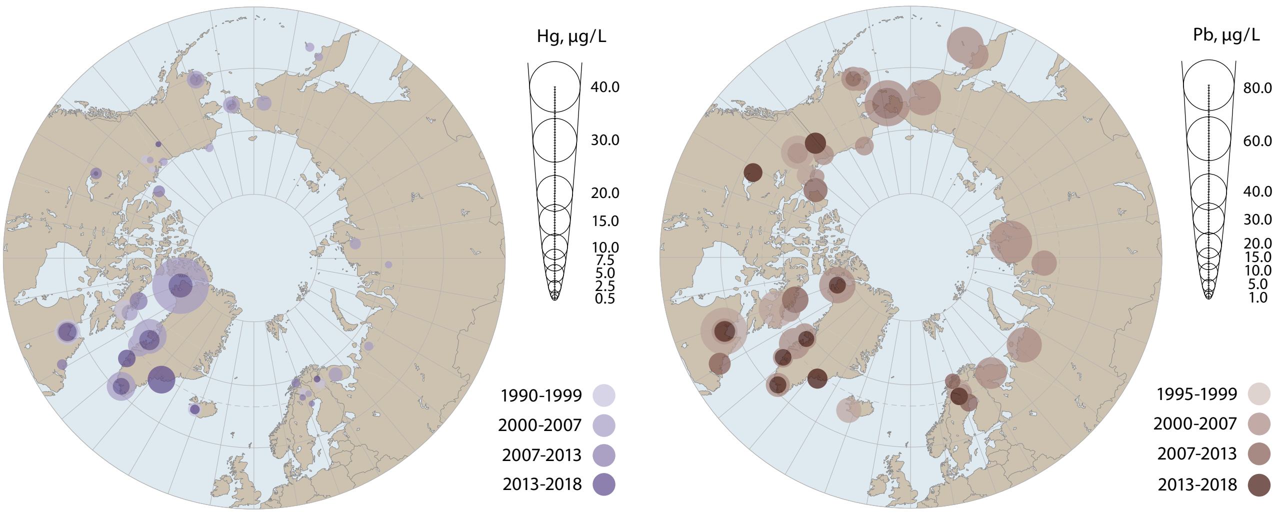


Figure 3.11 Circumpolar concentrations of Hg and Pb. Data from women of childbearing age (Yukon, Dehcho/Sahtú region, Inuvialuit Settlement Region, Nunavut and Nunatsiavut [Canada]), maternal blood (Alaska, Faroe Islands, Sweden, and coastal Chukotka [Russia]), blood of pregnant women (Nunavik [Canada], Greenland, Iceland, Norway, Sweden and the Pechenga district of Murmansk Oblast [Russia]).

When comparing levels of Hg and Pb in pregnant women and women of childbearing age across Arctic regions, clear differences are observed. Pregnant women's blood Hg levels were highest in Nunavik and Greenland, which were 4- and 5-fold higher than Hg levels in other regions. Conversely, within all regions, blood Hg levels have decreased over time and are markedly lower than some of the earliest Hg levels recorded in the 1990s. Mean blood Pb levels were higher in men than women in all Canadian Arctic regions, Sweden and in Murmansk Oblast Russia. The highest levels of blood Pb were generally in the Canadian Arctic, although levels were lower than those seen 10 years earlier in men and women from other regions of the Canadian Arctic from the Inuit Health Survey 2007–2008 (AMAP, 2015). The lowest Pb concentrations were observed in pregnant women from Greenland and Murmansk Oblast Russia, and women of childbearing age from Sweden. Concentrations of As were also measured in some regions, and were relatively low in adult men and women from the Yukon (Canada) and Finland (mean concentrations between 0.44 and 0.56 µg/L, respectively), compared to concentrations in adult men and women from Murmansk Oblast Russia (mean concentrations 4.43 and 5.19 µg/L, respectively) and pregnant women from Greenland (mean concentration 5.35 µg/L).

3.5 Human biomonitoring: contaminants of emerging Arctic concern

AMAP has identified a number of chemicals that are being detected in Arctic environments and Arctic wildlife, which warrant further research and monitoring in the Arctic (AMAP, 2017). Large representative surveys in many non-Arctic countries have reported exposures of these contaminants, and several human biomonitoring studies in Arctic countries have detected the presence of some of these contaminants in Arctic populations. Contaminants such as PFASs and PBDEs measured in human media are described in Section 3.3; this section reports available information on other contaminants including phthalates, PAHs and pharmaceuticals and personal care products (bisphenols) from Arctic countries. These contaminants are not persistent like POPs, but are being detected in some Arctic regions, probably due to local sources and/or presence in consumer goods. AMAP identified a number of groups of contaminants in various environmental media (AMAP, 2017), such as but not limited to chlorinated flame retardants, organophosphate flame retardants and plasticizers, short-chain chlorinated paraffins, siloxanes, and polychlorinated naphthalenes; however, no information on levels of these contaminants in human populations were available until recently in some parts of the Arctic.

3.5.1 Canada

3.5.1.1 Dehcho and Sahtú regions, NWT

In the Mackenzie Valley of the NWT, as part of a biomonitoring study investigating human exposure to contaminants in the Dehcho and Sahtú regions (see Section 3.3.2.2), participants provided urine samples which allowed analysis of additional contaminants including PAHs and phthalates. A number of PAH metabolites were measured and results are presented in Table 3.48 for those metabolites that were detected in a majority of samples (>70%); all PAH metabolites of benz[*a*]anthracene, benzo[*a*]pyrene, and chrysene were below the limits of detection, while only 2.1% of participants had detectable metabolite levels of fluoranthene. The predominant PAHs measured were fluorene metabolites (2-hydroxyfluorene, 9-hydroxyfluorene) and naphthalene metabolites (1-hydroxynaphthalene, 2-hydroxynaphthalene); of these contaminants, 2-hydroxynaphthalene had the highest concentrations with a median value of 7.77 µg/g creatinine, which was 5-fold higher than the next most predominant metabolite, 1-hydroxynaphthalene with a median value of 1.43 µg/g creatinine. Concentrations of PAHs in men and women were very similar for the majority of metabolites measured. When PAH metabolites were compared against the general population of Canada, many were slightly higher among NWT participants, particularly the 20–39 year age group (Ratelle et al., 2020b). This age group also happened to have the highest smoking rates among NWT participants (65%).

Smoking appeared to be a particularly important source of PAH exposure among participants. For example, levels of PAH metabolites were approximately two-fold higher in smokers than non-smokers. Questionnaire data suggested smoking rates among participants were approximately twice those of the Canadian general population (41% vs 19%, respectively). Notably though, non-parametric tests revealed significant associations between smoking status and age. Therefore, the higher PAH levels in smokers may be, in part, related to participant age (Ratelle et al., 2020b). Questionnaire data revealed associations between potential dietary sources of PAHs and biomarkers measured. For example, PAH levels were higher among participants that ate particular meats (bacon, roasted pork, steak, roasted moose, caribou) the day before urine was collected; these associations were significant for fluorene and phenanthrene metabolites (Ratelle et al., 2020b).

For phthalates, the majority of metabolites analyzed were detected in 100% of participants, with the exception of MCHP, MiNP and MnOP that were detected in a minority of samples (Table 3.49). Concentrations of phthalates were generally similar among male and female participants, although MBzP was twice as high in men than women (21.9 vs 12.5 µg/g creatinine, respectively) while MEP was twice as high in women than men (21.2 vs 12.2 µg/g creatinine, respectively). MBzP and MEP were also the most predominant metabolites measured, although concentrations of MEP were highly variable among both men and women (5th and 95th percentiles for men were 3.18 and 234.8 µg/g creatinine, and for women, 8.04 and 179 µg/g creatinine) (Ratelle and Laird, pers. comm., 2019).

3.5.1.2 Nunavik

As part of an exploratory study to assess Inuit exposure to a wide range of contaminants, pooled urine samples (n=30) were created from 1266 individuals recruited as part of the Q2017 survey who provided a urine sample. Pooled samples were formed based on grouping of sex, five age groups and three regions of residence in Nunavik (Hudson Bay, Hudson Strait,

Table 3.48 Concentrations of urine PAHs in adults across multiple First Nations communities in the Northwest Territories, Canada (2016–2018). Medians (5th – 95th percentile) are presented in creatinine-adjusted urine (μg/g creatinine). Source: Ratelle and Laird (pers. comm. 2019).

	Men		Women	
Years(s)	2016–2018		2016–2018	
Mean age, y (range)	51.1 (18–83)		52.2 (20–78)	
Sample size	n=54		n=36	
	μg/g creatinine	% <LOD	μg/g creatinine	% <LOD
1-Hydroxybenz[*a*]anthracene	<0.005[a]	100	<0.007[b]	100
1-Hydroxyphenanthrene	0.115 (0.049–0.282)	0	0.132 (0.073–0.428)	0
1-Hydroxypyrene	0.113 (0.044–0.361)	2	0.092 (0.048–0.348)	0
1-Hydroxynaphthalene	1.43 (0.272–10.3)	0	1.17 (0.344–9.88)	0
2-Hydroxychrysene	<0.004[a]	100	<0.006[b]	100
2-Hydroxyfluorene	0.408 (0.096–2.35)	0	0.339 (0.14–1.96)	0
2-Hydroxyphenanthrene	0.069 (0.022–0.171)	0	0.071 (0.04–0.279)	0
2-Hydroxynaphthalene	7.77 (1.559–16.5)	0	10.8 (2.13–25.3)	0
3-Hydroxybenz[*a*]anthracene	<0.005[a]	100	<0.007[b]	100
3-Hydroxybenzo[*a*]pyrene	<0.002[a]	100	<0.003[b]	100
3-Hydroxychrysene	<0.003[a]	100	<0.004[b]	100
3-Hydroxyfluoranthene	<0.008[a]	100	<0.012[b] (<0.012[b]–0.02)	94.3
3-Hydroxyfluorene	0.16 (0.03–1.02)	0	0.127 (0.033–0.914)	0
3-Hydroxyphenanthrene	0.089 (0.026–0.309)	0	0.073 (0.046–0.285)	0
4-Hydroxychrysene	<0.003[a]	100	<0.004[b]	100
4-Hydroxyphenanthrene	0.026 (<0.001[a]–0.103)	7.5	0.026 (<0.001[b]–0.178)	8.8
6-Hydroxychrysene	<0.006[a]	100	<0.009[b]	100
9-Hydroxyfluorene	0.258 (0.074–0.824)	0	0.281 (0.112–1.42)	0
9-Hydroxyphenanthrene	0.066 (0.014–0.333)	1.9	0.053 (0.025–0.326)	0

LOD: Limit of detection; values below the LOD were treated as LOD/2 for calculating the mean; [a]based on the geometric mean (1.0 g/L) of urine creatinine observed for male participants; [b]based on the geometric mean (0.67 g/L) of urine creatinine observed for female participants.

Ungava Bay), and the age group allowed comparisons with the general population (CHMS) and First Nations on-reserve population (FNBI) in Canada. Pooled samples were screened for a wide range of contaminants, including bisphenols, phthalates, alternate plasticizers and PAHs. Many of these contaminants were detected in the pooled urine samples; concentrations of bisphenols and PAHs that were detected in more than 60% of men and women are presented in Table 3.50, with all age groups and regions combined.

The most predominant bisphenols were BPA, BPS, and Bisphenol 4,4', while concentrations of BPE, BPF and BPZ were very low. BPA concentrations were not statistically different by sex, region or age group and BPA average concentrations adjusted for creatinine were approximately double those

Table 3.49 Concentrations of urine phthalates in adults across multiple First Nations communities in the Northwest Territories, Canada. Medians (5th – 95th percentile) are presented in creatinine-adjusted urine (μg/g creatinine). Source: Ratelle and Laird (pers. comm. 2019).

	Men		Women	
Year(s)	2016–2018		2016–2018	
Mean age, y (range)	49.0 (18–79)		49.9 (23–65)	
Sample size	n=13		n=9	
	μg/g creatinine	% <LOD	μg/g creatinine	% <LOD
MBzP	21.9 (3.54–60.3)	0	12.5 (3.76–30)	0
MCHP	<0.3[a] (<0.3[a]–0.93)	69.2	<0.448[b] (<0.448[b]–0.92)	77.8
MCPP	0.47 (0.32–1.75)	0	0.72 (<0.149[b]–1.84)	22.2
MECPP	4.8 (2.53–14.4)	0	8.4 (3.64–28.8)	0
MEHHP	6.86 (2.88–12.6)	0	5.8 (3.47–20.4)	0
MEHP	1.39 (0.41–2.28)	0	1.64 (<0.149[b]–6.28)	11.1
MEOHP	3.71 (1.85–7.26)	0	3.64 (1.8–10.8)	0
MEP	12.2 (3.18–234.8)	0	21.2 (8.04–179)	0
MiBP	9.24 (5.23-10.6)	0	8.5 (4.25–21.4)	0
MiNP	<0.4[a] (<0.4[a]–1.26)	61.5	<0.597[b] (<0.597[b]–0.76)	77.8
MMP	1.61 (0.95–3.51)	0	2.09 (1.52–4.03)	0
MnBP	13 (6.42–21.6)	0	13.7 (5.54–23.2)	0
MnOP	<0.4[a]	100	<0.299[b]	100

LOD: Limit of detection; values below the LOD were treated as LOD/2 for calculating the mean; [a]based on the geometric mean (1.0 g/L) of urine creatinine observed for male participants; [b]based on the geometric mean (0.67 g/L) of urine creatinine observed for female participants.

in CHMS Cycle 4, 2014–2015, CHMS Cycle 5, 2016–2017, and FNBI (Assembly of First Nations, 2013; Health Canada, 2017). BPF and BPS were not measured in the CHMS, but were included in NHANES 2013–2014 (CDC, 2019). The BPF average concentration in Q2017 (0.82 μg/g creatinine) was not significantly different to that measured in NHANES (0.53 μg/g creatinine), whereas the BPS average concentration in Q2017 (1.53 μg/g creatinine) was significantly higher than that measured in NHANES (0.43 μg/g creatinine). Moreover, BPS concentrations were significantly higher in Q2017 females (2.05 μg/g creatinine) than males (1.14 μg/g creatinine).

For PAHs, four chrysene metabolites (2-, 3-, 4- and 6-hydroxychrysene) and one fluoranthene metabolite (3-hydroxyfluoranthene) were not detected in the pooled samples, whereas concentrations of several phenanthrene metabolites, naphthalene metabolites, fluorene metabolites, and a pyrene metabolite were detected in nearly all samples (Table 3.50). Concentrations of 1-hydroxyphenanthrene,

Table 3.50 Concentrations of bisphenols and PAHs in pooled urine samples from adult Inuit men and women from Nunavik, Canada. Data are presented as geometric means (range) in urine (μg/g creatinine). Pooled samples (n=30) created from 1266 individuals, divided by sex, five age groups, and three regions of Nunavik. Source: Caron-Beaudoin et al. (2019b).

	Men		Women	
Year	2017		2017	
Age, y	16–86		16–86	
Sample size	n=15		n=15	
	μg/g creatinine	% <LOD	μg/g creatinine	% <LOD
BPA	1.96 (0.81–34.29)	0	1.99 (1.11–3.09)	0
BPE	0.029 (0.015–0.041)	0	0.037 (0.03–0.05)	0
BPF	nc	0	0.80 (0.17–9.17)[a]	0
BPS	1.14 (0.6–8.57)	0	2.05 (0.88–6.42)	0
BPZ	0.027 (0.01–0.041)	7.9	0.033 (0.021–0.05)	0
Bisphenol 4,4’	1.21 (0.65–2.15)	0	1.30 (0.94–1.92)	0
1-Hydroxyphenanthrene	0.14 (0.09–0.2)	0	0.16 (0.11–0.22)	0
2-Hydroxyphenanthrene	0.074 (0.042–0.106)	0	0.086 (0.058–0.115)	0
3-Hydroxyphenanthrene	0.13 (0.06–0.17)	0	0.14 (0.1–0.18)	0
4-Hydroxyphenanthrene	0.051 (0.023–0.081)	0	0.061 (0.038–0.1)	0
9-Hydroxyphenanthrene	0.12 (0.07–0.16)	0	0.14 (0.09–0.19)	0
1-Hydroxypyrene	0.16 (0.07–0.22)	0	0.17 (0.12–0.23)	0
1-Hydroxynaphthalene	5.72 (2.86–8.13)	0	7.20 (4.09–100)	0
2-Hydroxynaphthalene	9.88 (4.83–12.73)	0	12.26 (8.24–16)	0
2-Hydroxyfluorene	0.93 (0.49–1.31)	0	1.14 (0.69–1.6)	0
3-Hydroxyfluorene	0.52 (0.27–0.75)	0	0.61 (0.41–0.93)	0
9-Hydroxyfluorene	0.22 (0.12–0.41)	0	0.27 (0.18–0.44)	0

LOD: Limit of detection; nc: data too unreliable to be present as the coefficients of variation are greater than 33.3%; [a]caution: the coefficient of variation is between 16.6% and 33.3%.

Table 3.51 Concentrations of phthalate metabolites in pooled urine samples from adult Inuit men and women from Nunavik, Canada. Data presented as geometric means (range) in urine concentrations (μg/g creatinine). Pooled samples (n=30) created from 1266 individuals, divided by sex, five age groups, and three regions of Nunavik. Source: Caron-Beaudoin et al. (2019b).

	Men		Women	
Year	2017		2017	
Age, y	16–86		16–86	
Sample size	n=15		n=15	
	μg/g creatinine	% <LOD	μg/g creatinine	% <LOD
MBzP	38.8 (32.0–47.2)	0	52.5 (43.7–62.9)	0
MCiNP	0.94 (0.66–1.34)	0	1.40 (0.85–2.32)[a]	0
MCiOP	1.35 (1.03–1.78)	0	2.07 (1.28–3.36)[a]	0
MCMHP	1.17 (0.90–1.52)	0	nc	0
MCPP	0.59 (0.47–0.73)	0	0.80 (0.53–1.22)[a]	0
MECPP	4.69 (3.99–5.50)	0	8.21 (4.42–15.25)[a]	0
MEHHP	3.76 (3.26–4.33)	0	6.16 (3.70–10.24)[a]	0
MEHP	0.88 (0.76–1.01)	0	1.23 (0.85–1.78)[a]	0
MEOHP	1.98 (1.72–2.28)	0	3.30 (1.93–5.65)[a]	0
MEP	12.8 (9.66–17.0)	0	38.5 (20.0–74.2)[a]	0
MHBP	2.10 (1.79–2.47)	0	2.45 (2.13–2.81)	0
MHiDP	0.60 (0.50–0.71)	0	0.64 (0.50–0.82)	0
MHiNP	1.26 (0.90–1.76)	0	1.66 (1.02–2.72)[a]	0
MiBP	5.12 (4.55–5.76)	0	7.05 (6.33–7.85)	0
MiNP	nc	49.1	0.34 (0.22–0.51)[a]	28.6
MMP	1.99 (1.41–2.81)	0	2.17 (1.85–2.54)	0
MnBP	12.4 (10.61–14.55)	0	16.0 (14.0–18.2)	0
MOiDP	0.53 (0.43–0.64)	0	0.56 (0.47–0.67)	0
MOiNP	0.69 (0.49–0.97)	0	1.00 (0.62–1.62)[a]	0
2-OH-MiBP	2.66 (2.35–3.02)	0	3.71 (3.22–4.29)	0

LOD: Limit of detection; nc: data too unreliable to be present as the coefficients of variation are greater than 33.3%; [a]caution: the coefficient of variation is between 16.6% and 33.3%.

2-hydroxyphenanthrene, 4-hydroxyphenanthrene and 9-hydroxyphenanthrene were generally higher in women. When comparing specific age groups (data not shown), concentrations of several phenanthrene metabolites and 1-hydroxypyrene were generally higher in the 40–59 year-old age group, when compared to the general population from CHMS Cycle 4, 2014–2015 (Health Canada, 2017). For naphthalene metabolites, the 1-hydroxynaphthalene concentration tended to be higher in women, and the concentration in the 40–59 year-old age group from the Hudson Strait region was approximately 5- to 8-fold higher than in the general Canadian population of the same age (Health Canada, 2017). Several fluorene metabolites were also higher in women, and concentrations in women from the Hudson Strait region in the 20–39 and 40–59 year-old age groups were much higher than in the general population from CHMS Cycle 4, 2014–2015 (3-hydroxyfluorene was 5- to 6-fold higher). Although the overall PAH exposure profile was similar between Nunavik and the NWT, several PAHs, particularly hydroxynaphthalenes and hydroxyfluorene, were higher in Nunavik than the NWT.

A total of 24 phthalate metabolites were measured in the pooled samples (MBzP, MCHP, MCHpP, MCiNP, MCiOP, MCMHP, MCPP, MECPP, MEHHP, MEHP, MEOHP, MEP, MHBP, MHiDP, MHiNP, MiBP, MiDP, MiNP, MMP, MnBP, MnOP, MOiDP, MOiNP, 2OH-MiBP). MCHP, MCHpP, MiBP, MiDP and MnOP were not detected in the pooled samples, whereas the other phthalate metabolites were detected in nearly all samples (Table 3.51). Concentrations of MEP, MiBP and 2-OH-MiBP were statistically higher in women compared to men. Concentrations of MBzP were lower in the Ungava Bay region. Concentrations of MCiNP were lower in the Hudson Bay region (Caron-Beaudoin et al., 2019b). Compared to the general population from CHMS Cycle 5, 2016–2017, concentrations of MBzP were 12-fold higher in Nunavik. Concentrations of MnBP, MCPP, MEHHP, MEOHP, MEP and MiBP in Nunavik were generally similar to those in the general population from CHMS Cycle 5, 2016–2017.

For alternate plasticizers, two TXIB metabolites (TMPD, HTMV), two CHDA metabolites (*cis*-CHDA, *trans*-CHDA), five DINCH metabolites (*trans*-MINCH, OH-MINCH, oxo-MINCH, *trans*-cx-MINCH, *cis*-cx-MINCH) as well as three TOTM metabolites (1-MEHTM, 2-MEHTM, 4-MEHTM) were measured in the pooled urine samples of 1266 individuals recruited in the Q2017 study, and data are presented for all men and all women in Table 3.52. *cis*-CHDA and 2-MEHTM were detected in only 8.3% and 13.6% of the pooled urine samples, respectively, while *trans*-MINCH, *trans*-cx-MINCH, 1-MEHTM and 4-MEHTM were not detected in any of the pooled urine samples. TMPD, HTMV, OH-MINCH, oxo-MINCH and *cis*-cx-MINCH were detected in most samples, with the exception of *cis*-cx-MINCH in men (59.9% <LOD). TMPD was the most predominant, at geometric mean concentrations that were approximately six-fold higher than the next most predominant compound, HTMV, in both men and women. Concentrations of OH-MINCH, oxo-MINCH, and *cis*-cx-MINCH were very low (maximum concentrations well below 1 μg/g creatinine). Concentrations in Nunavik were not statistically different between sex, age group or region (Caron-Beaudoin et al.,

Table 3.52 Concentrations of alternate plasticizers and their metabolites in pooled urine samples from adult Inuit men and women from Nunavik, Canada. Data presented as geometric means (range) in urine concentrations (µg/g creatinine). Pooled samples (n=30) created from 1266 individuals, divided by sex, five age groups, and three regions of Nunavik. Source: Caron-Beaudoin et al. (2019b).

	Men		Women	
Year	2017		2017	
Age, y	16–86		16–86	
Sample size	n=15		n=15	
	µg/g creatinine	% <LOD	µg/g creatinine	% <LOD
TMPD	46.11 (38.85–54.73)	0	59.11 (47.12–74.16)	0
HTMV	8.15 (6.50–10.22)	0	10.25 (7.83–13.42)	0
OH-MINCH	0.10 (0.07–0.14)	9.2	0.17 (0.13–0.22)	4.5
oxo-MINCH	0.030 (0.019–0.046)[a]	29.1	0.056 (0.044–0.070)	7.6
cis-cx-MINCH	nc	59.9	0.045 (0.037–0.055)	13.3

LOD: Limit of detection; nc: data too unreliable to be present as the coefficients of variation are greater than 33.3%; [a]caution: the coefficient of variation is between 16.6% and 33.3%.

Table 3.53 Concentrations of phthalate metabolites in Greenlandic pregnant women and their male partners from the INUENDO study. Data presented as medians (5th – 95th percentile) in µg/L serum. Source: Lenters et al. (2015, 2016); Toft (pers. comm. 2019).

	Pregnant women		Men	
Year(s)	2002–2004		2002–2004	
Mean age, y (range)	27 (18–44)		30 (20–43)	
Sample size	n=513		n=196	
	µg/L serum	% <LOD	µg/L serum	% <LOD
MEHHP	0.68 (0.24–1.07)	0	1.02 (0.44–2.55)	2
MEOHP	0.12 (0.05–0.23)	1	0.21 (<LOD–0.55)	51
MECPP	0.58 (0.25–2.22)	0	1.07 (0.45–3.72)	0
MHiNP	0.24 (0.07–0.54)	5	0.3 (0.12–0.86)	7
MOiNP	0.02 (<LOD–0.06)	10	0.03 (<LOD–0.11)	61
MCiOP	0.23 (0.07–0.88)	0	0.52 (0.21–1.61)	1

LOD: Limit of detection.

2019b). Compared to the general population from CHMS Cycle 5, 2016–2017, concentrations of HTMV were 2- to 3-fold higher in Nunavik, and concentrations of TMPD were 3-fold higher in Nunavik. OH-MINCH, oxo-MINCH and *cis*-cx-MINCH were detected at low concentrations in the pooled urine samples from Nunavik, and concentrations in the general population from CHMS Cycle 5, 2016–2017 were also low, although comparisons are difficult to make due to the percentage of samples below the limit of detection.

3.5.2 Greenland

Several phthalate metabolites were measured in serum as part of an analysis of blood samples from women recruited in the INUENDO study (2002–2004) and their male partners, and included the following: MEHHP, MEOHP, MECPP, MHiNP, MOiNP, and MCiOP. These phthalate metabolites were detected in the majority of samples for both pregnant women and men, except for MEOHP and MOiNP in men which were only detected in 49% and 39% of samples, respectively. Results for men and pregnant women show that the main metabolites measured in both sexes are MEHHP and MECPP, which were at least 2-fold higher than other metabolites (Table 3.53). It was also observed that levels of phthalates were nearly twice as high in men as in pregnant women for most metabolites. Both MEHHP and MEOHP are metabolites of DEHP, and levels of MEHHP were strongly correlated to levels of MEOHP (spearman correlation = 0.75). Both MOiNP and MCiOP are metabolites of MiNP, and levels of MOiNP were strongly correlated with levels of MCiOP (spearman correlation = 0.58) (Lenters et al., 2015, 2016).

3.5.3 Sweden

In the northern Sweden MONICA study undertaken in 2014, measurements in urine of ten phthalate metabolites, pesticide metabolites (3-phenoxybenzoic acid, trichloropyridinol), and alkylphenols (bisphenol A, bisphenol F, triclosan) were added to the environmental screening in young adults (men and women 25–35 years) and women 50–59 years (Wennberg et al., 2015).

Comparisons were made between the young men and women from the northern Sweden MONICA study and young men and women from southern Sweden (Skåne) (Wennberg et al., 2018b). The young adults in northern Sweden had higher concentrations of most of the phthalates compared to southern Sweden. Use of heating under plastic floors in the north did not explain this difference. Thus the reason for higher phthalates in young adults in northern Sweden can only be speculated, but differences in building and ventilation may be worth considering. However, it must be stated that youth in southern Sweden were younger (high school seniors, mean age 18 years) compared to the young adults age group from the MONICA project (25–34 years) and thus other lifestyle differences of relevance to phthalate exposure may be present.

Bisphenol A in urine was measured for participants in the MONICA study in 2009 and 2014 (Wennberg et al., 2015). Levels were substantially lower in all examined groups in 2014 compared to 2009.

Concentrations of phthalate metabolites and phthalate alternatives were measured in urine from participants in the Riksmaten Adolescents 2016–2017 study as shown in Table 3.54. Overall, girls had significantly higher urine concentrations of a majority of the phthalate metabolites (MEHP, 5-oxo-MEHP, 5-cx-MEPP,

Table 3.54 Density-adjusted urine concentrations of phthalates, phthalate alternatives and bisphenols in adolescents from Sweden. Data presented as arithmetic means (5th – 95th percentile) in urine (µg/L). Source: Livsmedelsverket and Naturvårdsverket (2020).

Year(s)	2016–2017	
Mean age, y	14.7	
(range)	(10–21)	
Sample size	n=1104	
	µg/L urine	% <LOD
Phthalates		
MEHP	3 (1–6)	1.6
5-OH-MEHP	12 (3–26)	0.2
5-oxo-MEHP	9 (2–21)	0.2
5-cx-MEPP	11 (3–25)	0
MEP	112 (10–353)	0
MBzP	13 (1–45)	0.2
MnBP[a]	52 (15–119)	0.1
OH-MiNP	11 (1–37)	0
cx-MiNP	16 (2–49)	0
cx-MiDP	1 (0.1–2)	5.4
Bisphenols		
BPA	1 (0.3–4)	7.1
BPS	0.3 (0.04–1)	6.9
4,4-BPF	1 (<0.03–2)	21.4

LOD: limit of detection; [a]n=1098.

MEP, MnBP, MBzP, OH-MiNP, cx-MiNP, oxo-MiNP, cx-MiDP) than boys (Livsmedelsverket and Naturvårdsverket, 2020). Concentrations of the phosphorus flame retardants DPP and DBP, the pesticide metabolite 3-PBA, bisphenol S and triclosan were also higher in girls (Livsmedelsverket and Naturvårdsverket, 2020). A possible explanation for the observed gender differences for phthalates is a higher exposure from personal care products and cosmetics in girls.

Concentrations of all DINCH-metabolites (oxo-MINCH, cx-MINCH, OH-MINCH), bisphenol A, 4,4-bisphenol F and the PAH metabolite 2-OH-PH were similar in boys and girls (Livsmedelsverket and Naturvårdsverket, 2020).

There were no consistent associations between age/grade and urine levels of phthalate metabolites or phenolic compounds (Livsmedelsverket and Naturvårdsverket, 2020). The direction of the associations varied between compounds and gender, and may be explained by chance or by differences in lifestyle or food consumption.

Levels of MBzP, MnBP and BPA per region and adjusted for grade and gender are shown in Figure 3.12. The different letters in the figures indicate significant differences between regions ($p<0.05$) according to Tukey's multiple comparison test. Umeå is the region that represents the northern part of Sweden and significantly higher levels were seen there for MBzP. For MnBP, levels in Umeå were significantly higher than in Stockholm and Örebro. Thus the finding of higher concentrations of several phthalate metabolites in young adults in northern Sweden compared to southern Sweden (Wennberg et al., 2018b) was in accordance with the findings for the Riksmaten adolescents

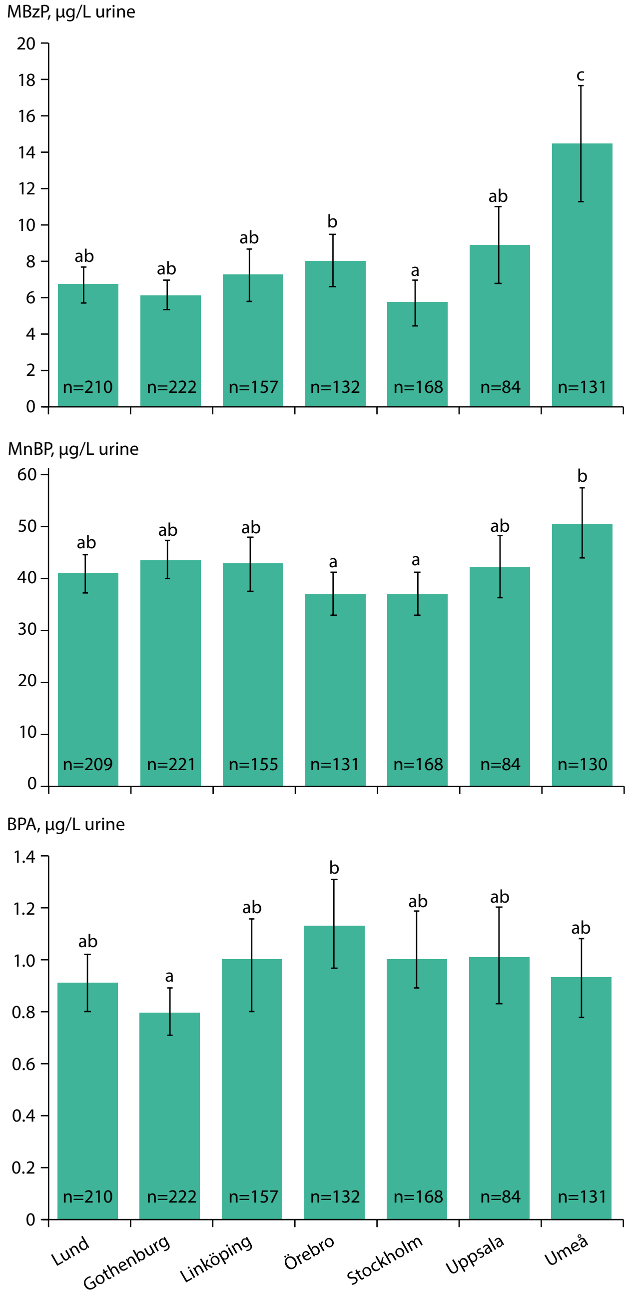


Figure 3.12 Density-adjusted concentrations of MBzP, MnBP and BPA in urine from Swedish adolescents per region adjusted for grade and gender, and interactions between all factors (back-transformed least squares means with 95% confidence intervals from the analysis of log values). Different letters indicate significant differences between regions ($p<0.05$) according to Tukey's multiple comparison test. The number of observations per region are shown at the base of each bar.

2016–2017. No regional differences between Umeå and the other regions were seen for BPA.

In the POPUP study, time trends of phthalates and phenolic substances in urine from the same first-time mothers as described in Box 1.2 and are available from 2009 to 2018 (Bjermo et al., 2019). All phthalate metabolites detected show decreasing trends over time (Figure 3.13). In contrast, oxo-MINCH (a metabolite of DINCH, the alternative plasticizer which replaces phthalates in several items) shows an increasing trend. BPA is decreasing over time but no trend is apparent for BPS, while BPF shows an initial increasing trend until 2013 before becoming a decreasing trend thereafter (Figure 3.14).

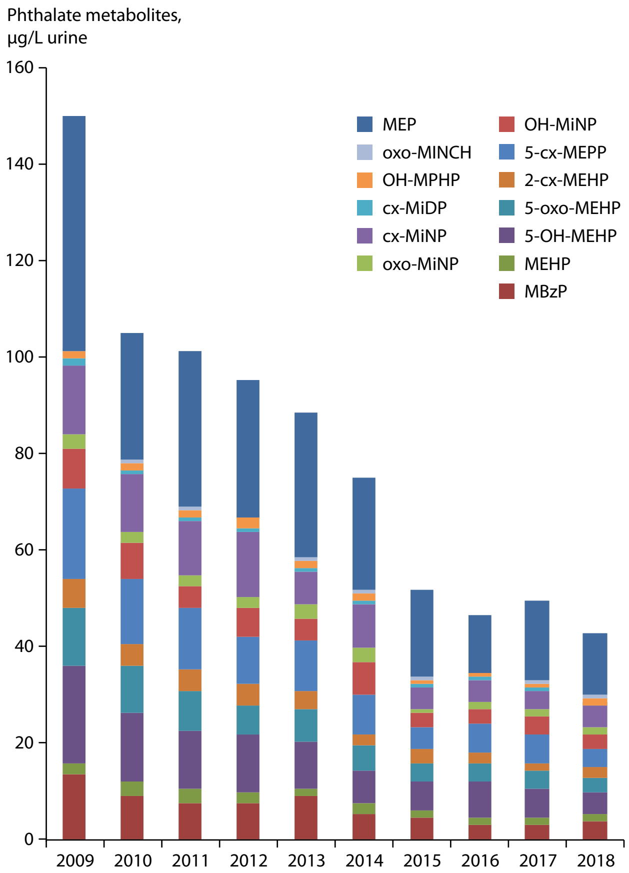


Figure 3.13 Trends in density-adjusted urine concentrations of phthalate metabolites and DINCH metabolites in Swedish first-time mothers. Samples collected three weeks after delivery. Data presented as median concentrations (Bjermo et al., 2019).

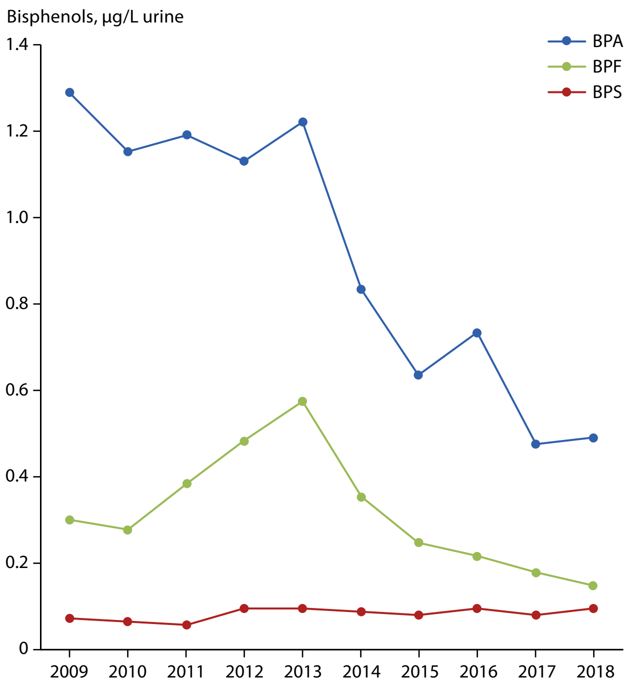


Figure 3.14 Trends in density-adjusted urine concentrations of BPA, BPS, 4,4-BPF in Swedish first-time mothers. Samples collected three weeks after delivery. Data presented as median concentrations (Bjermo et al., 2019).

3.5.4 Summary discussion

A number of contaminants of emerging concern have been detected in water, air, and biota in the Arctic environment (AMAP, 2017). While data are still limited for many of these substances in environmental media, there are even fewer data available for many of these substances in Arctic human populations, with no data available in most regions and only a few datasets available in the Canadian Arctic and Greenland. Sweden is the exception, with substantial time trend information available on phthalates and some bisphenols in Swedish first-time mothers since 2009.

In the Canadian Arctic, several PAHs were detected in men and women from the NWT and Nunavik (pooled samples). In both regions, the predominant PAHs measured were 1- and 2-hydroxynaphthalene. While concentrations of some PAHs were similar in these regions, others such as 2-hydroxyfluorene, 3-hydroxyfluorene, 3-hydroxyphenanthrene and 4-hydroxyphenanthrene were higher in Nunavik (generally 2-fold higher). For the two most predominant PAHs, concentrations of 1- and 2-hydroxynaphthalene were both higher in Nunavik samples, especially 1-hydroxynaphthalene at 5.72 and 7.20 µg/g creatinine in Nunavik men and women, respectively, compared to 1.43 and 1.17 µg/g creatinine in men and women from the NWT (up to a six-fold difference in means).

Phthalates have widespread occurrence in products and have been found in air, seawater and biota in the Arctic environment (AMAP, 2017). In Arctic human populations, phthalates have been detected in those regions where urine samples were collected for analysis of phthalates. Comparisons of phthalates between Arctic regions are limited due to different reporting methodologies, because phthalates measured in urine were creatinine-adjusted in the Canadian Arctic, density-adjusted in Sweden, and measured in serum in Greenland. In the Canadian Arctic, concentrations of many phthalates were generally similar between First Nations communities in the NWT and in Inuit from Nunavik; however, concentrations of MBzP and MEP (in women) were much higher in Nunavik, while MiBP was higher in the NWT. Although concentrations of most phthalates were similar between men and women, Nunavik women had higher concentrations of MBzP, MECPP, MEHHP, MEOHP, MEP, MiBP and MnBP than Nunavik men (often two-fold higher); however, this should be interpreted with caution due to the high coefficients of variation. In the NWT, while women had higher concentrations of MEP, men had higher concentrations of MBzP. In both regions, the predominant phthalates were MBzP, MEP, MiBP and MnBP.

While time trend information is not available for phthalates across most of the Arctic, substantial trend information has been collected in Swedish first-time mothers. Of the phthalate metabolites and DINCH metabolites, the majority appear to be decreasing over time (2009 to 2018), and a similar decreasing trend is also seen for BPA and BPF (2013 onwards) in Swedish first-time mothers.

While these contaminants of emerging concern have been measured in a variety of environmental media across several regions of the Arctic (AMAP, 2017), few data are available for these substances in human populations. Baseline data are available in some Arctic regions, but more are needed to enable more comprehensive circumpolar comparisons, while time trend information is still only available in Sweden.

3.6 Dietary exposure to contaminants in traditional foods

Consumption of subsistence foods as part of a traditional diet among many Indigenous populations in the Arctic is a major source of exposure for POPs and several metals and elements (AMAP, 1998, 2003, 2009, 2015). Due to the chemical characteristics of POPs, which bioaccumulate and biomagnify within Arctic food webs, predators at the top of food chains such as polar bears, whales and seals, typically have the highest concentrations of POPs. These are primarily stored in fatty tissue as they are lipophilic, with the exception of PFASs which do not bind readily to lipids but instead bind to proteins. Concentrations of Hg, specifically MeHg, are also elevated among species at the top of food chains; however, Hg tends to reside more in muscle tissue than fatty tissue. The main storage organ for Hg is the liver in marine mammals and birds (where it accumulates as inorganic Hg-Se crystals), and the kidney in land mammals.

Extensive reviews of contaminant levels in Arctic wildlife have been presented in previous AMAP reports (AMAP, 2011, 2016) as well as time trends for some parts of the Arctic extending back several decades, which together provide insight into concentrations of POPs and Hg in traditional foods. While concentrations of many POPs in biota are decreasing in the Arctic, concentrations of others such as chlordane, nonachlor and oxychlordane have actually increased slowly in some biota, including polar bears and ringed seals in eastern Greenland and beluga in Canada (AMAP, 2016). For the sum of DDT, significant decreasing trends in concentration were observed in 46% of time series analyzed (AMAP, 2016). Contrary to these POPs, time series for PFASs are more complicated. Time series in polar bears and ringed seals from eastern Greenland reveal increasing trends for PFOS to the mid-2000s, followed by a rapid decrease (AMAP, 2016). Like POPs, concentrations of MeHg increase through food chains and are particularly elevated in top predators, such as in beluga meat, seal liver and older lake trout (Lemire et al., 2015). Mercury time series are up to four decades long and there are increasing trends in several top predator species in some regions, although significant regional differences have also been observed, such as between western and eastern Greenland (AMAP, 2011). The following sections highlight some of the recent work to identify key sources of dietary exposure to POPs and metals, and levels in traditional foods.

3.6.1 Alaska

There are two main Indigenous populations in Alaska, the Yupik (primarily residing in the Yukon-Kuskokwim delta, along the Kuskokwim River, and in parts of Southern Alaska) and the Inupiat (on the northern slopes of Alaska). Yupik communities are also found on St. Lawrence Island in the Bering Sea, not far off the coast of the Chukotka region of Russia, which is home to several Chukchi communities. Pacific walrus is an important subsistence species for Indigenous coastal populations, particularly in the Bering Sea region and Chukchi region.

As part of a walrus biosampling program run in conjunction with the annual spring harvest in Gambell and Savoonga, walrus liver, kidney and muscle samples were collected from 225 walruses between 2012 and 2016; of these a total of 42 walruses collected between 2012 and 2014 were analyzed for Hg and organochlorines (Quakenbush et al., 2016). Concentrations of Hg and Pb were highest in liver, and Cd concentrations were highest in kidney. Organochlorines measured included several HCH compounds, chlordane compounds, DDT compounds, and PCBs. In general, concentrations of organochlorines were highest in blubber, at an order of magnitude higher than in liver, which were in turn an order of magnitude higher than in kidney and muscle. The predominant groups of compounds were HCH compounds, followed by PCBs, chlordanes and DDT compounds. Of these, the main contaminants were β-HCH, oxychlordane, dieldrin, mirex, and among the PCB congeners in blubber, PCB153/132 predominated. Concentrations of contaminants in walrus blubber were similar to those reported in St. Lawrence Island walruses collected in 2005–2009 (Welfinger-Smith et al., 2011).

3.6.2 Canada

Consumption of country foods is important to many Inuit and First Nations communities, and while the types of food consumed and proportions of each food type consumed may vary across the Canadian Arctic, country foods can be a major source of important nutrients and essential minerals including Se, several vitamins and omega-3 fatty acids, although some may accumulate high concentrations of POPs and Hg.

3.6.2.1 Dehcho and Sahtú regions, NWT

Past health surveys have found that communities in the western Canadian Arctic typically have lower levels of POPs and metals in blood samples than Inuit communities in the eastern Canadian Arctic (AMAP, 2015), and this difference has been assumed to reflect regional and cultural differences in country food consumption. In addition to Inuit communities, First Nations communities also rely on the consumption of country foods for cultural, economic and nutritional benefits.

In the NWT, several First Nations communities rely on country food consumption for nutrition, including the consumption of fish, game birds, and land mammals such as caribou and moose. Past research has found high levels of Cd in the organs of moose in some parts of the NWT.

Moose liver samples (n=14) harvested in the Dehcho region (in 2016) near the community of Jean Marie River, and South Slave region (in 2010), were analyzed for POPs including but not limited to PCBs, PBDEs and PFASs (Larter et al., 2017). Concentrations of POPs were generally low (<1 ng/g wet weight), and PFASs were the predominant contaminants, particularly PFCAs which were 1.3- to 2-fold higher than PFSAs. PFAS concentrations were higher in the Dehcho region (0.81–2.5 ng/g ww) than the South Slave region (0.63–1.2 ng/g ww), and while the regional difference was statistically significant for PFSAs (sum of C4–C10), this was not the case for PFCAs (sum of C4–C16). Metal levels in moose kidney and caribou kidney (Larter et al., 2016, 2018) resulted in food consumption notices to reduce their consumption.

Harvesting of fish from local lakes in the Dehcho region, in the Mackenzie Valley of the NWT, is an important part of the diet of First Nations communities (Evans et al., 2005). A profile of Hg and omega-3 PUFAs was generated for key fish species harvested from eight lakes in the Dehcho region, including burbot, cisco, lake trout, lake whitefish, longnose sucker, northern pike, walleye, and white sucker (Laird et al., 2018). After results were pooled across all years and lakes sampled, piscivorous fish (e.g., northern pile, walleye, burbot, lake trout) were identified as having higher Hg levels (up to 8.6-fold higher) than benthivorous and planktivorous fishes (e.g., cisco, lake whitefish, sucker). Levels of Hg in most fish were low, although median Hg concentrations in northern pike were above commercial sale guidelines (>0.5 μg/g). Fish size (length) was also strongly linked to Hg concentration in fish (except for white sucker). In this study; however, the goal was also to establish which species would provide the highest benefit/risk ratio based on PUFA measurements. Lake trout was found to have the highest concentrations of fatty acids; however, based on a fatty acid : Hg ratio, lake trout was higher than other predatory species. The highest ratios were in cisco, lake whitefish and sucker, although the fatty acid : Hg ratios varied within species depending on the lake from which the fish were sampled.

3.6.2.2 Nunavik

In Nunavik, several studies have investigated country foods as sources of MeHg, Se and long-chain PUFAs. The contribution of different traditional foods to MeHg, Se, and PUFAs in Nunavik Inuit adults was estimated using country food consumption data in the Nunavik 2004 Inuit Health Survey and the most recent data on MeHg, Se and PUFAs in Nunavik wildlife species (Lemire et al., 2015). Within Nunavik, regional differences in Inuit exposure to Hg were observed, with the highest concentrations of MeHg occurring in the Hudson Strait region, followed by the eastern Hudson Bay and Ungava Bay regions. The regional differences also corresponded with different traditional food intakes, as residents in the Hudson Strait region consumed significantly more marine mammals and notably beluga meat than eastern Hudson Bay and Ungava Bay residents, who consumed more fish/seafood and land animals/game birds. MeHg concentrations were generally low in the country foods sampled, with the exception of beluga meat, beluga *nikku*, beluga liver, ringed seal liver and lake trout (all >1.0 μg/g). Concentrations of Se were also found to be high in beluga *mattaaq*, followed by walrus meat and fish eggs. When combined with data on traditional food consumption, estimated intake could be calculated for each of the three regions. While caribou meat and Arctic char may have been the most commonly consumed traditional foods in all three regions, the highest contribution of MeHg exposure came from beluga *nikku*, and beluga meat. Indeed, while not the most commonly consumed item, beluga meat contributed almost two-thirds of the MeHg intake among residents of the Hudson Strait region (and about a third in the other two regions). Beluga *mattaaq*, however, was not a major contributor to MeHg exposure but was the largest source of Se (ranging from 23% to 45% in the three regions).

To better define Se status in Nunavimmiut (Inuit of Nunavik) in relation to the consumption of marine foods, Achouba et al. (2019) quantified selenoneine (suspected of being a major Se source in marine foods) in archived red blood cells of Nunavimmiut along the Hudson Strait, and in beluga *mattaaq*, a traditional food known to be a major dietary source of Se for Nunavimmiut. Selenoneine was identified in red blood cells as the major Se species in Nunavimmiut and in beluga *mattaaq* (from the skin layer) from two locations in the Canadian Arctic (Arviat, Nunavut and the west coast of Hudson Bay). Further analysis found strong associations between the concentrations of total Se and selenoneine (Little et al., 2019). Self-reported consumption of beluga *mattaaq* was positively associated with whole blood concentrations of Se, and selenoneine concentration in red blood cells. When Nunavimmiut were grouped by tertile of beluga *mattaaq* consumption, it was found that those consuming more beluga *mattaaq* also had significantly higher concentrations of selenoneine in their red blood cells and total Se in whole blood; however, this trend was not observed for plasma Se concentrations, as selenoneine was not found in plasma.

3.6.2.3 Nunavut, Inuvialuit Settlement Region and Nunatsiavut

The Inuit Health Survey (2007–2008) measured blood concentrations of contaminants in 2172 Inuit from three main regions of the Canadian Arctic (Inuvialuit Settlement Region, Nunavut, Nunatsiavut) and collected dietary survey information. This information was used to identify which traditional foods contributed most to the dietary intake of Hg and Se for Inuit participants (Laird et al., 2013). Dietary intakes were calculated from dietary survey information and concentrations of Hg in traditional foods, based on contaminant databases for traditional foods (Chan et al., 1998).

Estimated dietary intakes of Hg and Se (based on Musing Monte-Carlo simulations using the Crystal Ball model) were significantly correlated to their respective blood concentrations in Inuit participants. Mean dietary intake of Hg was 7.9 μg/kg per week for participants from all three regions, which is over the Health Canada Toxicological Reference Value of 5 μg/kg per week (35% of participants exceeded this value). Based on Monte-Carlo simulations, the primary traditional food sources of Hg were ringed seal liver, Arctic char meat, beluga *muktuk*, ringed seal meat and caribou meat. Ringed seal liver was responsible for a disproportionately large amount of Hg intake (59%) compared to other food sources despite only being consumed in small quantities (in terms of weight), and while only providing 19% of Se intake. Consumption of Arctic char and beluga *muktuk* (skin and fat) provided 7.3% and 20% of Se intake, respectively, while only representing 8.4% and 4.1% of Hg intake, respectively.

Older Inuit (over 40 years of age) typically ate more traditional foods more frequently than younger Inuit, and men ate larger portions than women. In general, caribou and/or Arctic char were the most frequently consumed traditional food (by weight), although variations in consumption rates were observed in the three Inuit regions, along with the corresponding intakes of Hg and Se.

In the Inuvialuit Settlement Region, the major source of Se intake was beluga *mattaaq* (skin: 24%, skin and fat: 23%), while sources of Hg intake were more varied: beluga *muktuk* (skin only: 14%), Arctic char (11%), caribou (11%), whitefish (10%), beluga *muktuk* (skin and fat: 10%) and fish eggs (9%). For those Inuit with the highest dietary Hg intake, the main source of Hg was fish eggs (Chan et al., 2012a).

In Nunavut, the primary sources of Se intake were a combination of caribou meat (15%), beluga *muktaaq* (skin and fat: 14%), Arctic char (14%), beluga *muktaaq* (skin only: 13%), and ringed seal liver (13%). The primary source of Hg intake was ringed seal liver (25%), while Arctic char and caribou meat represented 18% and 14% of Hg intake, respectively (Chan et al., 2012b).

In Nunatsiavut, the primary dietary sources of Hg were ringed seal liver (23%) and Arctic char (20%), while the primary sources of Se were also Arctic char (27%) and ringed seal liver (22%) (Chan et al., 2012c).

3.6.3 Greenland

Greenlandic Inuit are primarily exposed to POPs through their reliance on a traditional diet of fish and marine mammals. Despite an increase in imported foods in the modern Greenlandic diet, traditional foods remain an important part of the diet (Deutch et al., 2007). Marine mammals at the top of the food chain are a significant source of exposure to many POPs.

A survey of the Greenlandic diet and measurement of serum levels of several POPs including several organochlorine pesticides, PCBs, and brominated flame retardants, illustrated the association between intake of Greenlandic food items and serum concentrations of these contaminants (Schaebel et al., 2017). Median concentrations were calculated for participants with different dietary intakes of traditional foods (<20%, 20–39%, 40–59%, 60–79%, 80% traditional Greenlandic diet). Statistically higher concentrations of organochlorine pesticides, PCBs and PBDEs were observed among participants who consumed more foods that are traditional. Recent studies show that the intake of traditional food including marine mammals has declined among pregnant ACCEPT women (2010–2015) (Knudsen et al., 2015; Terkelsen et al., 2018); however, POP levels are still higher in women with the highest intake of traditional marine food.

3.6.4 Russia

Consumption of traditional/country foods is common in many Indigenous communities in the Russian Arctic including but not limited to Aleuts, Chukchis, Chuvans, Dolgans, Enets, Siberian Yupik, Itelmens, Kamchadals, Koryaks, Nenets, Nganasans, Saami, and Yukaghirs. Which wildlife species and the proportions of each may vary across the Russian Arctic, but these country foods can be a major source of important nutrients and essential minerals, as well as a source of POPs and Hg and other toxic metals and elements.

3.6.4.1 Pechenga district of Murmansk Oblast

Dietary consumption of local foods and wildlife is the primary source of exposure to contaminants in the territories with point sources of pollution in the Arctic. The Pechenganickel industrial complex on the Russian Kola Peninsula (Murmansk Oblast), located near the border between Norway, Finland, and Russia, in Nickel town along with the briquetting facility in the town of Zapolyarny, approximately 25 km from the smelter, comprises one of the largest Ni–Cu smelters in the world (Hansen et al., 2017). As part of the trilateral KolArctic project *Food and Health Security in the Norwegian, Russian and Finnish border regions: linking local industries, communities and socio-economic impacts 2012-2015*, a study was developed to assess the impact of emissions from the Ni–Cu smelter in the Pechenganickel complex on concentrations of metals in commonly used local wild foods. Sampling of local foods took place in 2013–2014 at 41 sites in Russia, Norway and Finland, at various distances from the Pechenganickel complex, and included fish, game, wild and garden berries, vegetables and mushrooms (Dudarev et al., 2015a,b; Hansen et al., 2017).

POPs in local foods

Concentrations of POPs including HCB, PCBs and DDTs were measured in Russian wildlife, including game and fish, collected in autumn 2013 in the Pechenga district of Murmansk Oblast. HCHs, TetraCBs, PentaCBs, chlordanes, aldrin and mirex were below the limit of detection in all local foods sampled. Concentrations of several POPs in local foods are presented in Figure 3.15.

Mean concentrations of ΣDDT were highest in king salmon (4.5 µg/kg ww), followed by whitefish and burbot (3.7 µg/kg ww), while other species were much lower (<1.7 µg/kg ww); all DDT concentrations were far below Russian maximum permissible concentrations. Concentrations of DDE and DDT in moose and birds were also low, although the low DDE:DDT ratios in moose, grouse and ptarmigan indicate potentially recent exposure, compared to the high DDE:DDT ratios in most fish species measured, which indicate 'old' exposure.

Mean concentrations of HCB in all samples of game, freshwater fish and marine cod were <0.25 µg/kg ww, except for migratory king salmon (0.82 µg/kg ww). This trend was also noted among PCB concentrations. ΣPCBs in most samples were between 1.2 and 4.3 µg/kg ww, while concentrations in king salmon were up to 9 µg/kg ww, although still much below Russian maximum permissible concentrations for fish. While most samples had similar concentrations of congeners PCB118, PCB138 and PCB153, concentrations of PCB138 were significantly higher than for other congeners in king salmon. In general however, concentrations of POPs were very low in all food samples measured and would be considered a minor contribution to total exposure to contaminants (Dudarev et al., 2015b).

Metals in local foods

Concentrations of metals in local foods are presented in Figure 3.16. Mushrooms were observed to accumulate high concentrations of toxic elements, and should be considered as the main 'sorbents' of the majority of metals measured, and as the main food contributor to human exposure to metals.

Mean lead concentrations in all Russian samples of the local fauna and flora were low (<0.05 mg/kg ww), except for milky-cap mushrooms and ptarmigan (up to 0.2 mg/kg ww) (Dudarev et al., 2015a).

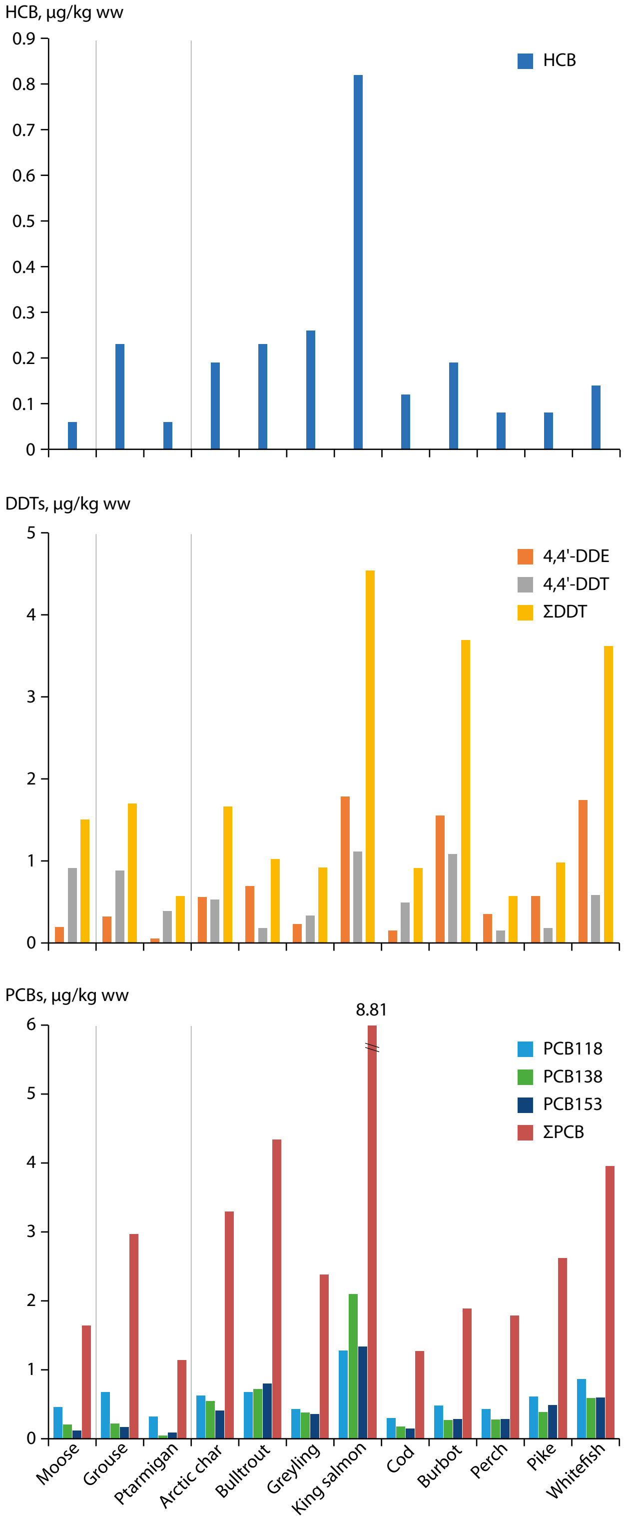


Figure 3.15 Concentrations of HCB, DDTs and PCBs in local food collected in the Pechenga district of Murmansk Oblast. Samples are pooled and data presented as mean concentrations (adapted from Dudarev et al., 2015b).

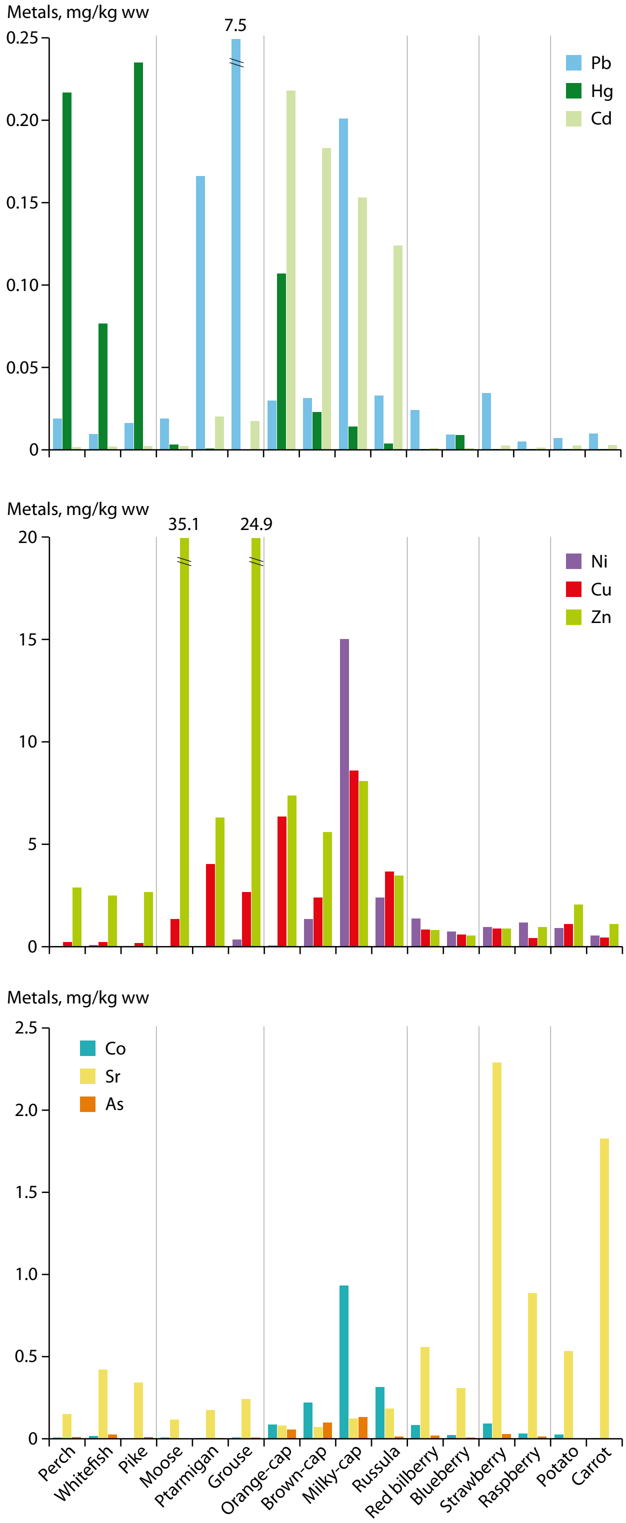


Figure 3.16 Concentrations of metals (Pb, Hg, Cd, Ni, Cu, Co, Sr and As) in local foods collected in the Pechenga district of Murmansk Oblast. Samples are pooled and data presented as mean concentrations (adapted from Dudarev et al., 2015a).

Mercury levels in samples of meat, poultry, wild and garden berries and vegetables were very low (<0.003 mg/kg ww); in all mushroom species the mean Hg concentrations were <0.02 mg/kg ww, except for orange-cap boletus (0.11 mg/kg ww). Hg levels in marine cod and migratory great salmon were <0.025 mg/kg ww. Concentrations of Hg were highest in freshwater fish samples, and increased in the sequence: Arctic char and grayling (maximum 0.05 mg/kg ww), burbot (maximum 0.1 mg/kg ww), whitefish and bulltrout (up to 0.15 mg/kg ww), perch (up to 0.37 mg/kg ww), and pike (up to 0.52 mg/kg ww).

Cadmium levels in samples of fish, meat, poultry, wild and garden berries and vegetables were very low (<0.002 mg/kg ww). In all mushroom species the Cd content was above 0.1 mg/kg ww, and in orange-cap boletus reached as high as 0.32 mg/kg ww.

Arsenic levels in samples of meat, poultry, wild and garden berries, and vegetables were <0.01 mg/kg ww; in all mushrooms the As content was <0.15 mg/kg ww. Concentrations of As were highest in marine cod and migratory great salmon (0.45 and 0.75 mg/kg ww, respectively) and in freshwater fish were 15- to 25-fold lower (<0.03 mg/kg ww).

Nickel levels in all fish (freshwater, migratory, marine) were <0.2 mg/kg ww, in moose and ptarmigan <0.1 mg/kg ww; in wood grouse 0.35 mg/kg ww. Ni concentrations in wild berries ranged up to 2.3 mg/kg ww, in garden berries up to 1.2 mg/kg ww, and in potato and carrot up to 0.7 mg/kg ww. Mean concentrations of Ni were highest in mushrooms: nearly 1.4 mg/kg ww in brown and orange-cap boletus, 2.4 mg/kg ww in russula, and 15 mg/kg ww in milky-caps.

Copper levels in fish were in the range 0.2–0.7 mg/kg ww; in meat and poultry, 1.4–4.1 mg/kg ww; and in wild and garden berries and vegetables, 0.4–1.6 mg/kg ww. Concentrations of Cu were highest in mushrooms: up to 2.4 mg/kg ww in brown-cap boletus, 3.7 mg/kg ww in russula, 7.4 mg/kg ww in orange-cap boletus, and up to 8.6 mg/kg ww in milky-caps.

Cobalt levels in all samples of flora and fauna, except mushrooms, were <0.1 mg/kg; the highest concentration for mushrooms was in milky-caps (0.95 mg/kg). Strontium was present in all foods in the range 0.1–0.6 mg/kg, with the maximum concentration found in strawberry and carrot (2–2.5 mg/kg). Manganese in wild berries (20–50 mg/kg ww) was 20-fold higher than in garden berries, vegetables, mushrooms, meat and poultry. Concentrations of Mn in fish did not exceed 0.3 mg/kg. Chromium and vanadium in all samples of flora and fauna were very low, in many samples below the detection limit (Dudarev et al., 2015a). Exceedances of Russian MALs (maximum allowable levels) for metals in local foods in the Pechenga district of Murmansk Oblast are presented in Chapter 5.

Another important task of the Russian part of the KolArctic project was the analysis of metals (using the same list of metals as for the food analyses) in drinking water in Nickel and Zapolyarny, because the daily intake of contaminants reflects intake through food and drinking water. Samples of the centralized piped drinking water (as well as water from neighboring lakes used as water sources) in both towns were highly contaminated by Ni due to proximity to ore mining and processing enterprises. The Ni concentration in drinking water was 43–64 µg/L which is 2- to 3-fold higher than the Russian MPC (maximum permissible concentration) (Doushkina et al., 2015).

Comparison of metals in foods between the border regions of Norway, Finland, and Russia

In berries and mushrooms, except for Pb, Cd, and Hg in mushrooms, concentrations of all toxic elements investigated were highest at sites closest to the Ni–Cu smelter and generally decreased with distance in a northeastern direction. This decrease in concentration with distance was strongest for Ni, As, and Co, which clearly shows the Ni–Cu smelter as a source of these toxic elements in berries and mushrooms (Hansen et al., 2017). Compared to the border regions of Norway and Russia, samples from the border region of Finland had lower concentrations of Ni, As, and Cd in some berries. Of all the food groups, mushrooms had the highest concentrations of all metals except Hg (Hansen et al., 2017).

In game meat, concentrations of As in reindeer samples from Pasvik (Norwegian border region 20 km northwest of Nickel) were 2.4-fold higher than in Paistunturi (Finland region 160 km northwest of Nickel); however, a reverse spatial trend was observed for Pb and Cd with concentrations in Paistunturi 2.8- to 3.5-fold higher than in Pasvik. Too few samples were collected for a more detailed spatial assessment.

Spatial trends of metals varied for the different local foods and wildlife, although results clearly indicate that metals emitted from the Ni–Cu smelter are present in these local foods in the border region between Norway, Finland and Russia (Hansen et al., 2017).

3.6.4.2 Nenets Autonomous Okrug

There has been limited information on POPs and metals in some parts of the Russian Arctic; however, recent studies in the Nenets Autonomous Okrug of the Russian Arctic have measured concentrations of contaminants in fish consumed by local Indigenous People. Fish species were selected based on a nutritional survey among the population of Indiga (Sobolev et al., 2019a), with samples collected in 2017–2018 for POPs analysis. The predominant POPs were PCBs and DDT metabolites (primarily *p,p′*-DDE), and Arctic char and pink salmon were found to have the highest ΣPCB concentrations (1.58 and 1.54 µg/kg ww, respectively), while the lowest mean concentrations were found in northern pike muscle (0.32 µg/kg ww) (Lakhmanov et al., 2020). The predominant PCB congener measured in all fish species except northern pike was PCB153. Concentrations of ΣPCB in northern pike in this study were approximately 4-fold lower than in pike from the Kola Peninsula and 7-fold lower than in pike from the Chukotka Peninsula (Lakhmanov et al., 2020). The main DDT metabolite measured was *p,p′*-DDE among all fish species, with the highest average concentrations found in pink salmon (1.61 µg/kg ww). Positive correlations were found between POPs and fat content, with higher POPs concentrations in fatty fish (pink salmon, Arctic char) than less fatty fish (northern pike, humpback whitefish).

Seven of the most commonly consumed species, as mentioned on food frequency questionnaires collected from three Nenets villages, were sampled and analyzed for metals (Sobolev et al., 2019b). Fish were sampled in the Pechora River and Indiga River, and the species collected included inconnu, northern pike, roach, Arctic char, navaga (cod), pink salmon and humpback whitefish. The highest Hg concentrations were found in muscle of northern pike (arithmetic mean 188 µg/kg), which was 2-fold higher than for roach (arithmetic mean 94 µg/kg), and 3- to 4-fold higher than other fish species measured. Arithmetic mean concentrations of Se were highest in navaga, followed by pink salmon and Arctic char. Se:Hg ratios were highest in pink salmon, followed by Arctic char and navaga. Average concentrations of metals measured (except for Ni) in Arctic char, pink salmon, and navaga were significantly different to less anadromous fish (Sobolev et al., 2019b).

3.6.4.3 Coastal Chukotka

A community-based dietary and lifestyle survey was undertaken in spring 2016 in the Providensky district of eastern coastal Chukotka (settlements of Enmelen, Nunligran, and Sireniki) (Dudarev et al., 2019a,b,c) alongside sampling of local foods for analysis of environmental POPs and metals.

POPs

Concentrations of POPs were very low in fish, and land and marine mammal meat compared to concentrations measured in marine mammal blubber: ΣHCH (90 µg/kg ww), ΣCHL (70 µg/kg ww), ΣDDT (100 µg/kg ww), HCB (200 µg/kg ww), ΣPCB_{15} (150 µg/kg ww), mirex (10 µg/kg ww), and pentachlorobenzene (3.7 µg/kg ww). None of the POPs analyzed exceeded allowable limits (Dudarev et al., 2019b).

In the context of the summarized POPs data, gray whale blubber and *mantak* (a Yupik name for the layer of whale skin with a thin layer of adjacent blubber) was the most contaminated of the marine mammal fatty tissues studied, characterized by the highest levels of HCHs, chlordanes and HCB, and some of the highest levels of DDTs and PCBs (although DDTs and PCBs were higher in seal blubber). Whale blubber and *mantak* contained high levels of β-HCH (up to 70–80 µg/kg ww), heptachlor epoxide (up to 12 µg/kg ww), *trans*-chlordane (up to 25 µg/kg ww), and oxychlordane (up to 5.2 µg/kg ww), which were very low in the other marine mammal tissues analyzed. *Trans*-nonachlor levels were high only in whale blubber and *mantak* (21 and 35 µg/kg ww, respectively) and in seal blubber (up to 30 µg/kg ww). Whale blubber and *mantak* did not contain mirex (found in seals, bearded seals and walrus) or pentachlorobenzene (found in ringed seals and bearded seals).

Blubber from ringed and spotted seals was the second most contaminated tissue, although levels of DDTs, PCBs and pentachlorobenzene were the highest of the marine mammal species studied. Bearded seal blubber had relatively low levels of HCHs, chlordanes and HCB, but higher levels of DDTs, PCBs and pentachlorobenzene compared to some other marine mammal species. Walrus blubber was the least contaminated of the marine mammal blubbers analyzed, with the lowest levels of all POPs except mirex, for which concentrations were highest in walrus blubber at 7–10 µg/kg. The DDE/DDT ratio was high in all blubbers (ranging from 7 to 50), suggesting that DDT contamination of all marine mammals was 'old'.

Studies of the estimated daily intakes of POPs showed that over 90% of the dietary exposure of local people to POPs was due to the consumption of marine mammal blubber.

Temporal changes in the levels of POPs in local foods identified in the present study and the coastal Chukotka study (15 years ago in Uelen settlement) indicate that, against the backdrop of falling (or stable) levels for most POPs, there is a tendency for rising levels of HCB, mainly in marine mammals. These observations are generally consistent with the circumpolar and global decline in levels of the majority of POPs in marine, freshwater, and terrestrial biota over recent decades.

In terms of regional variation, POPs in marine mammals (pinnipeds and cetaceans) sampled in Chukotka were generally far lower than in the corresponding species sampled in Alaska and northern Canada. Owing to the transport of Yukon River discharge by the Alaska Coastal Current from the Bering Sea and along the Alaskan coast to the Beaufort Sea (where contamination is higher due to discharges from the Mackenzie River), the food base for marine mammals in Chukotka coastal waters is less contaminated by POPs (and other pollutants) than in Alaskan and northern Canada coastal waters.

Analysis of additional sources of in-home food contamination (home-brewed alcohol, domestic insecticides, wash-outs from the kitchen walls) reveals relatively high levels of HCHs, DDTs and PCBs, which although lower than in coastal Chukotka 15 years ago, still represent a share of the dietary exposure of local people to POPs (Dudarev et al., 2019b).

Metals

Fish (marine, migratory, freshwater), terrestrial mammals (reindeer, hare), marine mammals (meat and blubber of whale, walrus, and seals), mushrooms, berries, wild plants, seaweeds, ascidians, and mussels sampled in the three communities on the Chukchi Peninsula were analyzed for 18 metals (Pb, As, Cd, Hg, Cu, Zn, Ni, Cr, Al, Mn, Ba, Sr, Co, V, Be, Mo, Sn, Sb). Concentrations of Pb and Hg were generally low in all foods, with the highest Hg concentrations found in fish and marine mammal meat (up to 0.1 mg/kg ww), while Pb was highest in land mammal meat (up to 2.3 mg/kg ww). Cadmium concentrations were highest in seafood (up to 2.9 mg/kg ww), with As concentrations highest in marine fish (up to 4 mg/kg ww), marine mammal blubber (up to 3.7 mg/kg ww) and seafood (up to 14 mg/kg ww). Wild plants (particularly *Rhodiola arctica*) were found to accumulate several metals, including Mn (up to 190 mg/kg ww), Al (up to 75 mg/kg ww), Ni, Ba, and Sr. Seafood is a powerful accumulator of certain metals: seaweed (*Laminaria saccharina*) contains very high levels of As (up to 14 mg/kg ww) and Sr (up to 310 mg/kg ww); ascidians (particularly *Halocynthia aurantium*) are contaminated by Cr, Sr, and Al (up to 560 mg/kg ww); blue mussel accumulates significant levels of Cd (up to 2.9 mg/kg ww) and Al (up to 140 mg/kg ww). The present study in the communities of the Chukchi Peninsula is the first to report contamination levels of wild plants and seafood (seaweed, blue mussels, ascidians) by 18 metals in the coastal region of the northern Bering Sea.

Comparison of Hg, Pb and Cd concentrations in land and marine mammals in the settlements of Enmelen, Nunligran and Sireniki in spring 2016 with measurements from 2001 in the coastal Chukotkan Uelen settlement revealed little change for marine mammal blubber, but a general decline in concentrations for fish and marine mammal muscle.

While consumption of marine mammal blubber was the main exposure route for POPs, dietary exposure to metals was primarily from fish, seafood, wild plants, mammal meat and fowl (Dudarev et al., 2019c). Estimated daily intakes (EDIs) and exceedances over Russian MALs for metals in local foods in coastal Chukotka are presented in Chapter 5.

Table 3.55 Concentrations of POPs in pooled blood plasma samples from pregnant women. Data are presented as geometric means (95% CI), organochlorines, PCBs and PBDEs are presented in µg/kg plasma lipids. Source: Caron-Beaudoin et al. (2019).

	Nunavik	Iceland	Norway	Sweden	Finland
Years	2013	2014–2015	2014–2015	2015–2016	2014
Sample size (pooled)	n=5	n=5	n=5	n=5	n=5
Aroclor 1260	425 (328–521)	135 (105–165)	103 (88.2–119)	98.8 (91.6–106)	94.3 (52.4–136)
PCB74	2.79 (1.93–3.66)	<LOD	<LOD	<LOD	<LOD
PCB99	9.78 (8.50–11.1)	<LOD	<LOD	<LOD	<LOD
PCB101	1.68 (1.13–2.22)	<LOD	<LOD	<LOD	<LOD
PCB105	1.82 (1.45–2.18)	<LOD	<LOD	<LOD	<LOD
PCB118	8.44 (7.08–9.79)	3.46 (2.81–4.11)	2.24 (1.82–2.67)	2.06 (1.95–2.16)	2.52 (0.498–4.54)
PCB138	24.3 (20.2–28.4)	8.51 (6.71–10.3)	6.35 (5.64–7.06)	6.66 (6.18–7.14)	5.99 (3.20–8.78)
PCB153	57.5 (43.2–71.9)	17.4 (13.4–21.5)	13.7 (11.1–16.2)	12.3 (11.2–13.5)	12.3 (6.84–17.7)
PCB156	1.87 (1.22–2.52)	<LOD	<LOD	<LOD	<LOD
PCB170	7.79 (5.53–10.1)	3.56 (2.65–4.48)	3.19 (2.57–3.81)	3.27 (2.75–3.78)	2.96 (2.07–3.84)
PCB180	24.9 (17.6–32.2)	9.95 (7.10–12.8)	8.39 (6.55–10.2)	7.41 (6.27–8.55)	7.38 (5.05–9.71)
PCB183	3.35 (2.77–3.94)	<LOD	<LOD	<LOD	<LOD
PCB187	12.4 (10.4–14.3)	3.15 (2.27–4.03)	2.7 (2.24–3.17)	2.01 (1.80–2.22)	2.08 (1.13–3.04)
PCB194	4.47 (2.86–6.08)	<LOD	<LOD	<LOD	<LOD
PCB203	2.54 (1.93–3.16)	<LOD	<LOD	<LOD	<LOD
Dieldrin	10.8 (9.20–12.3)	<LOD	<LOD	<LOD	<LOD
cis-Nonachlor	8.83 (7.69–9.96)	0.744 (0.396–1.09)	<LOD	<LOD	<LOD
trans-Nonachlor	57.8 (49.4–66.2)	3.9 (2.76–5.03)	2.07 (1.65–2.49)	1.06 (0.927–1.19)	1.87 (0.730–3.02)
Oxychlordane	33 (26.7–39.2)	2.18 (1.69–2.67)	1.29 (1.09–1.49)	0.714 (<LOD–0.934)	1.23 (0.560–1.91)
p,p′-DDE	170 (144–195)	28.7 (22.2–35.2)	20.1 (16.4–23.8)	15.3 (13.6–16.9)	23.1 (5.76–40.5)
HCB	27.4 (23.8–30.9)	11 (9.31–12.6)	7.96 (6.95–8.97)	7.8 (6.82–8.78)	10.4 (7.52–13.3)
Heptachlor epoxide	5.03 (4.36–5.70)	<LOD	<LOD	<LOD	<LOD
β-HCH	3.77 (3.22–4.33)	2.85 (2.49–3.21)	<LOD	<LOD	3.6 (<LOD–8.77)
Mirex	4.64 (3.43–5.84)	<LOD	<LOD	<LOD	<LOD
Toxaphene Parlar 26	8.352 (7.11–9.60)	<LOD	<LOD	<LOD	<LOD
Toxaphene Parlar 50	13.2 (11.1–15.2)	1.18 (0.987–1.37)	<LOD	<LOD	<LOD
PBDE47	15.3 (<LOD–31.4)	<LOD	<LOD	<LOD	<LOD
PBDE99	9.78 (<LOD–24.2)	<LOD	<LOD	<LOD	<LOD
PBDE153	3.86 (3.22–4.49)	<LOD	<LOD	<LOD	<LOD
PBDE209	<LOD	<LOD	<LOD	4.5 (3.45–5.56)	<LOD

LOD: limit of detection; values below the LOD were treated as LOD/2 for calculating the mean.

Table 3.56 Concentrations of PFASs in pooled blood plasma samples from pregnant women. Data are presented as geometric means (95% CI), PFASs in μg/L plasma. Source: Caron-Beaudoin et al. (2019).

Region	Nunavik	Iceland	Norway	Sweden	Finland
Years	2013	2014–2015	2014–2015	2015–2016	2014
Sample size (pooled)	n=5	n=5	n=5	n=5	n=5
PFBA	<LOD	<LOD	<LOD	0.184 (0.104–0.264)	<LOD
PFDA	0.418 (0.336–0.500)	0.284 (0.245–0.323)	0.35 (0.203–0.497)	0.346 (0.176–0.516)	0.418 (0.336–0.500)
PFNA	2.64 (2.46–2.82)	0.54 (0.472–0.608)	0.554 (0.326–0.782)	0.574 (0.358–0.790)	1.5 (0.962–2.03)
PFOA	0.702 (0.626–0.778)	1.04 (0.890–1.19)	1.298 (0.548–2.05)	0.906 (0.695–1.12)	1.84 (1.45–2.24)
PFUnDA	0.85 (0.714–0.986)	0.316 (0.277–0.355)	0.264 (0.187–0.341)	0.246 (0.093–0.399)	0.298 (0.226–0.370)
PFHxS	0.366 (0.323–0.409)	0.258 (0.240–0.276)	0.4 (0.345–0.455)	0.572 (0.358–0.786)	1.98 (0.622–3.33)
PFOS	4.68 (4.09–5.27)	2.9 (2.19–3.62)	3.54 (2.92–4.17)	2.9 (2.12–3.68)	2.58 (2.18–2.98)

LOD: limit of detection; values below the LOD were treated as LOD/2 for calculating the mean.

3.7 MercuNorth

The MercuNorth project was created to establish baseline Hg levels across several Arctic regions for the purpose of assessing long-term Hg trends and the effectiveness of the Minamata Convention, which was ratified in 2017 (Adlard et al., 2021). Blood samples were collected from 620 pregnant women (aged 18 to 44 years) between 2010 and 2016 from sites across the circumpolar Arctic, including Alaska (USA), Nunavik (Canada), Greenland, Iceland, Norway, Sweden, northern Lapland (Finland) and Murmansk Oblast (Russia). Concentrations of Hg across these regions were reported by Adlard et al. (2021). Hg exposure during pregnancy was highest in Nunavik and Greenland (geometric mean: 5.20 μg/L and 3.79 μg/L, respectively), followed by Alaska (2.13 μg/L), compared to the other circumpolar regions (which ranged between 0.48 and 1.29 μg/L). Concentrations in Alaska, Nunavik, and Greenland were also significantly different from each other and all other Arctic regions (p <0.0001). Despite the higher concentrations in Nunavik, Alaska and Greenland, blood Hg concentrations have significantly declined since 1992, 2000, and 2010, respectively. Concentrations of Hg in Iceland, Norway, and Russia were similar and not significantly different from each other (p >0.05), and levels were lowest in Sweden although they were not significantly different from Finland (p-value = 0.0569). Pregnant Swedish women from Kiruna in 2015–2016 had the lowest mean Hg concentrations of all the regions (geometric mean: 0.48 μg/L).

While the MercuNorth study was originally designed to establish baseline levels of Hg in pregnant women across the Arctic prior to the Minamata Convention, pooled samples were prepared from five of the Arctic countries and considered for POPs analysis (Caron-Beaudoin et al., 2019a). A total of 240 individual plasma samples were available from Iceland, Norway, Finland, Sweden and Nunavik (n=36, n=50, n=25, n=51, n=78, respectively), and samples from each country were used to establish five pooled samples per country (randomly selected individual samples) for a total of 25 pooled samples across all regions. Samples were analyzed for organochlorines, dioxins, PBDEs and PFASs. The results of these analyses are presented in Tables 3.55, 3.56, and 3.57, with organochlorines, PBDEs and dioxins presented as lipid-adjusted concentrations (μg/kg lipids; ng/kg for dioxins), and PFASs presented as blood plasma concentrations (μg/L).

Comparison of PCB concentrations, including total PCBs (Aroclor 1260), across countries indicates that Nunavik women exhibit far higher exposure levels than women from other participating countries (Aroclor 1260 was approximately 4-fold higher in Nunavik). Similar to PCBs, the highest plasma concentrations of other organochlorines were measured in Nunavik. For some organochlorines, differences between Nunavik and other Arctic regions were even greater than observed for PCBs. For example, mean concentrations of *trans*-nonachlor in Nunavik were nearly 15-fold higher than in Iceland (57.8 vs 3.9 μg/kg lipids). In contrast to PCBs and organochlorines, concentrations of PCDD/F congeners were generally lower in Nunavik and higher in Iceland and Finland.

Concentrations of PFOS, PFNA and PFUnDA were higher in the Nunavik pooled samples than levels measured in samples from the other circumpolar Arctic countries. In contrast, concentrations of PFOA were lower in the Nunavik samples than in samples from the other circumpolar countries. Some differences were noted among Arctic countries; while PBDE47, PBDE99 and PBDE153 were only detected in Nunavik samples, PBDE209 was only detected in Swedish samples.

The POPs data should be interpreted with caution, since the results were based on pooled samples with a small sample size (n=5 per country), and concentrations of contaminants were below the limit of detection in many samples. While it is important to continue the monitoring of legacy contaminants, it is also important to screen for POPs of emerging Arctic concern. Future work could also explore use of targeted and non-targeted screening of samples to identify potential new compounds of interest.

Table 3.57 Concentrations of dioxins and furans in pooled blood plasma samples from pregnant women. Data are presented as geometric means (95% CI), dioxins and furans in ng/kg plasma lipids. Source: Caron-Beaudoin et al. (2019).

	Nunavik	Iceland	Norway	Sweden	Finland
Years	2013	2014–2015	2014–2015	2015–2016	2014
Sample size (pooled)	n=5	n=5	n=5	n=5	n=5
2378-TCDF	<LOD	1.43 (1.16–1.69)	<LOD	<LOD	<LOD
12378-PeCDF	<LOD	0.907 (<LOD–1.31)	<LOD	<LOD	<LOD
23478-PeCDF	1.13 (1.10–1.16)	2.76 (1.91–3.61)	2.25 (1.78–2.72)	2.16 (1.63–2.70)	2.89 (1.73–4.05)
123478-HxCDF	<LOD	1.25 (0.818–1.68)	<LOD	<LOD	1.18 (0.785–1.58)
123678-HxCDF	<LOD	1.44 (1.25–1.62)	<LOD	0.9 (0.824–0.976)	1.13 (0.586–1.67)
1234678-HpCDF	1.53 (1.27–1.79)	3.17 (2.66–3.67)	2.41 (1.45–3.37)	2.73 (2.44–3.03)	7.07 (2.05–12.1)
123678-HxCDD	4.1 (3.77–4.42)	1.86 (1.47–2.25)	2.01 (0.985–3.04)	1.57 (1.20–1.95)	3.96 (2.73–5.19)
1234678-HpCDD	5.33 (4.92–5.75)	6.51 (5.51–7.51)	6.05 (4.11–7.99)	5.69 (5.27–6.11)	11.6 (8.25–15.0)
OCDD	60.2 (55.2–65.1)	94 (81.1–107)	75 (61.8–88.2)	59.4 (55.8–63.0)	128 (94.2–162)

LOD: limit of detection; values below the LOD were treated as LOD/2 for calculating the mean.

3.8 Global comparisons

This section reports comparisons of Arctic data with biomonitoring data from other regions of the world to provide international context to the levels of contaminants observed in the Arctic. A compilation of available literature presenting data from a mixture of national biomonitoring surveys, and birth cohort, regional and targeted biomonitoring studies was conducted to provide relevant data for comparison. To provide a relevant comparison within a similar time frame (so that the timing of sampling would have minimal impact on comparisons of observed concentrations), datasets collected between 2010 and 2018 were selected. Biomonitoring data from several regions across the globe are presented in Tables 3.58 (organochlorines), 3.59 (PFASs) and 3.60 (Hg).

3.8.1 PCB153

Historically, North America and Europe were the principal producers and users of PCBs. This usage pattern is apparent in global PCB body burdens. Mean PCB153 concentrations in pooled serum samples from NHANES are typically between 5 and 50 μg/kg, with some older populations maintaining higher mean body burdens (CDC, 2019). Studies of adult populations in the Czech Republic, Belgium and Germany report median PCB153 concentrations of 79.4, 53.78, and 34 μg/kg, respectively (Fromme et al., 2015; Pirard et al., 2018). PCB153 concentrations from other areas of the world including New Zealand and Central America are typically below 10 μg/kg in the absence of a point source of exposure (Ochoa-Martinez et al., 2016; Coakley et al., 2018).

PCB153 concentrations in the Arctic are at the high end of the range reported worldwide, but not entirely outside the ranges seen worldwide. The mean PCB153 concentration in Faroese cord blood samples was 101 μg/kg with a range of up to 1227 μg/kg while in children the mean was 54.9 μg/kg with a range of up to 1030 μg/kg. In adult Greenlandic populations, the mean PCB153 concentration ranged from 65.6 to 667 μg/kg depending on sampling location, with most mean concentrations below 100 μg/kg. The maximum reported concentration across all Greenlandic sampling locations was 2700 μg/kg. In pregnant Inuit women from Nunavik, the mean PCB153 concentration was 30 μg/kg with a range of up to 190 μg/kg, whereas in Inuit adults, the mean concentrations were 50 and 56 μg/kg for men and women, respectively, with ranges of up to 2110 μg/kg. First Nations populations in Canada as measured by the FNBI (Assembly of First Nations, 2013) had slightly lower PCB153 concentrations, with means of 18 and 14 μg/kg in men and women, respectively.

While there is a range of exposure in the Arctic, certain sub-populations maintain high PCB body burdens despite a general downward trend in exposure. PCB153 exposure among Faroese, Nunavik and Greenlandic populations are not dissimilar to a Slovakian population exposed to industrial PCB contamination. The mean concentration of PCB153 reported in the Slovakian population was 204.37 μg/kg with a 95th percentile of 962 μg/kg. A similar industrially exposed population in Anniston Alabama exhibited a geometric mean concentration of 176 μg/kg and a 95th percentile of 1070 μg/kg (Pavuk et al., 2014). While mean PCB153 concentrations in the Arctic are lower than those in industrially exposed populations, the high end of the ranges of exposure are similar.

Table 3.58 Comparative PCB153, *p,p'*-DDE and PBDE47 geometric mean concentrations in adult men, women and pregnant women across the globe from 2010–2018 (µg/kg lipid weight).

Country	Population	Mean age (range)	Years	n	Matrix	PCB153, µg/kg lw	DDE, µg/kg lw	PBDE47, µg/kg lw	Source
Germany	Men and women	42[a] (4–76)	2013	70	Whole blood	55[a]		0.597[a]	Fromme et al., 2015
USA	Men and women	(18–39)	2013	409	Serum	11.3	90.8		Savadatti et al., 2019
Czech Republic	Men and women	(18–65)	2015	300	Whole blood	71.6	101		NIPH, 2016
Lebanon	Men and women	25.6 (17–65)	2013–2015	316	Serum	3.0	18.90		Helou et al., 2019
New Zealand[b]	Men and women		2011–2013	49	Serum	11	220	2	Coakley et al., 2018
Belgium	Men and women	58.2 (49.8–65.8)	2014	201	Serum		224		Schoeters et al., 2017
Mexico	Men and women	40.5 (20–60)	2010	123	Serum	1.9		1.4	Orta-Garcia et al., 2014
China	Men and women	33.4 (19–55)	2010–2011	124	Serum			0.24[a]	Huang et al., 2014
	Women	50.3 (25–777)	2014	32	Serum			4.44	Wang et al., 2016
USA[c]	Women	20–39	2013–2014	[b]	Serum	6.92[a]	72.3[a]	19.1[a]	CDC, 2019
USA[d]	Women	20–39	2013–2014	[b]	Serum	5.3[a]	79.9[a]	17.3[a]	CDC, 2019
USA[e]	Women	20–39	2013–2014	[b]	Serum	10.6[a]	397[a]	15.7[a]	CDC, 2019
USA[f]	Women	20–39	2013–2014	[b]	Serum	11.5[a]	275[a]	13.8[a]	CDC, 2019
USA	Pregnant women	24.9 (16–42)	2011–2012	36	Serum			25.75	Zota et al., 2013
Denmark	Pregnant women	28.1 (18–40)	2011–2014	73	Serum		32.12		Rosofsky et al., 2017
Arctic									
Faroe Islands	Men and women	28	2013–2016	703	Plasma	101	189		Petersen pers. comm., 2019
Alaska	Women	28 (18–45)	2013–2014	47	Serum			10.4	Byrne et al., 2017
Russia	Women	45.2 (26–65)	2013	32	Serum	26.8	139.3		Dudarev et al., 2016a
Canada (NWT)	Women	49.2 (18–80)	2016–2018	122	Serum	14	59	6	Ratelle and Laird pers. comm., 2019
Greenland	Pregnant women	27.5 (18–45)	2010–2015	491	Plasma	94.5[a]	226.5		Hjermitslev et al., 2020
Iceland	Pregnant women	31.6 (22–43)	2015	50	Plasma	16	21	1.9	Ólafsdóttir pers. comm., 2019
Canada (Nunavik)	Pregnant women	24 (15–38)	2017	97	Plasma	30	100	<LOD	Lemire and Blanchette pers. comm., 2019

[a]Arithmetic mean; [b]pooled samples; [c]non-Hispanic white; [d]non-Hispanic Black; [e]Hispanic; [f]Asian.

Importantly, unlike populations in industrialized areas, PCBs in most of the Arctic are primarily from atmospheric transport and bioaccumulation and therefore difficult to mitigate via environmental remediation.

3.8.2 *p,p'*-DDE

DDE exposure in the Arctic varies, but overall has greatly declined. In many Arctic populations, DDE body burdens are comparable to other areas of the world. However, exposure in some Arctic populations is at the high end of the observed range of exposure. Importantly, DDE exposure is elevated in the Arctic despite historically limited DDT usage in the region.

Mean DDE concentrations in Arctic populations are generally between 100 and 300 µg/kg. Mean DDE concentrations comparable to those in the Arctic have been reported in the general populations of Australia (218.6 µg/kg) and the Czech Republic (101 µg/kg) (Chen et al., 2017). Mean DDE concentrations in pooled serum from NHANES in the USA ranged from 40.4 µg/kg in adolescent non-Hispanic white females, to a high of 2320 µg/kg among Asian women over the age of 60 years (CDC, 2019). In both Europe and North

Table 3.59 Comparative PFAS geometric mean concentrations in adult men, women and pregnant women across the globe from 2010–2017 (µg/L).

Country	Population	Mean age (range)	Years	n	Matrix	PFOA, µg/L	PFNA, µg/L	PFOS, µg/L	Source
New Zealand[a]	Men and women	(19–64)	2011–2013	63	Serum	2.4	0.66	3.4	Coakley et al., 2018
Czech Republic	Men and women	(18–65)	2015	300	Whole blood	0.716	0.3	2.3	NIPH, 2016
Canada	Men and women	3–79	2016–2017	1055	Plasma	1.3	0.51	3.4	Health Canada, 2019
USA	Men and women	12+	2015–2016	1993	Serum	1.56	0.577	4.72	CDC, 2019
Denmark	Pregnant women	28.1 (18–40)	2011–2014	73	Serum	1.55	0.58	5.55	Rosofsky et al., 2017
China	Pregnant women	27 (19–38)	2013–2014	385	Serum	9.6[b]			Wang et al., 2018
	Pregnant women	28.4	2010–2013	369	Serum	39.27	0.78	4.25	Han et al., 2018
	Pregnant women	27.8	2012	981	Serum		1.79	10.78	Tian et al., 2018
Arctic									
Greenland	Pregnant women	27.5 (18–45)	2010–2015	499	Serum	1.22	1.39	10.8	Hjermitslev et al., 2020
Canada (Nunavik)	Pregnant women	24 (15–38)	2017	97	Serum	0.55	2.5	3.3	Lemire and Blanchette pers. comm., 2019
Alaska	Women	28 (18–45)	2013–2014	47	Serum	0.85	2.07	3.29	Byrne et al., 2017
Faroe Islands	Men and women	28	2013–2016	703	Plasma	1.23	0.94	6.27	Petersen pers. comm., 2019
Norway	Men and women	41 (20–66)	2013–2014	58	Whole blood	1.19[b]	0.43[b]	3.57[b]	Poothong et al., 2017

[a]pooled samples; [b]arithmetic mean.

Table 3.60 Comparative geometric mean mercury concentrations in adult men, women and pregnant women across the globe from 2010–2018 (µg/L).

Country	Population	Mean age (range)	Years	n	Matrix	Hg, µg/L	Source
Czech Republic	Men and women	(18–65)	2015	302	Whole blood	0.689	NIPH, 2016
Canada	Men and women	(20–39)	2016–2017	1037	Whole blood	0.55 (0.43–0.69)	Health Canada, 2019
USA	Men and women	All	2015–2016	4988	Whole blood	0.678	CDC, 2019
New Zealand	Men and women	19–64	2014–2016	304	Whole blood	1.646	Mannetje et al., 2018
Korea	Men and women	19–70+	2012–2014	6457	Whole blood	3.11	Choi et al., 2017
China	Men and women	0–60+	2016–2018	477	Whole blood	1.96	Zeng et al., 2019
Japan	Pregnant women	31 (22–46)	2015	17997	Whole blood	3.83	Nakayama et al., 2019
Arctic							
Greenland	Pregnant women	27.5 (18–45)	2010–2015	497	Whole blood	5.7	Bank-Nielsen et al. 2019
Iceland	Pregnant women	31.6 (22–43)	2015	50	Whole blood	1.29	Ólafsdóttir pers. comm., 2019
Faroe Islands	Men and women	28	2013–2016	703	Whole blood	3.93	Petersen pers. comm., 2019
Russia (Murmansk Oblast)	Women	45.2 (26–65)	2013	32	Whole blood	2.18	Dudarev et al., 2016a
Canada (Nunavik)	Pregnant women	24 (15–38)	2017	123	Whole blood	5.4	Lemire and Blanchette pers. comm., 2019

America, DDE body burden is strongly associated with age, with older populations tending to have higher concentrations; for example, mean DDE concentrations of 50.6 µg/kg in Belgian adolescents and 224 µg/kg in an adult population with a mean age of 58.2 years (Schoeters et al., 2017). It is likely this trend exists anywhere that DDT was historically used.

As already stated, DDE exposure among Arctic populations appears highly variable. First Nations populations in the NWT of Canada have DDE concentration at the low end of the range observed in North America. While the overall geometric mean concentration of DDE in Greenland (129 µg/kg) is slightly elevated compared to other Arctic regions, concentrations in eastern Greenland are exceptionally high, with a mean of 1037 µg/kg and range of 110 to 8800 µg/kg. This is comparable to DDE concentrations in Thailand, an area with both high fish consumption and relatively recent DDT usage. Mean DDE concentrations in a study of several hundred Thai adults were just over 1500 µg/kg in both men and women (Teeyapant et al., 2014).

3.8.3 PBDEs

The USA continues to maintain the highest body burdens of PBDEs globally. Mean concentrations of PBDE47 in pooled samples of blood serum from NHANES ranged from 8.0 to 38.7 µg/kg (CDC, 2019). Similar data from pooled serum samples in Australia reported a range in mean concentrations of 2.8–4.48 µg/kg (Toms et al., 2018). Several small biomonitoring studies in China reported mean or median concentrations below 5 µg/kg; similar or lower mean concentrations have been reported in Europe (Huang et al., 2014; Fromme et al., 2015).

Compared to the population of the USA, Arctic populations maintain relatively low body burdens of PBDEs. Mean concentrations of PBDE47 in Arctic populations are typically below 10 µg/kg, with most closer to 1–2 µg/kg. In contrast, Arctic Indigenous populations in Alaska have PBDE concentrations more similar to those in the contiguous United States than the rest of the Arctic. Mean PBDE47 and PBDE153 concentrations on St. Lawrence Island Alaska were reported to be 10.64 µg/kg and 7.28 µg/kg, respectively, in women. This suggests that the built environment and indoor exposure are important exposure routes in the Arctic USA despite the remote location.

3.8.4 PFASs

Arctic PFOA concentrations are comparable to those in developed nations (see Table 3.59). Mean concentrations are often 0–2 µg/L with 95th percentiles of 4–5 µg/L. Body burdens of PFOA in China are outside the range of exposure in other countries, with mean concentrations of 10–40 µg/L frequently reported (Bjerregaard-Olesen et al., 2017; Han et al., 2018; Tian et al., 2018). While there is high variation, PFOA body burdens in China appear to be approximately ten-fold higher than in Europe, the USA, Australia or any Arctic population. China is major producer and consumer of PFASs, and some populations in industrial areas have exceptionally high exposure to these compounds (Han et al., 2018).

In many areas of the Arctic, mean PFOS concentrations have declined and are now below 10 µg/L and similar to concentrations reported in many developed countries. Globally, mean PFOS concentrations are 1–10 µg/L and 95th percentiles as high as 20–30 µg/L are common. This is true for most developed countries including the USA, most of Europe, Australia, and many studies in China. Overall, most Arctic populations are similarly exposed to PFOS despite no local sources. Indeed, some populations in the Arctic may be exposed at levels above those in the general populations of the USA, Australia and European Nations. Specifically, PFOS concentrations in Greenland are higher than those of North America or Europe, with a geometric mean concentration of 9.06 µg/L, ranging up to 61.3 µg/L in pregnant women between 2010 and 2015. While not as pronounced as the trend for PFOA, the population of China is also highly exposed to PFOS. A large sample of Chinese adults reported a median concentration of 24 µg/L, and another study of young children in Guangdong China reported an arithmetic mean PFOS concentration of 50.8 µg/L with a maximum concentration of 1354 µg/L (Zhang et al., 2018).

Exposure to PFHxS in Arctic populations is broadly similar to that of the general populations of developed countries. Globally, mean PFHxS concentrations are generally below 1 µg/L in the absence of point source exposure; some populations have mean concentrations up to approximately 2 µg/L (CDC, 2019; Toms et al., 2019). A similar range is seen in the Arctic. Populations highly exposed to PFASs through water contamination have mean PFHxS concentrations of 2–5 µg/L often with 95th percentiles of 20 µg/L or above. Exposure in Arctic populations does not approach this range.

Concentrations of PFNA are elevated in the North American Arctic. Both Alaskan and Canadian Arctic biomonitoring studies show mean concentrations of several ng/ml in serum while studies of non-Arctic European and North American populations have mean concentrations below 1 ng/ml (Zhang et al., 2018; CDC, 2019). Interestingly, populations in northern Europe do not show the same increased concentration of PFNA, but do show a trend for higher PFUnDA (another long-chain PFAS) in Greenland where mean PFUnDA concentrations were above 2 ng/ml and as high as 18.2 ng/ml. Average concentrations of PFUnDA in the general population of North America and Europe are often below detection limits (CDC, 2019; Health Canada, 2019). Several studies in Europe have reported 95th percentile concentrations of below 1 ng/ml, suggesting overall low exposure to PFUnDA (Dereumeaux et al., 2016; Ingelido et al., 2018). Meanwhile, studies in Alaska and Arctic Canada report mean concentrations of between 0.1 and 1.0 ng/ml. Studies from China report variable concentrations of PFUnDA, with some studies reporting comparable concentrations to those found in Arctic North America, while others report low concentrations more similar to those in Europe and the USA. The data suggest that some long-chain perfluoroalkyl acids (PFASs), specifically PFNA and PFUnDA, may be elevated in Arctic populations, with changing exposure patterns most likely to be due to different sources of their precursors such as fluorotelomers, which are not yet fully regulated (Muir et al., 2019).

3.8.5 Mercury

Although they have declined considerably over recent decades, concentrations of blood Hg in the Arctic remain elevated compared to the general populations of North America, as well as reports from small studies in European countries (see Table 3.60). Mean Hg concentrations in pregnant women from different Greenland regions were between 3.32 and 10.2 µg/L, and in Nunavik adult men, women and pregnant women were between 5.4 and 10 µg/L (up to 240 µg/L) in 2017; some of the highest mean concentrations of Hg reported in the recent literature. The Canadian blood Hg guideline is set at 8 µg/L for pregnant women, children and women of childbearing age, and at 20 µg/L for the other adults. The CDC guideline is 5.8 µg/L for the global population. Thus, a significant proportion of these Inuit populations are at risk from Hg exposure. Blood Hg concentrations in a cohort of Faroe Island children decreased from a geometric mean of 2.5 µg/L in 2012–2014 to a geometric mean of 1.4 µg/L in 2016–2018. However, the range was similar between survey cycles, with both reporting maximum concentrations of over 40 µg/L. Conversely, a small sample of pregnant women from Iceland reported a mean concentration of 1.29 µg/L. A sample of more than 200 individuals from several First Nations communities in the NWT of Canada suggests that Hg exposure in these communities is similar to that of the general population of Canada.

Indeed, large samples of the general populations of Canada and the USA report median concentrations of Hg below 1 µg/L and occasionally below the detection limits (Haines et al., 2017; CDC, 2019). Anglers from these areas have slightly elevated mean blood Hg concentrations compared to national averages, showing fish consumption is the principal source of Hg (Savadatti et al., 2019). Mercury concentrations in the Arctic are more similar to those reported in East and Southeast Asia. As may be expected, blood Hg concentrations in East and Southeast Asia are elevated compared to North America and European populations, probably due to the high intake of marine-based foods. A sample 6457 adult Koreans reported a mean concentration of 3.1 µg/L (Choi et al., 2017). A study of 17,997 pregnant women in Japan reported a geometric mean concentration of 3.8 µg/L (Nakayama et al., 2019). Both studies reported 95th percentile concentrations of just over 9 µg/L. A study of several hundred Thai children reported arithmetic mean concentrations of just over 2 µg/L (Teeyapant et al., 2015). The mean blood Hg concentration of recent Burmese immigrants in New York State, USA (3.7 µg/L) was approximately twice that of a sample of licensed fisherman from the same area (1.5 µg/L) (Savadatti et al., 2019).

Median blood Hg concentration among pregnant women exposed to gold mining activity in Tanzania was 1.2 µg/L, while a similar study in Ghana reported a mean blood Hg concentration of 8 µg/L (Afrifa et al., 2018; Nyanza et al., 2019). These concentrations are similar to the range reported in Greenland and Nunavik. Mercury exposure remains an important issue for Arctic populations that rely heavily on marine or aquatic food sources, particularly where marine mammals play a key role in the local diet as in Greenland and Nunavik.

3.9 Conclusions

Despite being banned in many countries worldwide, levels of POPs are still elevated in some Arctic human populations, such as in Greenland, the Faroe Islands, Nunavik (Canada), the Pechenga district of Murmansk Oblast (Russia), and the Chukotka Autonomous Okrug (Russia), compared to many regions outside the Arctic. Consumption of traditional foods, particularly marine mammals, is a major source of exposure to POPs in some Arctic regions, as most POPs are lipophilic (the exception being PFASs) and accumulate in the blubber of marine mammals. Levels of Hg in Arctic populations are primarily from the consumption of predatory fish and marine mammal meat and organs. Levels of Hg in many non-Arctic areas are also driven by seafood consumption, but levels are generally highest in those Arctic populations consuming the greatest quantities of particular marine mammals. Levels of Hg in human populations living in Arctic regions such as Nunavik, Greenland, and the Faroe Islands are several-fold higher than in other Arctic regions and many regions outside the Arctic. The Global Mercury Assessment 2018 (AMAP/UN Environment, 2019) reported Hg levels in adults and children based on national biomonitoring programs from around the world, and levels observed in Nunavik, Greenland and the Faroe Islands were elevated in comparison to levels in non-Arctic countries.

While there are still some regions of the Arctic with limited biomonitoring data, levels of most POPs and metals are declining in Arctic regions where time trend data exist, although these declines are neither uniform nor consistent across all regions. Large declines are observed when comparing current levels with levels first measured in the 1990s; however, the declines observed in recent years have been much smaller for many contaminants in some regions. Multiple cohort studies in the Faroe Islands show levels of POPs and Hg are decreasing, probably due to decreasing consumption of pilot whale meat, as the levels in pregnant women and children in the latest cohort (Cohort 5) are much lower than those observed in the first Faroe Island cohort. As maternal levels of POPs decrease, so too does maternal transfer of POPs to infants.

While consumption of some marine species contributes to POPs and Hg exposure, it can also provide an excellent source of essential nutrients and minerals. Along with Hg, levels of Se have been measured in many marine foods, and analysis of beluga *mattaq* (a traditional food comprising a layer of beluga skin) in Nunavik has identified this as an important source of Se and selenoneine for Inuit in the region, which may offer some protective effects against Hg.

Unique results have been noted for some POPs and metals in parts of Russia. A study in coastal Chukotka (Dudarev et al., 2019b) found additional sources of in-home food contamination, as relatively high levels of HCHs, DDTs and PCBs were found in home-brewed alcohol (produced in plastic barrels), although these levels were lower than had been observed 15 years previously. The impact of this potential exposure source and its relative proportion of the total POPs intake is unclear and needs further study. Extensive collection of wild plants and seafood in the coastal Chukotka region found these to be an important dietary source of metals exposure for

Indigenous People consuming these local foods. High levels of metals were found in wild plants (Mn, Al, Ni, Ba, Sr), ascidians (Al, Cr, Sr), blue mussel (Cd, Al) and seaweed. Levels of As and Sr in seaweed were especially high, as well as levels of Al in ascidians and blue mussel.

In the Kola Peninsula region of Russia, elevated levels of certain metals (Mn, Co, Ni, Cu, Zn, As, Pb) were observed among populations living near a major point source of pollution (Ni-Cu smelter), and have been linked to the consumption of local foods with high concentrations of these metals. Elevated levels of metals in local foods and wildlife have not only been observed in Russia, but also in foods in the bordering regions of Norway and Finland. In addition, drinking water was identified as a key source of exposure to Ni.

While biomonitoring and exposure information for PBDEs and PFASs may be more limited than for other POPs and metals, new Arctic data have established baseline levels, and in some regions limited temporal trend data. PBDEs have been measured in some Arctic regions, although levels appear very low in most regions with some congeners barely above detection limits. The exception is Alaska, where levels of PBDEs are an order of magnitude greater than in other Arctic regions. Baseline levels of PFASs are now available for several Arctic regions (Alaska, Yukon, Nunavik, Greenland) and time trend data for several other regions (Nunavik, Faroe Islands, Sweden, Finland). PFOS continues to be the predominant PFAS across most populations, with PFOA the second most predominant PFAS in Arctic countries other than Alaska and Arctic Canada, for which the second most predominant PFAS is PFNA. In Greenlandic adults, concentrations of PFUnDA were higher than for PFNA and higher than in Nunavik and Alaskan Indigenous communities. Temporal patterns of PFASs are not consistent and vary by region; however, available trend data suggest that levels of PFOS and PFOA are declining in Arctic populations, including in Nunavik, Greenland, the Faroe Islands, Sweden and Finland, while levels of long-chain PFASs are rising in Nunavik, Greenland, and Sweden. Indeed, levels of PFNA and PFDA appear to have increased in pregnant Greenlandic women (between 2002–2004 and 2010–2015) and pregnant women from Nunavik, and slight increases in PFNA, PFDA, and PFUnDA have been observed in Swedish mothers, while no clear upward or downward trend has been observed for other PFASs in children from the Faroe Island cohorts. Some studies suggest diet may not be the most important source of exposure to contaminants such as PBDEs. In contrast, a growing number of studies suggest country foods, especially seafood and marine mammals, are the key sources of PFOS and long-chain PFAS exposure (Byrne et al., 2017; Dassuncao et al., 2018; Caron-Beaudoin et al., 2020).

With the ratification of the Minamata Convention and the Stockholm Convention, and subsequent effectiveness evaluations that will be completed, the need for more biomonitoring in Arctic populations is evident. This includes further establishing baseline levels of POPs including POPs of emerging Arctic concern in different sub-populations (children, adults, pregnant women, women of childbearing age) for different regions of the Arctic, but also continued biomonitoring in identified vulnerable populations to establish and monitor temporal changes in the levels of these contaminants, ideally at the time of year when most country foods are consumed in the study region. While there have been several regional studies that have generated valuable information on contaminant levels in children and adults, there is still a need for maternal blood biomonitoring studies. Many of the earliest Arctic biomonitoring studies prioritized the sampling of pregnant women and this has provided AMAP with valuable time trend information; however, it is still as important today to continue this work, either through maternal blood monitoring programs or with new birth cohorts, to follow existing trends and improve understanding of the impact of Arctic contaminants on human health. Continued monitoring for establishing new temporal trend data will become ever more important as chemicals are phased-out and replacement chemicals are developed. Indeed, strong efforts will be needed in terms of contaminants of emerging concern in biomonitoring studies, as the number of new chemicals on sale is expected to double by 2030 (UNEP, 2020b). Predictive models have attempted to identify persistent contaminants of potential concern in the Arctic and several of these chemical substances should be considered for human biomonitoring, some of which have already been detected in Arctic biota (Gibson, 2020). Owing to the 'Arctic dilemma', health authorities in some Arctic regions will have to continue to strike a balance between the benefits of consuming traditional foods and limiting human exposure to Arctic contaminants. Biomonitoring among Arctic populations coupled with dietary intake data and wildlife monitoring are essential to inform Arctic health authorities and support the health and wellbeing of Arctic populations.

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4. Health effects associated with measured contaminants in the Arctic

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Key findings

- *Contaminants found in the Arctic, such as mercury, lead, PCBs, and PFASs, have known or suspected adverse health impacts on humans – especially on developing fetuses and children. Lifestyle, diet and nutrition, and genetics can influence the risk of these impacts.*
- *Dietary exposure to some POPs, PFASs, and metals such as mercury can have negative impacts on the brain and immune system, increase the risk of childhood obesity, increase the risk of type 2 diabetes later in life, and negatively affect fetal growth and development.*
- *Foods with high levels of mercury can diminish the cardiovascular benefits of omega-3 fatty acids. Mercury toxicity also has been associated with adverse neurological outcomes, which may be underestimated in studies that fail to account for the beneficial effects of omega-3 fatty acids.*
- *Genetic makeup, lifestyle, nutrition status, and contaminants interact to influence the risk of adverse effects such as cancer, reproductive effects, impacts on fetal and child growth, metabolic disease, and nervous system disorders. Exposure to contaminants, including some POPs, PFASs, and phthalates, plays a role in the increased incidence of cancer in Arctic regions.*

4.1 Introduction

Environmental contaminants such as methylmercury (MeHg), polychlorinated biphenyls (PCBs), and perfluorinated compounds are ubiquitous and persistent environmental chemicals with known or suspected toxic effects on developing fetuses, children and adults. Ongoing research focuses on the circumpolar area, where diet mainly consists of fish and marine animals, in which accumulation of toxic compounds can be high. Fetuses and young children are most vulnerable to exposure, and therefore much research is focused on prospective studies of child cohorts.

This chapter provides an overview of recent research into the detrimental effects caused by environmental contaminants in the Arctic. It builds on the 2015 AMAP Assessment of Human Health in the Arctic (AMAP, 2015), specifically Chapter 4 on health effects associated with measured levels of contaminants in the Arctic and the published overview of ongoing cohort and dietary studies in the Arctic (Weihe et al., 2015). This chapter is divided into eight themes, for which each has a summary of past research, a discussion on recent research, and a conclusion. More detailed information on the studies discussed can be found in the reference list.

4.2 Central nervous system / Neurobehavioral effects

4.2.1 AMAP Assessment 2015: conclusions

Effects associated with MeHg exposure have been documented in humans at successively lower exposures and it is clear that the developing brain is the most vulnerable organ system. Prenatal exposure to MeHg has been associated with detrimental effects on the developing brain. Cohort studies in the Faroe Islands have demonstrated that children exposed to MeHg *in utero* exhibit decreased motor function, attention span, verbal abilities, memory and other mental functions. Follow-up of these children to the age of 22 years indicates that these deficits appear to be permanent. Similarly, a study in Nunavik of child development at age 11 years showed that mercury (Hg) exposure was associated with poorer early processing of visual information, lower estimated IQ, poorer comprehension and perceptual reasoning, poorer memory functions, and increased risk of attention problems, specifically attention-deficit hyperactivity disorder (ADHD) behavior. Beneficial effects of seafood nutrients may mask some of the adverse effects of MeHg on neurodevelopment. Neurophysiological assessment of brain functions also indicates that postnatal exposure up to adolescence can cause harm. Thus, both pregnant women and children are at increased risk from MeHg exposure. Studies indicate that certain genetic factors may increase vulnerability to MeHg toxicity. Neurophysiological assessments of children from the Faroe Islands and Nunavik have not indicated clear associations regarding the effects of prenatal exposure to PCBs.

4.2.2 New peer-reviewed literature

Methylmercury can cause adverse effects on the developing nervous system and is found in particular in seafood high in the food chain. However, long-chain omega-3 polyunsaturated fatty acids (PUFAs) from seafood have proven to provide beneficial effects on brain development. In the Kuopio Ischaemic Heart Disease Risk Factor Study, higher serum long-chain omega-3 PUFA concentrations were found to be associated with better performance on neuropsychological tests of frontal lobe functioning in older men and women. The beneficial effect of marine fat must be considered as negatively confounding and likely to result in underestimating both Hg toxicity and nutrient benefits, unless mutual adjustment is included in the analysis (D'Ascoli et al., 2016).

In human development the brain continues to develop well beyond birth until early adulthood. The extent to which postnatal MeHg exposure contributes to neurobehavioral delays is uncertain. The neurotoxicity from prenatal and postnatal exposure to MeHg might be confounded, because the child's dietary exposure is likely to correlate with that of its mother.

Using regression analyses of the Faroese Birth Cohort 1 data (Grandjean et al., 2014), child current total blood-Hg at age 7 years showed only weak associations with the neuropsychological test variables, but visuospatial memory revealed a significant negative association. Mutual adjustment showed a weaker effect of prenatal exposure. However, such adjustment may lead to underestimations due to the presence of correlated, error-prone exposure variables. In structural equation models, all Hg exposure parameters (Hg concentrations in maternal hair at parturition, cord blood, and child blood and hair) were instead entered into a latent exposure variable that reflected the total Hg load. This latent exposure showed significant association with neurodevelopmental deficits, with prenatal exposure providing the main information. However, postnatal Hg exposure appeared to contribute to neurotoxic effects, with regard to visuospatial processing and memory in particular. Further studies with better information on exposure profiles are needed to characterize the effects of postnatal Hg exposure.

Negative confounding by essential fatty acids in MeHg neurotoxicity associations was examined in Faroese children born in 1994–1995 (Choi et al., 2014). The relative concentrations of fatty acids were determined in cord serum phospholipids, and neuropsychological performance in verbal, motor, attention, spatial, and memory functions was assessed. Multiple regression and structural equation models showed that a short delay recall in the California Verbal Learning Test (CVLT) was associated with a doubling of cord blood MeHg. The association was stronger after the inclusion of fatty acid concentrations in the analysis. In structural equation models, poorer memory was associated with a doubling of prenatal exposure to MeHg after the inclusion of fatty acid concentrations in the analysis.

In conclusion, associations between prenatal exposure to MeHg and neurobehavioral deficits in memory function were strengthened after fatty acid adjustment, thus suggesting that omega-3 fatty acids need to be included in analysis of similar studies to avoid underestimating the associations with MeHg exposure.

Studies have reported some evidence of adverse effects of persistent organic pollutant (POP) exposure on child development, but the results have been inconsistent and few studies have evaluated associations with child behavior.

In a Faroese cohort (n=539), the association between prenatal, 5- and 7-year exposure to perfluoroalkylated substances (PFASs) and behavioral problem scores was assessed. Hyperactivity, peer relationship, and conduct problems showed a significant association with higher serum PFAS concentration at ages 5 and 7 years, but not prenatally, as well as for internalizing and externalizing problems and autism screening composite scores (Oulhote et al., 2016).

In the Mother and Child Cohort of Norwegian preschool children no association was found between low level PCB153 in maternal dietary exposure and ADHD symptoms and cognitive function, but exposure was significantly associated with poorer expressive language skills in preschool girls (Caspersen et al., 2016).

Exposure to PFASs during pregnancy and their effect on child behavior at age 5 to 9 years examined in the INUENDO cohort in Greenland and Ukraine (Høyer et al., 2017) showed a weak negative effect of prenatal exposure on child behavioral development and increased hyperactivity. This association was strongest in Greenland, whereas no association was seen in the Ukrainian children.

In the same INUENDO cohort, prenatal and postnatal PCB153 and *p,p'*-dichlorodiphenyldichloroethylene (DDE) exposure was associated with a higher prevalence of abnormal scores for conduct and hyperactivity (Høyer et al., 2015a). Furthermore, the same study found *in utero* exposure to PCB153 and *p,p'*-DDE was not associated with parentally retrospectively assessed developmental milestones in infancy or parentally assessed motor skills at an early age (Høyer et al., 2015b).

A lack of sun in the Arctic, especially in winter with reduced sunlight, has been linked to vitamin D deficiency (Dalgård et al., 2010). Recent evidence now indicates that environmental toxins may even trigger further vitamin D deficiency (Mousavi et al., 2019). Vitamin D deficiency has been proposed as a possible risk factor for developing autism spectrum disorder. In a cross-sectional population-based study in the Faroe Islands (Koçovska et al., 2014), individuals with autism spectrum disorder (aged 15 to 24 years) had significantly lower 25-hydroxyvitamin D3 (25(OH)D3) levels than their siblings without autism spectrum disorder, along with their parents and other healthy age- and gender-matched comparisons. There was a trend for males having lower 25(OH)D3 than females. The authors proposed that the low 25(OH)D3 levels in the autism spectrum disorder group suggest an underlying pathogenic mechanism.

In the Norwegian Mother-and-Child Cohort Study low habitual iodine intake in pregnant women (Adalsteinsdottir et al., 2020), i.e., lower than the recommended intake for non-pregnant women, was associated with mothers reporting poorer child language, school performance, and increased likelihood of special educational services at the age of 8 years (Abel et al., 2019). Similar findings were observed at age 3 years with symptoms of child language delay, behavior problems, and reduced fine motor skills associated with maternal iodine intake below the estimated average requirement during pregnancy (Abel et al., 2017a). In the same Norwegian Mother-and-Child Cohort Study, insufficient maternal iodine intake was associated with increased child ADHD symptom scores at eight years of age, but not with ADHD diagnosis (Abel et al., 2017b).

4.2.3 Summary of latest findings

The extent to which postnatal MeHg exposure contributes to neurobehavioral delays is uncertain. The prenatal exposure to MeHg could explain most of the neurodevelopmental deficits.

However, postnatal MeHg exposure appears to contribute, especially when it comes to visuospatial processing and memory. Further studies with better information on exposure profiles are needed to characterize the effects of postnatal MeHg exposure. Associations between prenatal exposure to MeHg and neurobehavioral deficits were strengthened after fatty acid adjustment, thus suggesting that omega-3 fatty acids need to be included in analyses of similar studies to avoid underestimation of the effects of MeHg exposure. This is in line with the findings in the Kuopio Ischaemic Heart Disease Risk Factor Study, where higher serum long-chain omega-3 fatty acid concentrations were associated with better performance on neuropsychological tests of frontal lobe functioning in older men and women.

Prenatal exposure to PFASs and organochlorine compounds appear to have indications of a negative effect on child behavior. Whereas, higher prenatally exposure to serum PCB153 and DDE concentrations were not associated with parent-reported behavioral problems.

Vitamin D deficiency might be caused by environmental toxins and people with autism spectrum disorder were found to have lower vitamin D levels compared to people without the diagnosis.

Association is not always causality and associations should be treated with caution in risk assessments. In a recent review, the significant and non-significant associations between maternal exposure to Hg and child development were studied in 73 publications. The median number of child development outcome variables in papers reporting significant (n=35) and non-significant (n=38) results was 4 versus 7, respectively. Authors often report health outcome variables based on their *p*-values rather than on stated primary research questions. Such a practice probably skews the research evidence (Nieminen et al., 2015).

4.3 Immunological effects

4.3.1 AMAP Assessment 2015: conclusions

Certain environmental pollutants can adversely affect the development of the immune system. Young children in Nunavik were found to have had a high incidence of infectious diseases (such as meningitis, bronchopulmonary infections and middle ear infections). Studies investigated the possibility that this is partly due to maternal transfer of organochlorine compounds with known immunotoxic properties during breastfeeding. Results indicate that prenatal exposure to organochlorine compounds does increase susceptibility to infectious diseases (otitis media, in particular). Most experimental evidence points to the role played by dioxin-like PCB congeners. Immunotoxic effects have also been seen in combination with routine childhood immunizations. Faroese children exhibiting elevated levels of PCBs and especially perfluorinated compounds show reduced immune response to routine vaccinations. These findings suggest a decreased effect of childhood vaccinations and may indicate a more general immune system deficit. The implications of inadequate antibody production highlight the need for a significant reduction of immunotoxicant exposure in Arctic populations, as well as the need for long-term assessments of the health risks associated with exposure to immunotoxic contaminants.

4.3.2 New peer-reviewed literature

Several papers from the circumpolar Arctic reported a negative impact on the immune system from toxic environmental exposure.

In a Faroese cohort (n=559), PFAS exposure at age 5 years was associated with an increased risk of asthma among measles, mumps and rubella (MMR)-unvaccinated children but not among MMR-vaccinated children at the age of 13 years. While PFAS exposure appears to impair immune system functions, MMR vaccination might potentially negate this effect (Timmermann et al., 2017a).

In the same cohort, at age 7 years, total and grass-specific serum immunoglobulin E (IgE) was quantified, and at age 13 years the children underwent skin prick tests. MMR vaccination was associated with a two-third reduction in the odds of developing asthma and allergy at ages 5 and 13 years, and may therefore be considered to have a protective effect (Timmermann et al., 2015).

Prenatal exposure to POPs has been linked to asthma, but associations with allergic sensitization and lung function have been minimally explored. A Danish cohort study of 965 pregnant women found no association between maternal concentrations of POPs and offspring allergic sensitization at 20 years of age. Maternal concentrations of POPs were, however, found to be positively associated with offspring airway obstruction and could indicate that chronic obstructive lung diseases may at least partly originate in early life (Hansen et al., 2016). Maternal concentrations of PCB118 and hexachlorobenzene (HCB) were found to be associated with an increased risk of asthma in offspring that were followed through 20 years (Hansen et al., 2014).

Atopic allergy is much more common in Finnish Karelia than Russian Karelia, although these areas are geographically and genetically close. A random sample of 200 individuals, 25 atopic and 25 non-atopic school-age children and their mothers, showed higher concentrations of common environmental chemicals in Russian compared with Finnish Karelian children and mothers (Koskinen et al., 2016). Chemical presence could not explain the higher prevalence of atopy in Finnish children.

Developmental exposure to environmental immunotoxicants appears to impact white blood cell count in childhood. In a Faroese birth cohort, prenatal Hg and organochlorine compound exposure was associated with depleted total white blood cell count, especially for lymphocytes and neutrophils, respectively. Conversely, increasing serum PFAS concentrations presented with higher basophil counts. Reduced subpopulations of T-cells may suggest impaired cellular immunity effects and dysregulation of T-cell mediated immunity (Oulhote et al., 2017). Furthermore, postnatal exposure to PFASs was associated with lower serum concentrations of specific antibodies against certain childhood vaccines in a Faroese birth cohort. Diphtheria antibody concentrations decreased at elevated serum PFAS concentrations. Few associations were observed for anti-tetanus concentrations (Grandjean et al., 2017a).

PFAS-associated attenuated antibody responses to childhood vaccines may be affected by PFAS exposure during infancy, where breastfeeding adds to PFAS exposure. Prenatal exposure of a Faroese cohort showed inverse associations with antibody concentrations produced from tetanus and diphtheria vaccines five years later, with a decrease of up to 20% for each two-fold increase in exposure. Modeling of serum-PFAS concentration showed that concentration estimates for ages 3 and 6 months had the strongest inverse association with antibody concentrations at age 5 years, particularly for tetanus. The estimated PFAS concentrations at age 3 and 6 months were based on breastfeeding history up to that age. Joint analyses showed a statistically significant decrease in tetanus antibody concentrations at age 5 years for each doubling of PFAS exposure in early infancy. These findings provide a good indication that the developing adaptive immune system is particularly vulnerable to immunotoxicity during infancy, when breastfeeding affects PFAS exposure level (Grandjean et al., 2017b).

In a Faroese birth cohort, age 7 years blood-Hg concentrations were positively associated with multiple neural- and non-neural-specific antibodies. Prenatal blood-Hg and blood-PCB levels were negatively associated with anti-keratin immunoglobulin G (IgG), and prenatal perfluorooctane sulfonic acid (PFOS) exposure was negatively associated with anti-actin IgG. Thus, this pilot study demonstrates that autoantibodies can be detected in the peripheral blood following exposure to environmental chemicals. An unexpected association of exposure with antibodies specific for non-neural antigens may indicate toxicities that have not yet been recognized (Osuna et al., 2014).

A study investigated the effects of POP concentration on inflammation in Inuit living predominately on the traditional marine diet in Greenland. Serum inflammatory markers YKL-40 and hsCRP were higher in Inuit compared to non-Inuit and increased with age and with the intake of Greenlandic food items. This supports a pro-inflammatory role of POPs to promote chronic diseases (rheumatoid arthritis and cardiovascular diseases) common to populations in Greenland (Schaebel et al., 2015, 2017).

The incidence of inflammatory bowel disease is higher in the Faroe Islands than in any other European country. Studies have reported that the genetic component is not as significant as previously indicated. Therefore, Faroese emigrants to Denmark were examined, where inflammatory bowel disease incidence is lower. Incidence in first-, second- and third-generation immigrants from the Faroe Islands to Denmark was studied to assess the extent to which immigrants adopt the lower incidence of their new home country. Although some impact of genetic dilution cannot be excluded, environment does appear to play an important role, as inflammatory bowel disease risk in Faroese immigrants to Denmark disappeared over time; over one generation in men and two generations in women (Hammer et al., 2017). A case control study (n=5698) from six Faroese birth cohorts did not find it likely that marine contaminants caused the high incidence of inflammatory bowel disease (Hammer et al., 2019).

The INUENDO birth cohort found limited evidence to support a link between prenatal exposure to environmental chemical contaminants and childhood asthma and eczema (Smit et al., 2015). The contaminants included PFASs, metabolites of diethylhexyl and diisononyl phthalates, PCB153, and *p,p'*-DDE.

4.3.3 Summary of latest findings

Several studies in the circumpolar area indicate a negative impact on the immune system due to dietary exposure to environmental contaminants.

PFAS exposure at age 7 years was associated with a loss in diphtheria antibody concentration at age 13 years and a decrease in tetanus antibody concentration at age 5 years was associated with PFAS exposure in early infancy. While PFAS exposure may affect immune system function, these studies suggest that MMR vaccination might be a potential effect-modifier. MMR vaccination early in life may have a protective effect against allergy and asthma.

Data from Denmark indicate that prenatal exposure to POPs appears to be associated with airway obstruction but not allergic sensitization at 20 years of age. However, in a Russian/Finnish study in Karelia, environmental chemicals did not explain the higher prevalence of atopy on the Finnish side.

Markers of inflammation were higher in Inuit compared to non-Inuit and increased with age and with the intake of Greenlandic food items high in POPs.

In the Faroe Islands, the prevalence of inflammatory bowel disease is high. Interestingly, the excess risk in Faroese immigrants to Denmark disappeared over time, indicating a gene-environment interplay.

The INUENDO birth cohort found limited evidence to support a link between prenatal exposure to environmental chemical contaminants and childhood asthma and eczema.

All the mentioned associations between contaminant exposure and the functions of the immune system demonstrate the need for further mechanistic studies in order to find causal explanations. Furthermore, explorations are needed of windows of vulnerability pre- and postnatal, and identification of the most immunotoxic substances.

4.4 Reproductive effects

4.4.1 AMAP Assessment 2015: conclusions

Many Danish and Faroese men have a low level of semen quality compared to men from other European countries, and there are indications of lower capacity for testosterone production. Studies on sperm count and morphology did not show a relationship with PCB153 or *p,p'*-DDE levels in blood in Greenlanders; however, sperm motility was inversely related to PCB153 concentration in this population. Prenatal lead exposure is known to negatively affect growth of school-age children.

4.4.2 New peer-reviewed literature

4.4.2.1 Pregnant women's health in the Arctic

Female lifestyle and environmental exposures can affect fecundity, and exposure to POPs before and during pregnancy can affect fetal development, increasing health risk later in life (Toft et al., 2005; Jørgensen et al., 2014; Wang et al., 2016a; Rattan et al., 2017; Haugaard Rasmussen et al., 2019; Hjermitslev et al., 2020). A Greenlandic prospective mother-child cohort, ACCEPT (Adaption to Climate Change, Environmental Pollution, and dietary Transition), established during 2010–2015, included 592 pregnant Inuit women across the Greenlandic regions North, Disko Bay West, South, and East. The ACCEPT cohort is compatible with international/circumpolar mother-child cohorts studying transition in diet and lifestyle and public health in the next generation.

Lifestyle, reproductive factors and food intake of Greenlandic pregnant women were studied in the ACCEPT birth cohort (Knudsen et al., 2015; Terkelsen et al., 2018). Over recent decades, Greenland has shifted from a hunter society to a more western lifestyle, resulting in a lower intake of traditional foods such as marine mammals, fish and seabirds (see Chapter 2). These changes in living conditions and food habit might affect maternal health in Greenland. The study design of the ACCEPT birth cohort is cross-sectional, primarily sampled in the first trimester, and enables assessment of possible age and geographic differences. Participants were Inuit over 18 years in age and who had lived at least half of their life in Greenland. Information on lifestyle and food intake was obtained through questionnaires. Compared to earlier birth cohort studies, the population showed an increase in BMI, with pre-pregnancy BMI >25.0 kg/m^2 increasing from 43.3% of the population in 2010–2011 to 46.6% in 2013–2015. Smoking frequency is still high but the data suggest a decrease in smoking at the start of pregnancy, from 46.3% in 2010–2011 (Knudsen et al., 2015) to 29.0% in 2013–2015 (Terkelsen et al., 2018). In the study population 2013–2015, 54.6% of women had used hashish at some point in their life. Very few participants consumed alcohol during pregnancy. Younger women (<27–28 years) were less certain about their planned breastfeeding period and consumed more dried fish and 'fast food'. BMI, education level, personal income, previous pregnancies and planned breastfeeding period were significantly higher in pregnant women >28 years of age (Terkelsen et al., 2018). Although there was a very low intake of alcohol during pregnancy, regional differences showed that women living more than half of their life in the North, South and West regions had a higher alcohol intake during pregnancy compared to those in the Disko Bay and East regions (Knudsen et al., 2015). The East region had the highest number of previous pregnancies, the highest number of smokers during pregnancy and a higher intake of sauce with hot meals and fast food. No significant geographic differences were found for the intake of marine mammals or seabirds (Knudsen et al., 2015). Overall, compared to earlier studies, the data show higher BMI, with an increasing tendency. Smoking frequency in Inuit Greenlandic pregnant women is still very high especially in the East region, whereas a decreasing tendency is seen in the other regions. Data show differences for age and region, alcohol consumption, breastfeeding plans and food intake profile. These health issues for pregnant women in Greenland should be addressed in future recommendations.

Food intake and serum POPs have been reported for the Greenlandic pregnant ACCEPT women (Long et al., 2015). In general, Greenlandic Inuit have very high blood concentrations of environmental POPs. High POP concentrations have been associated with age, smoking and consumption of marine mammals, and studies have indicated that prenatal POPs exposure may adversely affect fetal and child development. Geographic differences exist in diet, lifestyle and POPs exposure among pregnant women in Greenland (Long et al., 2015). Higher intake of marine mammals was consistent with a higher omega-3/ omega-6 fatty acid ratio in the East and North regions. East region participants tended also to have a higher intake of terrestrial species, and a significantly higher seabird intake was seen for pregnant women in the West region. There were also significant regional differences in blood concentrations of organochlorine pesticides, PCBs, PFASs and Hg, with higher levels in the North and East regions. Suggesting similar sources, PFASs were significantly associated with PCBs and organochlorine pesticides in most regions. In the North region, PFASs were associated with both selenium (Se) and Hg, whereas polybrominated diphenyl ethers (PBDEs) showed no regional difference. Regional differences in blood POP and Hg levels reflect differences in intake of the traditional marine foods. Compared to earlier reports of Greenlandic pregnant women, the study found lower levels of POPs, Hg and lead (Pb), and perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), but similar levels for the PFAS congeners perfluorohexane sulfonic acid (PFHxS) and perfluorononanoic acid (PFNA) (see also Chapters 2 and 3). Therefore, continuing to measure POPs and heavy metal levels in maternal blood is important to determine fetal exposure and possible influence on fetal development (Long et al., 2015).

4.4.2.2 Prenatal exposure and fetal growth

The high levels of POPs in the Greenlandic population are linked with disturbance of child development, immune function (see Sections 4.2 and 4.3) and reproductive function. One ACCEPT study investigated associations between serum POP levels of pregnant women in Greenland and their infant's birth weight, length, head circumference and gestational age at birth (Hjermitslev et al., 2020). Pregnant Greenlandic women (n=504) were enrolled during 2010–2015 and serum levels of the lipophilic POPs (organochlorine pesticides, PCBs and PBDEs) and the amphiphilic POPs, PFASs, were measured. Significant inverse associations were observed between PFOA and birth weight, birth length (borderline) and head circumference, but a positive association was seen with gestational age (Figure 4.1). For the lipophilic POPs, the study found an overall trend of inverse associations with fetal growth indices. An earlier study showed that smoking increases POP bioaccumulation (Deutch et al., 2003). In this study, smoking frequency was significantly inversely associated with birth weight (data not reported). Thus, the data indicate that POPs have a negative effect on fetal growth (Hjermitslev et al., 2020).

Diet and lifestyle factors are important sources of toxic heavy metals and levels of essential metals. A recent study has examined metal exposure in pregnant ACCEPT women vs indices of fetal growth (Bank-Nielsen et al., 2019). The study included 509 pregnant Inuit women ≥18 years of age sampled

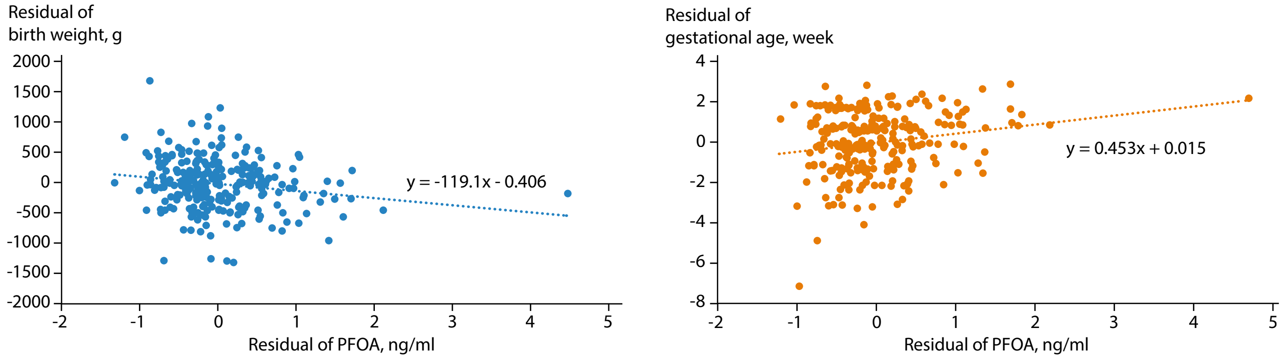


Figure 4.1 Partial regression plots of birth weight versus PFOA and gestational age versus PFOA, adjusted for confounding factors (maternal age, pre-pregnancy BMI, serum cotinine, parity, alcohol intake during pregnancy and in the case of birth weight versus PFOA, gestational week at birth). Residuals represents the distance between the observed value and the predicted regression line; dashed line. The 0:0 coordinate gives the adjusted mean residual for birth weight or gestational age (Y axis) and PFOA (X axis), corresponding to 3575±363 g (birth weight) / 39.1±1.53 weeks (gestational age) and 1.26 (SD: 0.68) ng/mL, respectively (Hjermitslev et al., 2020).

during 2010–2015, with data on population characteristics and birth outcomes based on interviews and medical records. Thirteen metals were determined in the blood samples. The proportion of current smokers was 35.8%. Compared to non-Arctic normal ranges, the levels of cadmium (Cd), chromium (Cr), and nickel (Ni) were significantly higher. There was a significant regional difference for several metals, smoking, and parity. Birth outcomes were inversely associated with levels of Cd and copper (Cu). There was a dose-dependent relationship between maternal blood heavy metal levels and fetal development and growth. The high frequency of maternal smokers early in pregnancy is a concern because prenatal exposure to heavy metals can affect fetal development and growth in Greenlandic Inuit (Bank-Nielsen et al., 2019).

The potential of the maternal serum POP mixture to activate the estrogen receptor function was measured as a biomarker of exposure effect. The combined POP-induced xeno-estrogenic activity was then analyzed for possible association with fetal growth in 504 ACCEPT pregnant women enrolled in 2010–2015 (Long et al., in prep). Preliminary results show that the serum lipoPOP mixture extracts, free of endogenous hormones such as estrogen-, androgen- and thyroid hormones, can activate the estrogenic and androgenic receptor, from now referred to as xeno-hormone activities. The xeno-estrogenic activity of the lipoPOP serum mixture was positively and significantly associated with the individual serum POP levels. The xeno-androgenic activity of the serum POP mixture was negatively and significantly associated with birth weight, especially for girls. In summary, the study shows that the lipophilic mixture of POPs in the serum of pregnant ACCEPT women has a hormone-disrupting effect that can interfere with both the estrogenic and androgenic receptor activity, which can have a disruptive effect on fetal development and growth (Long et al., in prep).

The INUENDO project included three cohorts established in 2002–2004 involving approximately 1400 pregnant women from Greenland, Poland and Ukraine, as well as studies on approximately 600 fertile couples from Sweden (fishermen and their wives). The Greenlandic part of the study included 438 men and 572 pregnant women. The overall aim of the study was the relation between diet, exposure to POPs and human fertility. The CLEAR study was a follow-up on the children from the INUENDO cohort undertaken in 2009–2012 (Weihe et al., 2016).

As a part of the INUENDO project, a study on the three birth cohorts elucidated prenatal phthalate, PFASs, and organochlorine exposures and the association with term birth weight highlighting possible intrauterine growth restrictions (Lenters et al., 2016). The study included a cohort of 1250 term (≥ 37 weeks gestation) singleton infants, born to 513 mothers from Greenland, 180 from Poland, and 557 from Ukraine, recruited during 2002–2004. Secondary metabolites of diethylhexyl phthalate (DEHP) and diisononyl phthalate (DINP), eight perfluoroalkyl acids (PFASs), and PCB153 and *p,p'*-DDE were quantified in 72–100% of maternal serum samples. The increase in mono (2-ethyl-5-hydroxyhexyl) phthalate (MEHHP), PFOA, and *p,p'*-DDE was associated with lower birth weight, whereas mono(4-methyl-7-oxo-octyl) phthalate (MOiNP) was associated with higher birth weight. This study suggests that some environmental contaminants, such as phthalates, PFASs, and organochlorine pesticides such as *p,p'*-DDE, can be independently associated with impaired fetal growth (Lenters et al., 2016).

In a Murmansk County Birth Registry, Kharkova et al. (2017) assessed associations between smoking behavior before and during pregnancy and selected adverse birth outcomes. The study included women who delivered a singleton pregnancy after 37 weeks of gestation (n=44,486). Data evaluation included self-reported smoking at the first prenatal visit, and potential confounding factors adjusted using logistic regression. The study found the highest frequency of infants with low values of birth weight, birth length, and head circumference to be among women who smoked both before and during pregnancy. Moreover, the ponderal index (PI=kg/m^3) and the Apgar score at 5 minutes after birth (derived from five criteria to quickly summarize the health of a newborn child: skin color, pulse rate, reflex, muscle tone, respiratory efforts) were also lower for women who smoked both before and during pregnancy. The study found a dose-response relationship between the number of cigarettes smoked per day during pregnancy and the odds of the aforementioned adverse birth outcomes. No significant outcome differences were seen among non-smokers and those who smoked before but not during pregnancy. Moreover, smoking reduction during pregnancy relative to its pre-gestation level did not influence the odds of the adverse birth outcomes. The findings emphasize a continued need for action against tobacco smoking during pregnancy (Kharkova et al., 2017).

The Norwegian Mother and Child Cohort (MoBa) studied prenatal Hg exposure and infant birth weight (Vejrup et al., 2014). The objective of the study was to examine the association between calculated maternal dietary exposure to Hg in pregnancy and infant birth weight. The study sample consisted of 62,941 women who answered a validated food frequency questionnaire which covered the habitual diet during the first five months of pregnancy. The weekly median exposure to Hg was 0.15 µg/kg body weight of which 88% of total Hg exposure was via seafood intake. Compared to women in the lowest quintile of Hg exposure, women in the highest quintile had offspring with 34 g lower birth weight and an increased risk of giving birth to small-for-gestational-age offspring. Although seafood intake was positively associated with increased birth weight, stratified analyses of seafood consumption showed negative associations between Hg exposure and birth weight (Vejrup et al., 2014).

Using novel physiologically-based pharmacokinetic models, the Norwegian Human Milk Study (HUMIS) birth cohort, including 2500 mothers and their children, was used to study the relation between postnatal exposure to lipophilic POPs and infant growth (Stigum et al., 2015). The study explored the exposure of breastfeeding infants to POPs for assessing postnatal health. The study presented postnatal exposure calculations to investigate the effect of HCB on infant growth in the first two years of life, as well as HCB measurements. To calculate HCB concentrations in breastmilk samples (2002–2008), the milk consumed each month by the infant in the first two years of life was included. The linear mixed model was used to estimate the association between HCB and infant growth. Children exposed via mother's milk reached HCB concentrations one- to five-fold higher than the mother's concentration. HCB was associated with lower weight gain in the first two years of life. The first three months was identified as a critical window of effect owing to stronger effects during this period. The equations for postnatal exposure to lipophilic POPs gave more precise estimates than the lactation exposure model. Thus, HCB exposure, especially during the first three months of life, has a negative effect on infant growth up to two years of age (Stigum et al., 2015).

Another study based on the HUMIS data also focused on environmental contaminants in breastmilk and infant growth (Criswell et al., 2017). The levels of 26 POPs in breastmilk were analyzed for their association with rapid infant growth, since rapid infant growth can be a risk factor for obesity later in life. In 789 women with a mean age of 29.6 years, sampled by overweight (45.3% being overweight or obese), the measured POPs included PCBs and pesticides, and heavy metals, in breastmilk one month after delivery. Growth was defined as change in weight-for-age z-score between 0 and 6 months, and rapid growth as a change in z-score above 0.67. 19% of infants displayed rapid growth and firstborns were more likely to be rapid growers. Increase in the interquartile range (IQR) of HCB and β-hexachlorocyclohexane (β-HCH) exposure was associated with lower growth. High exposure of newborns to β-HCH reduced infant growth, suggesting a link between early life β-HCH exposure and decreased growth with increased β-HCH concentration in breastmilk (Criswell et al., 2017).

Insufficient supply of vitamin D during early development may negatively affect offspring growth. Studies have suggested that POP exposure can cause vitamin D deficiency in humans (Yang et al., 2012; Morales et al., 2013). A study examined the association between umbilical cord serum 25-hydroxyvitamin D (25(OH)D) concentration and infant size in 1038 singleton infants at age 14 days (Dalgård et al., 2016). In 53% of newborns the umbilical cord serum levels were <25 nmol/L 25(OH)D. After adjustment, no relationship was found between birth weight or head circumference and umbilical cord 25(OH)D. However, after adjusting for birth weight, birth length was shorter for infants with a vitamin D status of <12 nmol/L compared to infants with a vitamin D status of >50 nmol/L. The data suggest that umbilical cord serum 25(OH)D concentrations are positively associated with infant length but not with birth weight or head circumference (Dalgård et al., 2016).

4.4.2.3 Exposure and female fertility

A prospective study demonstrated a negative association between perfluorooctane sulfonamide (PFOSA) concentrations and fecundability (Buck Louis et al., 2013). The study, based on the Norwegian Mother and Child Cohort Study, included 451 primiparous women enrolled in 2003–2004. Time-to-pregnancy was self-reported. The median plasma PFOSA concentration was 0.03 ng/ml at 18 weeks of gestation. The study suggested an association between plasma PFOSA concentration and weekly decreased fecundability odds ratio among primiparous women; other PFASs showed no association (Whitworth et al., 2016).

As part of the INUENDO cohort studies (Weihe et al., 2016), the association between PFASs and time-to-pregnancy was studied in couples from Greenland, Poland and Ukraine (Jørgensen et al., 2014). Serum levels of PFOA, PFOS, PFHxS and PFNA were measured in 938 women: 448 from Greenland, 203 from Poland, and 287 from Ukraine. Median levels of PFOA were 1.83 ng/ml, 2.67 ng/ml and 0.92 ng/ml, respectively; for PFOS, 20.32 ng/ml, 7.97 ng/ml and 4.93 ng/ml, respectively; for PFHxS, 2.04 ng/ml, 2.35 ng/ml and 1.55 ng/ml, respectively; and for PFNA, 0.70 ng/ml, 0.60 ng/ml and 0.60 ng/ml, respectively. Higher PFNA levels were associated with longer time-to-pregnancy in the pooled sample, especially in women from Greenland. In addition, infertility increased in the pooled sample and especially in women from Greenland. PFNA for women from Poland and Ukraine showed a weaker association. However, PFOS, PFOA and PFHxS were not consistently associated with time-to-pregnancy. Thus, although not consistent, there are indications, especially for Greenlandic women, that environmental exposure to PFASs impairs female fecundity (Jørgensen et al., 2014).

4.4.2.4 Exposure vs. male reproduction

As a part of the INUENDO project (Weihe et al., 2016), a study was undertaken on the effect of exposure to an array of environmental contaminants (phthalates, PFASs, metals, organochlorine pesticides, PCB153) on male reproductive function, as well as reproductive function in Greenlandic, Polish and Ukrainian men (Lenters et al., 2015). The cross-sectional study (n=602) aimed to identify exposure profiles associated with biomarkers of male reproductive function as part of a global assessment. This included male partners of pregnant women enrolled in 2002–2004 in Greenland, Poland and Ukraine. Fifteen contaminants were detected in more than 70% of blood samples, including metabolites of phthalates (DEHP and DINP), PFASs, metals and organochlorines. Twenty-two reproductive biomarkers were assessed, including serum levels of reproductive hormones, markers of semen quality, sperm chromatin integrity, epididymal and accessory sex gland function, and Y:X chromosome ratio. The exposure data showed large variations within and between the three study populations, differing across study populations for all contaminant exposures except MOiNP. Levels were higher in Greenland compared to Warsaw and Kharkiv for many exposures, especially for Hg and PCB153. Ten associations were found in eight outcomes of the exposure-outcome associations tested. Several associations were consistent in direction across the three study populations: positive associations between Hg and inhibin B, and between Cd and testosterone; inverse associations between DINP metabolites and testosterone, between PCB153 and sperm motility, and between a DEHP metabolite and a marker of epididymis function (neutral α-glucosidase). This assessment provides indications that organochlorine compounds and phthalates can adversely affect parameters of male reproductive health (Lenters et al., 2015).

It is generally accepted that phthalates exert their toxic action by inhibiting Leydig cell synthesis of testosterone, but *in vitro* studies have also shown anti-androgenic effects at the receptor level. An INUENDO cross-sectional study investigated the association between serum phthalates and biomarkers of reproductive function in 589 adult men from Greenland, Poland and Ukraine (enrolled 2002–2004) (Specht et al., 2014). The study also examined whether levels of DEHP and DINP metabolites in serum are associated with serum concentrations of male reproductive hormones and semen quality. The metabolic pathways of DEHP and DINP on semen quality and reproductive hormones were also analyzed. A significant inverse association was observed between serum levels of the DEHP and DINP metabolites, the proxies and serum testosterone, and negative associations between some metabolites and sex hormone-binding globulin, semen volume and total sperm count, respectively. These findings are in accordance with weak anti-androgenic action of DEHP metabolites, but less for DINP metabolites. Metabolic pathways differed significantly between the three study sites, without major effect on semen quality or reproductive hormones (Specht et al., 2014).

In the same INUENDO cohort, the association between environmental HCB exposure and human male reproductive function was studied using 589 spouses of pregnant women from Greenland, Poland and Ukraine enrolled between 2002 and 2004 (Specht et al., 2015). The mean HCB serum concentrations were higher in Ukraine (182.3 ng/g lipid) and Greenland (79.0 ng/g lipid) than in Poland (14.2 ng/g lipid). Sex hormone-binding globulin and free androgen index were associated with HCB in men from Ukraine and Poland. A positive association was seen for sex hormone-binding globulin and a negative association for free androgen index with high serum levels of HCB in fertile men, but without major consequences for semen quality (Specht et al., 2015).

PBDEs may affect male reproductive function (Toft et al., 2014). A cross-sectional study, including spouses of pregnant women from Greenland, Poland and Ukraine, analyzed PBDE exposure and male reproductive function focusing on PBDE47 and PBDE153 and effects on reproductive hormones, semen quality, and markers of DNA damage and apoptosis (Toft et al., 2014). Associations between PBDE47 or PBDE153 exposure and markers of male semen quality or reproductive hormones were weak, indicating that male reproductive function is not affected in fertile European or Arctic populations by the current exposure level of these compounds (Toft et al., 2014).

A study in the Faroe Islands aimed to investigate how exposure to POPs might affect sperm sex chromosome ratio (Kvist et al., 2014). The study aimed to evaluate whether PCBs and *p,p'*-DDE can influence sperm sex chromosome ratio in Faroese men, and whether these men differ regarding Y:X ratio compared to Greenlandic Inuit and Swedish fishermen. The study population (n=449) consisted of young men from the general population (n=276) as well as proven fertile men (n=173). The study found that the selected POPs were associated with Y:X ratio in fertile Faroese men, but not in the total population. Since *p,p'*-DDE and ΣPCB correlated significantly ($r=0.927$, $p<0.001$), the results involving the exposure variables can be regarded as a finding representing these two organochlorines. The Y:X ratio for the total Faroese population was 0.500±0.018, being statistically significantly lower than in both Greenlandic Inuit and Swedish fishermen (0.512 for both). Thus Faroese men presented a lower Y:X ratio than Greenlandic Inuit and Swedish fishermen. Although no direct health effects are expected due to the lower Faroese Y:X ratio, it could be indicative of adverse effects on the reproductive system (Kvist et al., 2014).

Although it is known that sperm aneuploidy contributes to early pregnancy losses (through congenital abnormalities), the causes are unknown, but may be associated with environmental contaminants. A study in men from the general population of the Faroe Islands evaluated sperm aneuploidy in Faroese men with lifetime exposure to *p,p'*-DDE and PCBs (Perry et al., 2016). Adult *p,p'*-DDE and ΣPCB serum concentrations were associated with significantly increased rates of XX18, XY18, and total disomy. *p,p'*-DDE and PCB concentrations at age 14 years were associated with significantly increased rates of XX, XY, and total disomy in adulthood. However, for cord blood concentrations of *p,p'*-DDE and PCBs and sperm disomic in adulthood, no consistent associations were found. Thus *p,p'*-DDE and PCB exposures at age 14 years and in adulthood were associated with sperm disomy, suggesting further research is needed on the impacts of POPs on testicular maturation and function (Perry et al., 2016).

Another cross-sectional study examined the possible association between PCB exposure and semen quality and reproductive hormones in Faroese fertile men related to spermatogenic capacity (Petersen et al., 2015). The study included serum sample PCB levels, hormone profiles and semen quality parameters obtained at the clinical examination. The study found a significant positive association between serum-PCB and the testosterone/estradiol ratio. Increased PCB exposure was associated with increased serum concentrations of sex hormone-binding globulin and follicle-stimulating hormone in the non-adjusted analyses, whereas there was no association between serum PCB concentration and the semen quality parameters. The PCB concentration was associated with a higher androgen/estrogen ratio. Further studies are needed to establish PCB-associated hormonal effects, windows of increased susceptibility, and the possible effect of PCBs in sub-fecundity (Petersen et al., 2015).

Persistent organic pollutants such as PCBs and PFASs are endocrine-disrupting compounds that may affect semen quality (Vested et al., 2014; Bach et al., 2016). A cross-sectional study investigated the reproductive function in a population of young Faroese men with high exposure to PCBs and PFASs (Petersen et al., 2018). Semen samples were analyzed for sperm concentration, total sperm count, semen volume, morphology and motility, and blood samples were analyzed for reproductive hormones, PCBs and PFASs. Results showed that ΣPCB and PFOS concentrations were positively associated with sex hormone-binding globulin and luteinizing hormone. Moreover, total testosterone was positively associated with ΣPCB. The increase in sex hormone-binding globulin by PCBs and PFOS might be liver-mediated. A compensatory adaptation might explain the higher total testosterone associated with PCBs, elevating sex hormone-binding globulin levels to obtain an unchanged free testosterone concentration. The positive association between luteinizing hormone and both PCBs and PFOS might suggest an adverse disturbing effect on Leydig cells and testosterone synthesis (Petersen et al., 2018).

As a part of the Russian Children's Study, longitudinal peripubertal serum organochlorine concentrations versus semen parameters were studied using 516 boys at age 8 to 9 years enrolled during 2003 through 2005 and followed for up to ten years (Minguez-Alarcon et al., 2017). At 18 to 19 years, 133 young men provided one or two semen samples (256 samples) collected about one week apart, analyzed for volume, sperm concentration, and motility. Compared with the lowest quartile, the highest quartile of peripubertal serum dioxins such as 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) and polychlorinated dibenzo-*p*-dioxin (PCDD) toxic equivalents (TEQs) were associated with lower sperm concentration, total sperm count, and total motile sperm count (p-trends ≤0.05), respectively. Similar associations were observed for serum PCDD TEQs with semen parameters. Serum PCBs, furans, and total TEQs were not associated with semen parameters. Thus higher peripubertal serum TCDD concentrations and PCDD TEQs were associated with poorer semen parameters (Minguez-Alarcon et al., 2017).

There are geographical differences between Denmark and Finland in the occurrence of diseases in male reproductive organs, including malformation in the reproductive tract. The reason for these differences is unknown, but differences in exposure to chemicals with endocrine-disrupting abilities including PFASs might be involved. A nested case-control study found no association between exposure to PFASs in cord blood and congenital cryptorchidism in 215 boys from Denmark and Finland upon adjustment for confounding factors (Vesterholm Jensen et al., 2014). The study included 29 Danish boys with congenital cryptorchidism, 30 healthy Danish matched controls recruited from 1997 to 2001, 30 Finnish cases, and 78 Finnish healthy matched controls recruited from 1997 to 1999. Additionally, 48 Finnish cases recruited from 2000 to 2002 were included. PFOA and PFOS were detected in all 215 Danish and Finnish cord blood samples, with significantly higher levels observed in the Danish samples (medians: PFOA, 2.6 ng/ml; PFOS, 9.1ng/ml) than in the Finnish samples (medians: PFOA, 2.1ng/ml; PFOS, 5.2ng/ml). The data indicate a different exposure to PFOA and PFOS of women in Denmark and Finland. Although, no statistically significant association between cord blood PFOA and PFOS levels and congenital cryptorchidism was seen, the study was small and larger studies are warranted (Vesterholm Jensen et al., 2014). There does not appear to be any study or new research on PFAS exposure and diseases in male organs in the Arctic populations. Future research might help identify whether there are possible health effects in Inuit male organs upon PFAS exposure.

4.4.2.5 Maternal exposure and sex ratio

Using prospective data from three Faroese birth cohorts, with 2152 healthy mother-child dyads recruited between 1986 and 2009, the secondary sex ratio was studied in relation to exposures to PCBs, DDE and MeHg (Timmermann et al., 2017b). The impact of maternal exposures to PCBs, DDE and MeHg on the secondary sex ratios (the ratio of male to female live births) was assessed over a span of 23 years. Maternal hair, serum or umbilical cord blood were used for exposure measurements. The associations between maternal exposures and the secondary sex ratio were assessed using confounder-adjusted logistic regression models. A doubling in ΣPCB, *p,p'*-DDE and Hg concentrations was associated with increased odds by 8%, 7% and 9%, respectively, of giving birth to a boy. Thus, maternal exposure to ΣPCB, DDE and MeHg was associated with a slightly increased secondary sex ratio of boys (Timmermann et al., 2017b).

4.4.2.6 Exposure models for hazard quotient

In a study including males and females of reproductive age in Greenland, Poland and Ukraine, the hazard quotient (HQ) profiles were assessed as a risk assessment tool for PFOS and PFOA serum levels (Ludwicki et al., 2015). Overall, results of PFOS and PFOA serum concentrations (589 males, 1437 females) obtained from the INUENDO database were used to calculate the HQs from the actual biomonitoring results and literature-based animal data linking toxicological outcomes and critical PFOS/PFOA serum levels. HQs for serum PFOS were calculated based on Points of Departure at 13 µg/mL (cynomolgus monkeys, 183 days, changes in thyroid-stimulating hormone (TSH) and triiodothyronine (T3)) and for PFOA at 7.1 µg/mL serum (male rats, 90 days, hepatocellular necrosis, increased liver weight). Uncertainty factors were applied to reflect interspecies differences and human variability. Serum HQs were expressed as a ratio relative to the point of departure for each of PFOS and PFOA. For three males (out of 196) in Greenland, the serum PFOS levels elicited HQ values exceeding 1, which suggests these serum levels may be of concern. The PFOS serum concentration was significantly higher in male compared to female populations. Although significant differences were observed between HQ profiles for PFOS and PFOA in participants from Greenland, Poland and Ukraine, the concentrations of these PFASs do not indicate a general concern, except for the three cases in Greenland. The HQ approach might help to interpret human exposure data and provide an important tool in risk assessment (Ludwicki et al., 2015).

4.4.3 Summary of latest findings

Health, exposure and birth outcome for pregnant women. A further transition from traditional to imported food was observed in Greenlandic pregnant women, as well as high smoking frequency, higher BMI and regional age differences for the pregnant women's plan for breastfeeding. The high level of POPs and heavy metals in maternal blood require further dietary recommendations to encourage increased intake of foods from the lower levels of the marine food chain, such as fish. The relatively high rate of tobacco smoking during pregnancy is of concern and was related to lower serum iron levels, which might affect oxygen transport in the body and thus to the fetus. Fetal growth and maternal smoking are inversely related. Exposure to POPs can also have negative effects on fetal growth. PFOA was significantly inversely associated with fetal growth indices, whereas gestation age was positively associated in the Greenlandic Inuit ACCEPT pregnant women. Fetal growth is also affected by prenatal exposure to heavy metals. In the pregnant ACCEPT women's serum, the lipophilic mixture of POPs has a hormone-disrupting effect interfering with both the estrogenic and androgenic receptor activity, which can have a disruptive effect on fetal development and growth. This was also observed for Danish pregnant women and their birth outcome.

Studies in Inuit and European cohorts report that phthalate, PFAS, and organochlorine chemical groups may independently be associated with impaired fetal growth. Moreover, β-HCH exposure might slow fetal growth when associated with an increased intake via breastfeeding. Cord blood serum 25(OH)D concentrations are positively associated with infant length but not with birth weight and head circumference. Possible long-term effects of late-pregnancy D hypovitaminosis deserve attention.

Exposure and female fertility and male reproduction parameters. Although there are indications that environmental exposure to PFASs may impair female fecundity (i.e., delaying time taken to conceive), the results do not provide consistent evidence to support this hypothesis.

Exposure to a mixture of organochlorines and phthalates can adversely affect parameters of male reproductive health. Metabolic pathways of phthalates differ significantly between European and Arctic study groups (Specht et al., 2014). DEHP metabolites, less for DINP metabolites, elicit weak anti-androgenic action but have no major effect on semen quality or reproductive hormones. A positive association for sex hormone-binding globulin and a negative association between free androgen index and high serum levels of HCB in fertile men was observed, but had little impact on semen quality. Faroese men had a lower Y:X ratio in sperm samples than Greenlandic Inuit and Swedish fishermen, but no direct reproductive health effect was found. Thus, the current studies on phthalates and POPs show no consistent exposure effect on female fertility and/or male reproduction parameters. However, high peri-pubertal serum TCDD concentrations and PCDD TEQs were associated with lower semen quality such as sperm concentration, total sperm count, and total motile sperm count. In addition, semen samples of high-exposure men to organochlorines at age 14 years and in adulthood were associated with sperm chromosomal disomy, suggesting impacts of POPs on testicular maturation and function.

In highly exposed fertile Faroese men, the serum PCB concentration was associated with a higher androgen/estrogen ratio. PCB exposure is associated with higher total testosterone and elevated sex hormone-binding globulin levels. PCBs and PFOS are positively associated with luteinizing hormone and might suggest an interfering effect on Leydig cells and testosterone synthesis. More research is needed on PCB- and PFAS-associated hormonal effects.

Exposure of women in Denmark and Finland to PFOA and PFOS shows differences in cord blood levels between countries, being highest in Denmark, but with no statistically significant association between cord blood PFOA and PFOS levels and congenital cryptorchidism. Future research on PFAS exposure and diseases in male organs in the Arctic populations might help identify whether there are possible health effects of PFAS exposure on Inuit male organs.

Maternal exposure to ΣPCB, DDE and MeHg was associated with an increase in the ratio of male to female live births.

Hazard quotient profiles used as a risk assessment tool for PFOS and PFOA serum levels in three European populations demonstrated that the HQ approach could help interpret human biomonitoring data and thus serve as an important tool in further risk assessment.

4.5 Cardiovascular effects

4.5.1 AMAP Assessment 2015: conclusions

Conflicting results have been reported regarding the impact of prenatal Hg exposure on blood pressure, with 7-year-old Faroese children exhibiting elevated blood pressure and children from Nunavik showing no association between blood pressure and prenatal Hg exposure. However, elevated blood pressure was found to be associated with Hg exposure among adults from the Faroe Islands and Nunavik. Decreased heart rate variability was associated with cord blood Hg concentrations in Faroese children at ages 7 and 14 years but not in 11-year-old children from Nunavik; however, contemporary blood Hg concentrations in these children from Nunavik were associated with decreased overall heart rate variability parameters. This was also the case for adults from Nunavik and for James Bay Cree adults.

4.5.2 New peer-reviewed literature

Long-chain omega-3 PUFAs, a measure of fish consumption, have been associated with a lower risk of cardiovascular disease, including sudden cardiac death. A marine diet also contains MeHg, which may attenuate the benefits of the long-chain omega-3 PUFAs, and has previously been associated with a higher risk of cardiovascular disease.

The association between serum long-chain omega-3 PUFAs and hair Hg with ventricular repolarization was investigated in the prospective, population-based Kuopio Ischaemic Heart Disease Risk Factor Study (Tajik et al., 2017). Serum long-chain omega-3 PUFA concentrations were inversely associated with heart QT and JT intervals and, during the mean 22.9-year follow-up, with lower sudden cardiac death risk. Hair Hg was not associated with either QT or JT intervals or sudden cardiac death risk, but did slightly attenuate associations of the serum long-chain omega-3 PUFA with QT and JT. Further study of these results in the Kuopio Ischaemic Heart Disease Risk Factor Study showed that a higher serum total long-chain omega-3 PUFA concentration was associated with lower resting heart rate. Higher hair Hg content had a trend towards lower peak heart rate. The findings suggest that higher serum long-chain omega-3 PUFA concentrations are associated with lower resting heart rate in middle-aged men from eastern Finland, which may partially explain the potential cardio protective effect of fish intake (Tajik et al., 2018).

Inuit in Canada have reported a low incidence of myocardial infarction, and this is mainly attributed to their traditional omega-3 fatty acid-rich marine diet (Hu et al., 2019). A rapid nutrition transition is occurring, and ischemic heart disease is now becoming a health concern. The Inuit traditional diet contains high levels of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), but also MeHg. The combined net effect of EPA, DHA and MeHg was estimated to reduce the relative risk of myocardial infarction by 1% in men and 2% in women, but the healthy Inuit diet is compromised by the adverse effects of MeHg. Encouraging Inuit to increase their intake of fish, which is rich in PUFAs but lower in MeHg, may reduce the risk of myocardial infarction (Hu et al., 2017).

The association between whole blood Hg and risk of developing cardiovascular disease in the Greenlandic population was prospectively assessed among 3038 Greenlandic Inuit participating in a population-based cohort study conducted from 2005 to 2010. High levels of whole blood Hg were observed in Greenland, yet no association was found between whole blood Hg and risk of developing cardiovascular disease (Larsen et al., 2018).

In a Finnish Fishermen study (n=255), participants represented a population with a high fish consumption and high exposure to environmental contaminants such as dibenzo-*p*-dioxins and dibenzofurans, PCBs and MeHg. Associations of fish consumption, omega-3 PUFAs and environmental contaminants with low-grade inflammation, early atherosclerosis, and traditional cardiovascular disease risk factors revealed that previously established hypotriglyceridemic and anti-inflammatory effects of omega-3 PUFAs were also seen in this study (Turunen et al., 2013). Omega-3 PUFAs seemed to decrease serum concentrations of triglycerides and inflammatory markers. Environmental contaminants were not associated with an increased risk of carotid artery plaques and environmental contaminants appeared to decrease insulin sensitivity and arterial elasticity (Turunen et al., 2013).

Among the Inuit in Nunavik, a resting heart rate was found to increase linearly with increasing amounts of blood MeHg concentrations. No significant association was observed between blood MeHg and systolic and diastolic blood pressure (Valera et al., 2013a), nor was a significant association observed between PCBs and organochlorine pesticides, and blood pressure in this highly exposed population (Valera et al., 2013b).

4.5.3 Summary of latest findings

Fish consumption and long-chain omega-3 PUFA intake have been shown to protect for cardiovascular disease. However, consumption of some fish also leads to a higher exposure to environmental contaminants, which may have adverse effects on health, including cardiovascular disease. In Finnish studies, hair Hg was not associated with sudden cardiac death. However, the associations of total long-chain omega-3 PUFAs with higher maximum rate of oxygen consumption were stronger among men with lower hair Hg levels. Higher serum long-chain omega-3 PUFA concentrations were associated with lower resting heart rate in middle-aged men from eastern Finland, which may partially explain the potential cardio-protective effect of fish intake.

The beneficial effect on myocardial infarctions of EPA and DHA in the traditional Inuit diet is diminished by the adverse effects of MeHg. Therefore, promoting the increased consumption of fish species with high EPA+DHA concentrations and low MeHg may help prevent myocardial infarctions among the Inuit.

No significant associations were observed between PCBs, organochlorine pesticides and blood pressure among Greenlanders.

A recent prospective study of Inuit in Greenland showed no association between blood Hg and risk of developing cardiovascular diseases.

4.6 Endocrine effects

4.6.1 AMAP Assessment 2015: conclusions

Endocrine-disrupting chemicals can mimic, interfere or block the function of endogenous hormones and so cause adverse developmental, reproductive, neurological, cardiovascular, metabolic and immune effects in humans. Studies have shown several POPs to be endocrine-disrupting chemicals, including PCBs, organochlorine pesticides and perfluorinated compounds. Exposure during fetal and neonatal development is especially critical and can disrupt normal development and risk of diseases later in life. In Greenlandic and European men, POPs (PCB153, *p,p′*-DDE) exposure seems to affect gonadotropin and steroid hormone-binding globulin levels.

High prenatal exposure to PCBs in the Faroe Islands may cause delayed puberty in boys with low serum luteinizing hormone levels due to a central hypothalamo-pituatary mechanism.

Exposure to POPs has been associated with modifications of thyroid hormone parameters in Inuit adults from Nunavik and the possible clinical significance merits further investigation.

Exposure to POPs can potentially influence Type 2 diabetes pathogenesis. High POP exposure was related to a decrease in fasting insulin concentration and a similar increase in fasting glucose. In persons with Type 2 diabetes, a PCB-induced β-cell deficiency may be involved in the pathogenesis. Moreover, studies suggest that vitamin D may provide protection against Type 2 diabetes in older persons.

The mixture of lipophilic POPs, extracted from adult Greenlandic Inuit serum and being free of endogenous hormones, elicits hormone disruptive effects affecting the estrogen-, androgen- and aryl hydrocarbon receptor function. The effect of the combined POP serum mixture on the androgen receptor was shown as a risk biomarker for breast cancer development in Inuit women.

4.6.2 New peer-reviewed literature

4.6.2.1 Exposure to endocrine-disrupting chemicals and effects on thyroid hormone system

Persistent perfluorinated compounds, which bioaccumulate in biota and humans, are suspected endocrine-disrupting chemicals that can also disrupt thyroid hormone (TH) homeostasis in humans. In an Alaska study, fasting blood samples from 85 native individuals from St. Lawrence Island were analyzed for the relationship between exposure to PFASs and serum TH levels, with concentrations of 13 PFASs, free and total thyroxine (T4), free and total triiodothyronine (T3), and thyrotropin (TSH) measured in serum samples (Byrne et al., 2018a). Several PFASs, including PFOA and PFNA, were positively associated with TSH concentrations when modeled individually. PFOS and PFNA were significantly associated with free T3 and PFNA was significantly associated with total T3 in models with PFAS-sex interactive terms. These results suggested negative associations in men and positive associations in women. PFASs were not significantly associated with concentrations of free or total T4. These data suggest that serum PFAS concentrations associate with circulating TH and the effects of PFAS exposure on TH homeostasis may differ between sexes (Byrne et al., 2018a).

Arctic Indigenous Peoples are exposed to PBDEs through their traditional diet including marine mammals. PBDEs can disrupt thyroid homeostasis. In another Alaska study, including 85 Yupik from St. Lawrence Island, the associations between serum PBDEs and TH were examined in a cross-sectional study (Byrne et al., 2018b). Measurements were undertaken on blood serum samples taken after fasting for at least 8 hours. The study found positive associations between serum concentration of penta-BDE congeners (PBDE28/33, PBDE47, and PBDE100) and concentrations of TSH and free T3, whereas serum concentrations of PBDE153 were negatively associated with total T3 concentrations. Both PBDE47 and PBDE153 remained significantly associated with THs in the adjustment model. Serum concentrations of PBDEs did not associate with either free or total T4. Thus, PBDEs associate with THs in serum although the effect differs by congener (Byrne et al., 2018b).

The influence of POPs on the maternal thyroid system is of special interest during pregnancy because such effects could impair infant thyroid homeostasis. The Northern Norway Mother-and-Child Contaminant Cohort Study (MISA) conducted a study on POPs association with maternal and infant thyroid homeostasis including 391 pregnant women in their second trimester and TSH concentrations in heel-prick samples from the infants (Berg et al., 2017a). The women were asked to be fasting or eat a light, non-fatty breakfast no later than 2 hours before the blood sampling. Blood samples of infants were collected three days after birth. Several POPs were significantly associated with TSH and thyroid hormones: PFOS was positively associated with TSH; PCBs, HCB, and nonachlors were inversely associated with T3, T4, and free thyroxine (FT4); and perfluorodecanoic acid (PFDA) and perfluoroundecanoate (PFUnDA) were inversely associated with T3 and free triiodothyronine (FT3). After adjusting for the other contaminants, only PFDA and PFUnDA remained significantly associated with T3 and FT3, respectively. Comparing infants born to mothers within the highest TSH quartile and children born to mothers in the lowest TSH quartile, the former had 10% higher mean concentrations of TSH. The results suggest that background exposures to POPs can alter maternal thyroid homeostasis and help with understanding the complexity of POP mixture exposure on maternal and infant thyroid function (Berg et al., 2017a).

Another MISA study assessed the mixed effects on the relationship between PFASs, TH and thyroid-binding proteins using a longitudinal study design including blood samples from women taken during pregnancy and postpartum 2007–2009 (Berg et al., 2015). The subjects included 391 women of the MISA cohort, which comprises 515 enrolled pregnant women. All participants answered a detailed questionnaire about diet and lifestyle at enrolment, and donated a blood sample at three visits/ time points related to their pregnancy. Fasting state was requested for blood sampling (around gestational week 18, and 3 days and 6 weeks after delivery). PFASs were determined in blood samples taken at gestational week 18. Thyroid hormones (TH, thyroid-binding proteins, thyroxin binding capacity and thyroid peroxidase antibody concentrations) were determined in non-fasting serum samples from three visits (second trimester, and 3 days and 6 weeks after delivery). The highest PFOS quartile elicited a 24% higher mean concentration of TSH compared to the first quartile, whereas the highest quartiles of PFDA and PFUnDA elicited a 4% lower mean concentration of T3 and a 3% lower mean concentration of FT3, respectively. Concentration differences and changes between time points were the same for the PFAS quartiles. All the THs and thyroid-binding proteins were associated with thyroxin-binding capacity. Maternal iodine status had no influence. These findings suggest that PFASs can modify TH homeostasis in pregnant women. The variation in TH levels between PFAS quartiles might not be of clinical significance, but the TH changes in pregnant women might have consequences for fetal health (Berg et al., 2015).

Exposure to organochlorine compounds during pregnancy can alter TH levels (Alvarez-Pedrerol et al., 2009). Iodine deficiency during pregnancy might influence maternal and fetal thyroid function causing a risk of offspring neurocognitive and psychomotor deficits. The MISA mother-child cohort also studied the relation between thyroid homeostasis in mother–child pairs and maternal iodine status (Berg et al., 2017b). Maternal blood and urine samples (n=197) were collected in the second trimester, 3 days and 6 weeks postpartum (time and fasting not given, although women were requested to fast before blood sampling). The median urine iodine concentration in the second trimester was 84 μg/L (range 18–522 μg/L) and 80% had urine iodine concentrations below the recommended level (<150 μg/L). Moreover, compared to iodine-sufficient women, iodine-deficient women had higher concentrations of T3, FT3 and FT4 of 0.10 nmol/L, 0.16 pmol/L and 0.45 pmol/L, respectively, although the concentrations were within normal reference ranges. However, iodine deficiency was observed in the majority of women with subclinical hypothyroidism. Maternal iodine status did not influence infant TSH concentrations in heel prick samples. This MISA study indicates iodine deficiency among pregnant women in northern Norway can be a risk factor influencing maternal thyroid homeostasis and fetal and infant development (Berg et al., 2017b).

Phthalate exposures may have an impact on child neurodevelopment; reports link prenatal exposure to phthalates with externalizing behaviors and executive functioning defects suggestive of an ADHD phenotype. A nested case-control of the MoBa Norwegian Mother and Child Cohort (2003–2008) studied risk of ADHD, prenatal exposure to phthalates and maternal thyroid function (Engel et al., 2018). The study included phthalate metabolites measured in maternal urine mid-pregnancy. The study included 297 ADHD cases and 553 controls. The sum of phthalate metabolites (ΣDEHP) was associated with increased risk of ADHD. Children of mothers in the highest quintile of ΣDEHP had three times the odds of an ADHD diagnosis as those in the lowest. For each log-unit increase in ΣDEHP exposure, the odds of ADHD increased by 47%. In this case-control study of clinical ADHD, maternal urinary concentrations of DEHP were associated with increased risk of ADHD. The study found no evidence of exposure–mediator/ interaction terms of the ΣDEHP-ADHD relationship by any of the measured maternal thyroid hormone biomarkers (Engel et al., 2018).

To examine early life exposure to endocrine-disrupting chemicals and TSH levels in newborns, heel-prick-blood-spot blood samples (taken within 4–6 days of birth) were collected on a filter paper from each newborn through heel puncture (timing not given). Three European mother-child cohorts were pooled: FLEHSI-Belgium, HUMIS-Norway, and the PCB cohort-Slovakia (n=1784) (de Cock et al., 2017). The order of median TSH concentrations was Slovak > Norwegian > Belgian (1, 1.10, and 2.76 mU/L, respectively). Children in the third exposure quartile of PCB153 and *p,p*'-DDE had 12–15% lower TSH at birth. Adjusting for birth weight and gestational weight did not influence the data. The study showed that early life exposure to PCB153 and *p,p*'-DDE affected newborn TSH levels in three European mother-child cohorts (de Cock et al., 2017).

A study on pilot whales (*Globicephala melas*) from the Faroe Islands examined the relation between concentrations of POPs and THs and vitamins A, E and D (Hoydal et al., 2016). The data showed higher TH levels in juveniles and higher α- and γ-tocopherol in liver in adults. Age and sex influenced the relationship between biomarkers and POPs and the study observed positive associations in the youngest juveniles and only a few significant correlations between single POPs, retinol, and vitamin D in plasma within the age groups. For further comparison to human studies, this pilot whale study showed that POPs exposure had a relatively minor effect on biomarkers of TH and vitamins (Hoydal et al., 2016).

4.6.2.2 Exposure to endocrine-disrupting chemicals: body mass index – obesity

Chemicals with endocrine-disrupting abilities may act as obesogens and interfere with the body's natural weight-control mechanisms, especially if exposure occurs during prenatal life.

The INUENDO project investigated prospectively the association between estimated postnatal serum concentrations and BMI z-scores in 5- to 9-year-old children and PCB153 and *p,p*'-DDE concentrations during maternal pregnancy (n=109; 2002–2004) (Høyer et al., 2014). This follow-up study of Greenlandic, Polish and Ukrainian populations found no clear association between pregnancy PCB153 and *p,p*'-DDE and child BMI, or for postnatal exposure to *p,p*'-DDE and PCB153 and BMI at age 5 to 9 years (Høyer et al., 2014).

Another INUENDO cohort study investigated child BMI and obesity in relation to prenatal PFAS exposure including 1022 pregnant women from Greenland and Kharkiv (Ukraine) (Høyer et al., 2015c). The pregnancy median range for PFOA was 1.8 (0.5–5.1) and 1.0 (0.2–9.8) ng/ml for Greenland and Ukraine, respectively, and for PFOS was 20.2 (4.1–87.3) and 5.0 (0.7–18.1) ng/ml for Greenland and Ukraine, respectively. The children were between 5 and 9 years old. The study found that prenatal PFOA and PFOS exposures might be associated with a child waist-to-height ratio >0.5, whereas exposures were not associated with overweight (Høyer et al., 2015c).

A prospective cohort study from the Faroe Islands, involving 656 pregnant women (1997–2000), studied the association between prenatal PCBs and *p,p*'-DDE exposure in serum and breastmilk (4 to 5 days after parturition) in relation to obesity at ages 5 and 7 years. ΣPCB is the sum of congeners PCB138, PCB153, and PCB180 multiplied by 2 (Tang-Péronard et al., 2014). For 7-year-old girls with overweight mothers, PCBs were positively associated with increased BMI, and PCBs and DDE were positively associated with an increase in BMI from age 5 to 7 years. No association with BMI was found for girls with normal-weight mothers. PCBs were significantly associated with increased waist circumference in girls with overweight mothers and normal-weight mothers. For DDE, increased waist circumference was found only in girls with overweight mothers. No associations were observed between PCBs or DDE and BMI in 5-year-old girls. No associations were observed for boys. This Faroe Island study suggests that prenatal exposure to PCBs and DDE may play a role in subsequent obesity development especially for girls whose mothers have a high pre-pregnancy BMI (Tang-Péronard et al., 2014).

A study, on Faroese children born 2007–2009, investigated early-life exposure to POPs and risk of overweight in preschool children (Karlsen et al., 2017). Maternal serum concentrations of HCB, PFOS and PFOA were associated with increased BMI z-scores and/or overweight, whereas no clear association was found for maternal serum PCBs, *p,p'*-DDE, PFHxS, PFNA and PFDA. These findings in Faroese children support a role of maternal exposure to endocrine disruptors in the childhood obesity epidemic (Kim et al., 2009).

Gestational diabetes is associated with increased availability of glucose and macronutrients in fetal circulation and macrosomia. A study on 604 pregnant Faroese women and their offspring born 1997–2000 investigated offspring birth size at high POP exposures in relation to gestational diabetes (Valvi et al., 2017). Maternal pregnancy serum concentrations of PCB congeners and DDE, and five PFASs, and hair and cord blood Hg concentrations were measured. Serum-DDE and hair-Hg concentrations were significantly associated with gestational diabetes. Upon multiple pollutant-adjusted structural equation models (SEMs) only a positive association between PCB and DDE exposure and gestational diabetes remained significant. PCB and overall organochlorine exposure were positively associated with head circumference, whereas overall PFAS exposure was inversely associated with birth weight. For many single PFASs, a pattern elicited inverse associations with birth weight and head circumference in boys, and positive or no associations in girls. No association was found with offspring length. Gestational diabetes neither modified nor mediated the associations with birth size measures. The study found associations with gestational diabetes and offspring birth size to be specific to the environmental pollutant or pollutant group, although the associations with birth size measures appear to be independent of gestational diabetes occurrence (Valvi et al., 2017).

A Scandinavian cohort, sampled in 1986–1988, prospectively studied whether prenatal exposure to POPs was related to child overweight/obesity at 5-year follow-up (Lauritzen et al., 2018). Serum samples from 412 pregnant Norwegian and Swedish women were analyzed for two PFASs (PFOS and PFOA) and five organochlorine compounds. An increased BMI-for-age-and-sex z-score, and increased triceps skinfold z-score were found in children at 5-year follow-up per natural logarithm unit (ln-unit) increase in maternal serum PFOS concentrations. Moreover, an increased odds for child overweight/obesity (BMI ≥85th percentile) was found for each ln-unit increase in maternal serum PFOS levels, with stronger odds among Norwegian children. The study found similar associations between maternal serum PFOA concentrations and child overweight/obesity. In addition, there were indications of non-monotonic dose-response relationships between PFOS and PCB153 and child overweight/obesity among Swedish children. Thus, the study reports positive associations between maternal serum PFAS concentrations and child overweight/obesity at 5-year follow-up, particularly among Norwegian participants and some evidence for non-monotonic dose-response relationships among Swedish participants (Lauritzen et al., 2018).

Dioxins and dioxin-like compounds are endocrine-disrupting chemicals. Experimental studies suggest perinatal exposure results in later obesity. However, few and inconclusive epidemiological investigations on dioxins are reported. Pooled data from three European birth cohorts (Belgian, Norwegian, Slovak) with exposure assessment in cord blood or breastmilk, were compared to infant growth, and BMI at 7 years of age in relation to prenatal exposure to dioxins and dioxin-like compounds (Iszatt et al., 2016). Dioxin exposure was highest in the Belgian cohort and lowest in the Norwegian cohort; median interquartile range of the pooled sample was 13 (12.0) pg CALUX-TEQ/g lipid. Perinatal exposure to dioxins and dioxin-like compounds appeared to be associated with increased growth between 0 and 24 months, and at 7 years of age, dioxin exposure was associated with a statistically significant increase in BMI in girls but not in boys. Furthermore, girls had a 54% increased risk of overweight at 7 years. The study demonstrated that perinatal exposure to dioxin and dioxin-like compounds is associated with increased early infant growth, and increased BMI in school age girls (Iszatt et al., 2016).

Data interpretation of the European Youth Heart Study (1997) assessed the associations between exposure to POPs in childhood and overweight up to 12 years later in a Danish population (Tang-Péronard et al., 2015a). In general, the POP serum concentrations were low: median ΣPCB 0.18 μg/g lipid, DDE 0.04 μg/g lipid and HCB 0.03 μg/g lipid. POPs were generally not associated with weight gain at 14–16 and 20–22 years of age, except for an inverse association among the highest exposed girls at 20–22 years of age. The data suggest that in this low-exposed Danish population, childhood serum concentrations of PCBs, DDE, and HCB are not associated with subsequent weight gain (Tang-Péronard et al., 2015a).

In most epidemiological studies, POPs have shown positive associations with serum markers of non-alcoholic fatty liver disease and, together with obesity, synergistic association with insulin resistance. Insulin resistance and obesity are critical in non-alcoholic fatty liver disease pathogenesis. A Finnish study investigated the association of serum POP levels with liver histology and alanine aminotransferase (ALT) in highly obese individuals (Rantakokko et al., 2015). The study included liver biopsies from participants of the Kuopio Obesity Surgery Study who underwent surgery 2005–2011 (Rantakokko et al., 2015). Serum concentrations of PCB118, β-HCH and several PFASs had an inverse association with lobular inflammation, possibly due to changes in bile acid metabolism. The study found negative associations between ALT and many POPs at baseline that turned positive at 12 months after major clinical improvements. There was an interaction between some POPs and sex at post-12 months, and in stratified data, positive associations mainly in females but not in males. The study found a negative association of serum concentrations of PCB118, β-HCH and several PFASs with lobular inflammation at baseline. Positive POPs-ALT associations at post-12 months among women suggest that increased POP concentrations may decrease the degree of liver recovery (Rantakokko et al., 2015).

4.6.2.3 Exposure to endocrine-disrupting chemicals and risk of diabetes

It is hypothesized that total Hg exposure (elemental, inorganic or organic) can lead to the development of diabetes. Metabolic syndrome is also a possible outcome as its symptoms link to those of diabetes. A systematic review assessed whether Hg exposure can cause diabetes, metabolic syndrome and insulin resistance (Roy et al., 2017). Thirty-four studies were included in the review. The epidemiological data assessment suggests a possible association between total Hg concentrations in different biological matrices and incidence of diabetes or metabolic syndrome, but the relationship is not consistent. *In vivo* and *in vitro* studies support the biological plausibility of the relation between Hg exposure and diabetes or metabolic syndrome. Five out of nine of Bradford Hill's criteria were fulfilled: strength, temporality, plausibility, coherence and analogy. The review reports that increased total Hg exposure may increase the risk of diabetes and metabolic syndrome. However, the lack of consistency of the epidemiological evidence prevents inference of a causal relationship. Additional prospective cohort studies and careful consideration of confounding variables and interactions are required to conclude whether there are causal relations between total Hg exposure and the development of diabetes or metabolic syndrome (Roy et al., 2017).

Based on data from a prospective Faroese Birth Cohort (n=656), recruited 1997–2000, prenatal exposure to POPs is associated with high insulin levels in 5-year-old girls (Tang-Péronard et al., 2015b). Previously, in the same cohort it was found that there are associations between prenatal POP exposures and increased BMI, waist circumference and change in BMI from 5 to 7 years of age, although only among girls with overweight mothers (Tang-Péronard et al., 2014). PCBs, *p,p′*-DDE and HCB were measured in pregnant women's serum and breastmilk. Children were followed up at 5 years of age when a non-fasting blood sample was taken (273 boys and 247 girls). Girls with the highest prenatal POP exposure were more likely to have high non-fasting insulin levels. No significant associations were found among boys, or with leptin. These findings from the Faroese Birth Cohort, suggest that for girls, prenatal exposure to POPs may play a role in later development of metabolic diseases through affecting the level of insulin (Tang-Péronard et al., 2015b).

A cross-sectional study examined dietary patterns in Greenland and their relationship with Type 2 diabetes mellitus, and glucose intolerance and impaired fasting glucose (Jeppesen et al., 2014). Participants with a traditional Greenlandic marine diet had high mean fasting plasma glucose and low β-cell function, and gave significantly higher risk for impaired fasting glucose and Type 2 diabetes compared to the 'balanced diet', 'imported meat diet', 'standard diet' and 'unhealthy diet'. The data suggest that the Greenlandic traditional marine food was positively associated with Type 2 diabetes, impaired fasting glucose and fasting plasma glucose, and negatively associated with β-cell function. In relation to glucose intolerance, imported meat was associated with the lowest fasting plasma glucose and had the lowest risk for impaired fasting glucose and Type 2 diabetes (Jeppesen et al., 2014).

Mercury exposure has been associated with glucose intolerance in Western populations. A cross-sectional study, involving 2640 Inuit (age 18+ years) with information on ancestry, smoking, waist circumference, total energy intake, and physical activity, reported associations between whole blood Hg and glucose intolerance among adult Inuit in Greenland (Jeppesen et al., 2015). Positive association was found between whole blood Hg increase (5 µg/L) and fasting glucose and 2-hour glucose. Moreover, Hg was associated with impaired fasting glycemia and Type 2 diabetes. In Greenlandic Inuit, these data suggest a statistically significant association between whole blood Hg and impaired fasting glycemia and Type 2 diabetes, but show no association with underlying disturbances in glucose homoeostasis (Jeppesen et al., 2015).

A study using a standard additive genetic model identified a *TBC1D4* gene loss-of-function variant with a large recessive impact on risk of Type 2 diabetes in homozygous carriers of this variant in Greenlanders (Moltke et al., 2014) (for further details, see Section 4.8.2.6). Aiming to identify additional genetic variation underlying Type 2 diabetes, a study used a recessive genetic model to better elucidate the detection of variants with recessive effects (Grarup et al., 2018). The study investigated three cohorts of Greenlanders. Of the 4674 genotyped individuals, 4648 had phenotype data available, and association analyses were undertaken for Type 2 diabetes for 317 individuals with Type 2 diabetes and 2631 participants with normal glucose tolerance. Two novel loci (rs870992 in ITGA1 chromosome 5, rs16993330 upstream of LARGE1 chromosome 22) associated with Type 2 diabetes were identified. Both variants were common in Greenlanders, with minor allele frequencies of 23% and 16%, respectively, and estimated to have large recessive effects on risk of Type 2 diabetes in Greenlanders, compared with inherited variants previously found in European populations. The findings give new insights into the genetics of Type 2 diabetes, and support the existence of high-effect genetic risk factors particularly in isolated populations such as from Greenland (Grarup et al., 2018).

The relationship between fish or omega-3 PUFAs and Type 2 diabetes is inconclusive and even contaminants in fish, such as Hg, may modify the effects. Using the Kuopio Ischemic Heart Disease Risk Factor population-based data, the risk of incident Type 2 diabetes was studied in Finnish men vs serum omega-3 PUFAs (Virtanen et al., 2014). Serum PUFA and hair Hg were used as biomarkers of exposure recording a four-day dietary intake. Type 2 diabetes was assessed by self-administered questionnaires, and fasting and 2-hour oral glucose tolerance test blood glucose measurement at re-examinations. During the follow-up (mean 19.3 years), 422 men were found to have developed Type 2 diabetes. Men in the highest versus the lowest serum EPA+DPA+DHA quartile had 33% lower risk for Type 2 diabetes. No statistically significant associations were found for serum or dietary α-linolenic acid, dietary fish or EPA+DHA, or hair Hg. The long-chain omega-3 PUFA serum concentration was associated with long-term lower risk of Type 2 diabetes in Finnish men (Virtanen et al., 2014).

Zinc (Zn), involved in antioxidant and anti-inflammatory activities, might play a role in the development of Type 2 diabetes. In the Kuopio Ischaemic Heart Disease Risk Factor Study, a project was conducted on serum Zn and risk of Type 2 diabetes incidence in middle-aged and older Finnish men as a 20-year prospective follow-up study involving 2220 Finnish men (Yary et al., 2016). The men were 42 to 60 years old at baseline in 1984–1989. Serum Zn was associated with higher BMI, serum insulin, insulin resistance, β-cell function and the binding protein IGFBP-1 and lower insulin sensitivity. During the follow-up (mean 19.3 years), 416 men were found to have developed Type 2 diabetes. Men in the highest quartile of serum Zn had 60% higher risk for incident Type 2 diabetes compared to men in the lowest quartile. This association attenuated after adjustment for BMI or lower insulin sensitivity, whereas adjustment for the other factors had less impact on the association. Thus, higher serum Zn was associated with higher risk of Type 2 diabetes; effects of Zn on BMI and insulin sensitivity might explain the association (Yary et al., 2016).

Differences in trace element levels between individuals with Type 2 diabetes and controls were reported in several studies for various body fluids and tissues, but results have been inconsistent. The HUNT study in Norway investigated as a case-control study the trace elements in an early phase Type 2 diabetes mellitus-A population-based study (Hansen et al., 2017). The study showed the association between whole blood levels of 26 trace elements and the prevalence of previously undiagnosed, screening-detected Type 2 diabetes. The prevalence of previously undiagnosed Type 2 diabetes increased across tertiles /quartiles for Cd, Cr, iron (Fe), Ni, silver (Ag) and Zn, and decreased with increasing quartiles of bromine (Br) (P_{trend} <0.05). After corrections for multiple testing, associations for Cr remained significant (Q_{trend} <0.05), while associations for Fe and Ag were borderline significant. The study found no associations for arsenic, boron, calcium, cesium, Cu, gallium, gold, indium, Pb, magnesium, manganese, Hg, molybdenum, rubidium, selenium, strontium, tantalum, thallium and tin. Although only significant for Cr, the study suggests a possible role of Br, Cd, Cr, Fe, Ni, Ag and Zn in the development of Type 2 diabetes but further studies are needed (Hansen et al., 2017).

Previous analysis examined the contribution of endocrine-disrupting chemical exposures to adult diabetes, but was limited to the effects of phthalates in middle-aged women and did not simultaneously examine multiple endocrine-disrupting chemicals. Using a prospective cross-sectional investigation of Uppsala seniors (about 1000 participants), a study investigated the risks and costs of diabetogenic chemical exposures in the elderly (Trasande et al., 2017). Estimated risk reductions were based on assuming identical 25% reductions across the levels of four compounds (PCB153, mono-ethylphthalate, DDE, PFNA), and diabetes costs saved in European men and women when diabetogenic exposures are limited. A decrease in exposures was associated with a 13% decrease in prevalent diabetes, compared with 40% resulting from an identical decrease in BMI. Extrapolating to Europe, 152,481 cases of diabetes in Europe and €4.51 billion per year in costs could be prevented, compared with 469,172 cases prevented by decreasing BMI. These findings for elderly in Europe support regulatory and individual efforts to reduce exposure to endocrine-disrupting chemicals in order to reduce the burden and costs of diabetes (Trasande et al., 2017).

Exposure to endocrine-disrupting chemicals such as POPs was linked to Type 2 diabetes and metabolic disturbances in epidemiological and animal studies, but little is known about POPs exposure during pregnancy and the development of gestational diabetes. A study investigated the POP level in early pregnancy and risk of gestational diabetes mellitus including in 939 women from the 'Rhea' pregnancy cohort in Crete, Greece (Vafeiadi et al., 2017). Concentrations of PCBs, DDE, and HCB were determined in the first maternal trimester. Seven percent of the pregnant women developed gestational diabetes, and serum concentrations of POPs were higher in women with gestational diabetes. After adjusting for pre-pregnancy BMI and several other confounding factors, women in the medium and high tertiles of PCBs had a 3.90- and 3.60-fold higher risk, respectively, of developing gestational diabetes compared to women in the lowest tertile of PCB exposure. Risk of gestational diabetes for women in the medium and high tertiles of dioxin-like PCBs was 5.63- and 4.71-fold higher, and for non-dioxin-like PCBs 2.36- and 2.26-fold higher, respectively. Prenatal DDE and HCB exposures were not significantly associated with gestational diabetes risk. These findings suggest that women with high PCB levels in early pregnancy have higher risk for gestational diabetes (Vafeiadi et al., 2017).

A number of studies have found a relation between POP concentrations and Type 2 diabetes, but with no clear causality. A pharmacokinetic model study conducted to confirm or reject the hypothesis of POPs causing Type 2 diabetes using pharmacokinetic analysis and dietary information included a group of 409 adult surgical patients with known PCDD/F concentrations and dietary information (Tuomisto et al., 2016). A model assuming a 10% annual decrease in past PCDD/F intake predicted the measured profile of toxic equivalent (TEQ) in the population. Age was the dominant determinant of PCDD/F level, and the level was associated with consumption of animal products. Predicted daily intakes correlated with diet and BMI, indicating that high consumption of foods containing PCDD/Fs relates to high BMI. These results from the pharmacokinetic analysis suggest that high intake of animal foods might explain both higher levels of POPs in the body and higher incidence of Type 2 diabetes, and BMI alone cannot explain the confounding caused by diet. Studies, including the analysis of food consumption, are needed to consider the pharmacokinetics of compounds, in order to address causality between POPs and Type 2 diabetes (Tuomisto et al., 2016).

4.6.2.4 Exposure to endocrine-disrupting chemicals: Trends, levels, effects and mechanisms

Risk assessment of mixture exposures is important because no individual is exposed to only one chemical at a time. Use of the 'concentration addition concept' as a reasonable worst-case approach to the predictive hazard assessment of chemical mixtures was described by Kortenkamp et al. (2009), and supported in a European Commission document (SCHER et al., 2012). The marine food chain is particularly important to the Arctic populations.

Trend and levels

The risk of POP mixtures on the Arctic food chain was reviewed, assessing exposure to POPs in the Arctic ecosystem (Villa et al., 2017). The highest levels of the Arctic food chain estimated the eco-toxicological risk for seals, bears, and bear cubs applying the concentration addition concept (Kortenkamp et al., 2009; SCHER et al., 2012). The risk of POP mixtures was low in seals, but two orders of magnitude higher for adult polar bears and even more for bear cubs. Based on temporal trends available, the trend of the mixture risk for bear cubs was calculated. Compared to the 1980s, the data show a decrease in risk from the POP mixture, explained by international regulations. However, the composition of the mixture changed due to the release of new chemicals, causing increases in POPs of emerging concern (particularly PFASs). These results support the effectiveness of regulations and control measures for chemicals listed in the Stockholm Convention, and the urgent need for their implementation for new and existing POPs of emerging concern (Villa et al., 2017).

The Fetotox project included five international birth cohorts and involved the measurement of PFAS concentrations in serum from pregnant women in four countries: Denmark, China, Norway, and Greenland (Bjerregaard-Olesen et al., 2017). The pooled birth cohorts included a total of 4718 pregnant women: the Danish National Birth Cohort (DNBC, 1996–2002, Denmark), the Aarhus Birth Cohort (ABC, 2008–2013, Denmark), the Shanghai Birth Cohort (SBC, 2013–2015, China), the Northern Norway Mother-and-Child Contaminant Cohort (MISA, 2007–2009, Norway), and the Greenlandic Birth Cohort (ACCEPT, 2010–2013, Greenland) (Bjerregaard-Olesen et al., 2017). The DNBC samples (taken 1996–2002) had the highest concentration of PFASs compared to samples from the other cohorts (i.e., 2007–2015) (Figure 4.2). The DNBC PFAS level was also significantly higher than for the other Danish cohort (ABC, 2008–2013), indicating a clear decreasing trend for PFOA, PFOS, Perfluoroheptane sulfonic acid (PFHpS) and PFHxS, which might be partly due to regulations. In contrast, PFNA, PFDA and perfluoroundecanoate (PFUnDA) seemed to increase in the Danish samples from 1996–2002 to 2008–2013. Comparing the PFAS level between cohorts in the period 2007–2015, the concentrations of all perfluoroalkane sulfonic acids (PFSAs) and one perfluorinated carboxylic acid (PFCA; PFUnDA) were highest in the Greenlandic ACCEPT women, whereas the other three PFCAs were highest in the Chinese women. The Danish ABC and the Norwegian MISA women elicited similar concentration and composition of serum perfluoroalkyl acids, whereas across the cohorts, the highest levels were found for the Chinese SBE and Greenlandic ACCEPT birth cohort. China is a producer of PFASs – but lifestyle and diet differences might also explain the different PFAS exposure profiles. The different concentrations and profile patterns between countries might affect health implications associated with high PFAS exposure (Bjerregaard-Olesen et al., 2017). For more detailed information on biomonitoring see Chapter 3.

Effects and mechanisms

The ATP-binding cassette transporters (ABC transporters) are a transport system superfamily that is one of the largest and possibly one of the oldest gene families (Wikipedia, 2010). Several ABC transporters expressed in the human placenta play a role in the transport of endogenous compounds and may protect the fetus from chemicals such as therapeutic agents, drugs of abuse, and other xenobiotics. Thus, many of these compounds are substrates and regulators of human placental ABC-transporters. The *ABCG2* protects the fetus against foreign chemicals such as environmental xeno-estrogens, like bisphenol A and *p*-nonylphenol found in consumer products such as plastics and for example cosmetics and paints, respectively (see also Chapter 3), which can mimic natural estrogens. The effects of bisphenol A, *p*-nonylphenol, diethylstilbestrol and estradiol on *ABCG2* expression were studied using human first trimester and term placental explants (Sieppi et al., 2016). The effect of chemicals on estrogen receptor (ER) function was studied using an ER antagonist. Term placenta expressed less *ABCG2* protein, and bisphenol A ($p<0.05$), *p*-nonylphenol ($p<0.01$) and estradiol ($p<0.05$) decreased the *ABCG2* protein expression after 48 hours of exposure, while after 24 hours of exposure, only estradiol decreased the expression significantly. The chemicals did not affect *ABCG2* in first trimester placentas. The ER antagonist ICI 182780 was used to clarify whether the effects of chemicals on *ABCG2* are mediated via ER. The ER antagonist affected the responses of chemicals differently. The study showed that these environmental xeno-estrogens downregulate placental *ABCG2* protein expression depending on gestational age (Sieppi et al., 2016).

Animal model studies

Although international prohibitions and restrictions are in place, dioxin-like chemicals and brominated flame retardants are ubiquitous in the environment and can accumulate in animals as well as humans. A study investigated the temporal trend in levels of POPs in bank voles (*Myodes glareolus*) in northern Finland (Murtomaa-Hautala et al., 2015). Concentrations of PCDDs/furans, PCBs and PBDEs were measured in liver and muscle of bank voles caught in Finnish Lapland between 1986 and 2007 at five time points: 1986, 1992, 1998, 2003 and 2007. In both females and males, the levels of PCDDs/furans and PCBs declined between 1986 and 2003, but then tended to increase again in 2007. Peak levels of the most abundant PBDE congeners (PBDE47, PBDE99, PBDE100, PBDE153) occurred in 1998 and 2003. These results reveal that the levels of dioxin-like chemicals remain high in rural areas in Lapland, whereas concentrations of brominated flame retardants decreased following the current restrictions (Murtomaa-Hautala et al., 2015).

There is limited research on exposure to the actual POP mixtures present in humans. In contrast, a series of studies have assessed the occurrence, levels, and potential adverse effects of POPs in fish from a lake in Norway where high levels of POPs were detected in biota. Such studies might help elucidate possible effects in humans. An experimental fish model was used to study the endocrine effects of real-life mixtures of POPs in wild fish from Lake Mjøsa, while fish from the nearby Lake Losna had background levels of POPs and served as a control (Berg et al., 2016). Significantly higher prevalence of mycobacteriosis and pathological changes were seen in burbot (*Lota lota*) from Mjøsa compared to burbot from Losna. Transcriptional profiling also identified changes in gene expression in burbot from Mjøsa compared to burbot from Losna, genes being associated with drug metabolism enzymes and oxidative stress. In the fish model, POPs extracted from burbot liver oil from the two lakes were used to expose zebrafish (*Danio rerio*) during two consecutive generations. For both generations, POP mixtures from both lakes increased the rate of mortality, induced earlier onset of puberty, and skewed the sex ratio toward males. Moreover, for both generations the exposed groups elicited opposite effects on weight gain compared to the controls. Ovarian follicle development suppression was associated with exposure to POPs from both lakes. Analyses of genome-wide transcription profiling identified functional

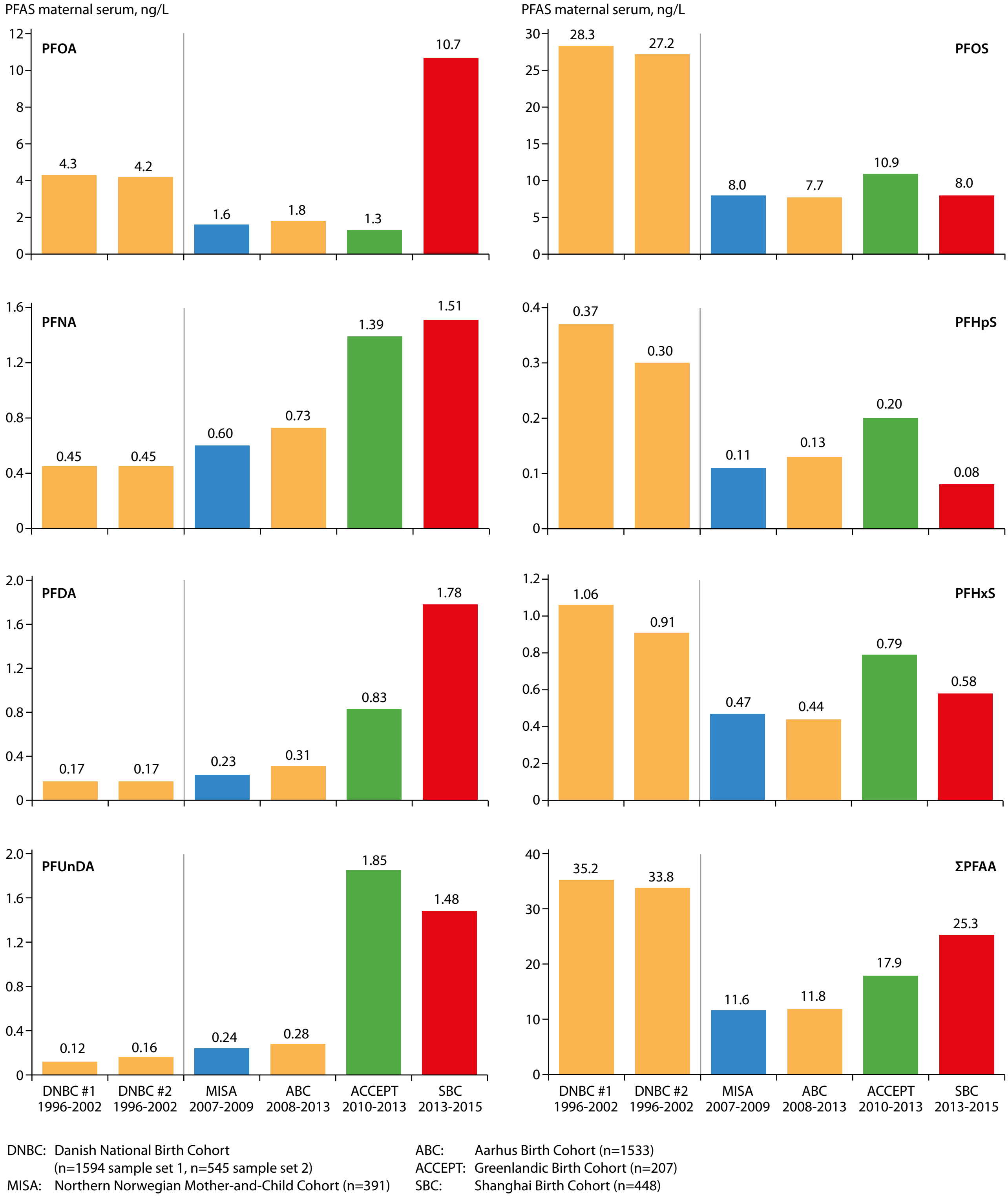


Figure 4.2 Geometric mean concentrations (ng/mL) of PFASs in maternal serum after adjusting for age and parity. ΣPFAA is the total concentration of all seven congeners (PFHxS, PFHpS, PFOS, PFOA, PFNA, PFDA, PFUnDA).

networks of genes associated with weight homeostasis, steroid hormone functions, and insulin signaling.

In human cell studies using adrenocortical *H295R*, primary porcine theca and granulosa cells, exposure to lake extracts from both populations modulated steroid hormone production significantly from controls. The results suggest that POPs from both lakes may possess the potential to induce endocrine disruption and may adversely affect health in wild fish (Berg et al., 2016).

4.6.3 Summary of latest findings

Exposure to POPs has the potential to interfere with thyroid hormone homeostasis. In Alaska Indigenous People, exposure to PFASs is associated with and can modify circulating thyroid hormone concentrations. The effects of PFAS exposure on thyroid hormone homeostasis may differ between sexes. A background exposed maternal population from northern Norway also indicated that PFAS exposure can modify thyroid hormone homeostasis, and changes in maternal thyroid hormones that might have significant consequences for fetal health. Early life exposure to PCB153 and *p,p'*-DDE affected newborn TSH (thyrotropin) levels in three European mother-child cohorts. Higher exposure levels were associated with 12–15% lower TSH levels. Individual PBDEs were reported to modify thyroid homeostasis in Alaska Inuit. Maternal urinary concentrations of DEHP were associated with increased risk of ADHD in a northern Norway case-control study of clinical ADHD. Elucidation of the mechanisms linking phthalates to ADHD needs further research. In addition, iodine deficiency among pregnant women in northern Norway (MISA) influences maternal thyroid homeostasis and is therefore a risk factor for fetal and infant development. An array of exposure and factors can thus disrupt the thyroid hormone system.

In contrast to humans, the relationship between POP exposure and TH or vitamins in pilot whales seems to have minor effects on TH level and vitamin concentrations. Future research might establish the mechanism differences between humans and pilot whales.

Although not consistent, several studies suggest an association between POP exposure and body weight. A follow-up study of Greenlandic, Polish and Ukrainian populations showed no clear association between pregnancy PCB153 and *p,p'*-DDE and child BMI, either for postnatal exposure to *p,p'*-DDE and PCB153 or for BMI at the age of 5–9 years. In contrast, a cohort study on Faroese children supported a role for maternal exposure to PCBs and DDE, and childhood obesity epidemic. Girls whose mothers have a high pre-pregnancy BMI seem most affected. Another Faroese study on pregnant women and their offspring found associations with gestational diabetes and offspring birth size related to environmental pollutants and/or pollutant group. Birth size measures appear independent of gestational diabetes occurrence. A study on pregnant Norwegian and Swedish women found positive associations between maternal serum PFAS concentrations and child overweight/obesity at 5 years of age, particularly among Norwegian participants. In contrast, in a low-exposed Danish population, childhood serum concentrations of PCBs, DDE, and HCB were not associated with subsequent weight gain. In a study on three European birth cohorts, perinatal exposure to dioxin and dioxin-like compounds was associated with increased early infant growth, and increased BMI in school age girls. Studies in larger sample sizes are required to confirm these sex-specific effects.

Previous studies have indicated a potential influence of POPs on Type 2 diabetes pathogenesis (AMAP, 2015). Further findings in a Faroese birth cohort suggest that, for girls, exposure to POPs prenatally may play a role in later development of metabolic diseases by affecting the level of insulin. Although in contradiction to other reports, a study on comparison with standard food intake, the Greenlandic traditional food was positively associated with Type 2 diabetes, impaired fasting glucose and fasting plasma glucose, and negatively associated with β-cell function. Imported meat seemed best in relation to glucose intolerance, with lowest fasting plasma glucose and lowest risk for impaired fasting glucose and Type 2 diabetes. Further studies are needed to confirm these Greenlandic data. Another study in Greenlandic Inuit found a weak but statistically significant association between whole blood Hg and both impaired fasting glycemia and Type 2 diabetes, but no associations with measures of underlying disturbances in glucose homoeostasis. A review showed that increased total Hg exposure may increase risk of diabetes and metabolic syndrome, but lack of consistency in the epidemiological evidence made it impossible to identify a causal relationship. Studies in non-Arctic populations support the findings on the relation between POP exposure and risk of Type 2 diabetes. In a Crete pregnancy cohort, women with high PCB levels in early pregnancy had a higher risk for gestational diabetes. Using a recessive genetic model in a small and isolated Greenlandic population identified a genetic risk in *TBC1D4* gene variants with loss-of-gene-function. The findings give new insights into the genetics of Type 2 diabetes, and support the existence of high-effect genetic risk factors in isolated populations such as Greenlanders. Higher serum Zn levels in Finnish men were associated with higher risk of Type 2 diabetes, partly explained by effects of Zn on BMI and insulin sensitivity. Moreover, studies in Finnish men showed that serum long-chain omega-3 PUFA concentrations were associated with long-term lower risk of Type 2 diabetes. A Norwegian study found a possible role of Br, Cd, Cr, Fe, Ni, Ag and Zn in the development of Type 2 diabetes. A study on elderly in Europe found regulatory and individual efforts to reduce chemical exposures might reduce the burden and costs of diabetes, indicating the need for further worldwide regulations. New results from pharmacokinetic analysis suggest that a third factor (e.g., high intake of animal foods) could explain both higher levels of POPs in the body and higher incidence of Type 2 diabetes. BMI alone is not enough to describe the diet confounding and pharmacokinetics of the studied compounds; including analysis of food consumption could help address causality between POPs and Type 2 diabetes.

The levels and trends of, for example, PFASs differ between countries and populations as illustrated by new data from five international birth cohorts: from Greenland, Denmark (two cohorts), Norway and China. The concentrations and composition of serum PFASs were similar for the Danish ABC women and the Norwegian MISA women but were otherwise different across cohorts, being higher in the Chinese SBE and Greenlandic ACCEPT birth cohort. The different exposure profiles might relate to differences in local PFAS production (e.g., in China) and in lifestyle and diet, and might have health implications.

POPs are endocrine-disrupting chemicals that can elicit xeno-estrogenic activity. Environmental xeno-estrogens can downregulate placental *ABCG2* protein expression (efflux transporters in the placenta) depending on gestational age.

As a marker of current POP regulations, levels of dioxin-like chemicals remain high in bank voles in northern Finland, whereas concentrations of brominated flame retardants decreased in line with current regulations concerning POPs listed under the Stockholm Convention.

4.7 Carcinogenic effects

4.7.1 AMAP Assessment 2015: conclusions

During the latter half of the 20th century, cancer incidence increased substantially among all circumpolar Inuit in the Arctic region, especially for the lifestyle-associated lung, breast and colon cancers. Lung cancer constitutes about 20% of all cancers in Inuit. Overall cancer rates now seem comparable to those of the United States, Canada and Denmark. The recent change in lifestyle and diet and thus environmental contaminant exposure of the Inuit might play a role in this.

4.7.2 New peer-reviewed literature

4.7.2.1 Cancer incidences and trends in the Arctic

A previous study found an inverse association between ambient air temperature and cancer incidence/mortality (Sharma et al., 2015). In the United States, the majority of the 50 counties with the highest cancer incidence rate are located above the latitude range 36°–37°N. The reason for this was examined in a later study by dividing the United States into two zones: north and south of 36.5°N (Sharma et al., 2017). The study proposed that females including American Indian and Alaska natives who lived north of 36.5°N had a 4.25- to 7.0-fold higher risk of cancer incidence than those living south of this latitude. Sharma et al. (2017) suggested that a cold environment could be an independent factor for cancer development.

A study determined and compared cancer incidence among the eight Arctic States and their northern regions, with a special focus on three cross-national Indigenous groups: Inuit, Athabaskan and Saami (Young et al., 2016). Data were extracted from national and regional statistical agencies and cancer registries, with direct age-standardization of rates to the world standard population. The 'world average' rates as reported in the GLOBOCAN database were used for comparison. Age-standardized incidence rates by cancer site were computed for the eight Arctic States and 20 of their northern regions for the decade 2000–2009 (Young et al., 2016).

The data showed that cancer of the lung and colon/rectum in both sexes are the most common in most populations. Combining the Inuit from Alaska, Northwest Territories, Nunavut and Greenland into a 'Circumpolar Inuit' group and tracking their cancer trends over four 5-year periods from 1989 to 2008, the data showed a marked increase in lung, colorectal and female breast cancers, while cervical cancer declined (Figure 4.3). Compared to the GLOBOCAN world average, Inuit are at extreme high risk for lung and colorectal cancer, and certain rare cancers such as nasopharyngeal cancer. Athabaskans (from Alaska and Northwest Territories) share some similarities with the Inuit but are at higher risk for prostate and breast cancer relative to the world average. In contrast, the published data from three cohorts in Norway, Sweden and Finland showed generally lower risk of cancer among the Saami than non-Saami. Cancer among certain Indigenous People such as Inuit and Athabaskans in the Arctic is therefore a growing public health concern, especially lung and colorectal cancer (Young et al., 2016).

Yousaf et al. (2018) reported cancer incidence and mortality in Greenland and compared the results with data for the other Nordic countries. The study included all individuals residing in Greenland and diagnosed with or dying from a cancer between 1983 and 2014. In this period, the total number of cancer cases in Greenland was 4716 and there were 3231 cancer deaths. Respiratory and gastrointestinal cancers had the highest incidence as well as mortality in Greenland

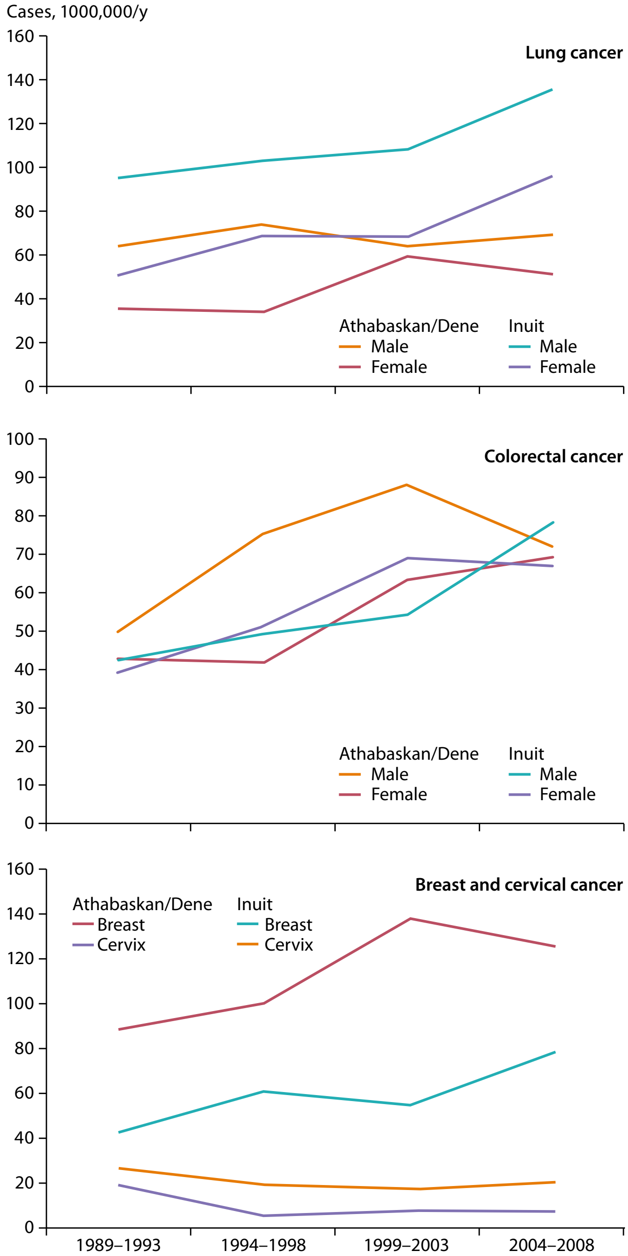


Figure 4.3 Temporal trends in the incidence of lung cancer, colorectal cancer, and breast and cervical cancer among circumpolar Inuit and Athabaskan/Dene, 1989–2008. Athabaskan/Dene were North American Indians (Young et al., 2016).

for the entire period and for both sexes. Compared to the other Nordic countries, Greenland had significantly higher incidence and mortality rates for several cancers. Cancer of the lip, oral cavity, and pharynx, respiratory cancer, and cancer of unknown sites had the highest incidence rate ratios (2.3–3.9) and mortality rate ratios (2.7–9.9) for both sexes. The time trend in cancer incidence in Greenland from 1983 to 2014 showed a significant increase with almost the same incidence level as the other Nordic countries. While cancer mortality decreased in the other Nordic countries during the period 1983 to 2014, there was no change in cancer-specific mortality in Greenland. These data underline a need to focus on cancer-specific mortality in Greenland and prevention of high-incidence cancers related to well-established risk factors (Yousaf et al., 2018).

4.7.2.2 Contaminant exposure and breast cancer

A case-control study on breast cancer and exposure to synthetic environmental chemicals among Alaska Native women (Holmes et al., 2014) showed that such chemicals may impair endocrine system function. Alaska Native women may be at higher risk of exposure to these endocrine-disrupting chemicals, which may contribute to breast cancer. This case-control study included 170 women (75 cases, 95 controls) recruited from the Alaska Native Medical Center between 1999 and 2002. Serum samples were analyzed for nine persistent pesticides, 34 PCB congeners, and eight PBDE congeners. Urine samples were analyzed for ten phthalate metabolites.

The results showed that serum concentrations of most pesticides and three indicator PCB congeners (PCB138/158, PCB153, PCB180) were lower in breast cancer case women than controls. PBDE47 was significantly higher in breast cancer case women (geometric mean 38.8 ng/g lipid) than controls (geometric mean 25.1 ng/g lipid) (p=0.04). Persistent pesticides, PCBs, and most phthalate metabolites were not associated with case status in univariate logistic regression. The odds of being a breast cancer case were higher for those with urinary mono-(2-ethylhexyl) phthalate (MEHP) concentrations that were above the median; this relationship was seen in both univariate (odds ratio 2.16, 95% CI 1.16–4.05) and multivariable (OR 2.43, 95% CI 1.13-5.25) logistic regression. Women with estrogen receptor (ER) / progesterone receptor (PR) negative tumor types (ER-/PR-) tended to have higher concentrations of persistent organochlorine pesticides than did ER/PR-positive (ER+/PR+) women, although these differences were not statistically significant.

It was concluded that exposure to di-2-ethylhexyl phthalate (DEHP), which is the parent compound of MEHP, may be associated with breast cancer. However, this study was limited by small sample size and an inability to control for the confounding effects of BMI. In addition, because MEHP is a short-lived compound, a more important limitation is that the temporality could not be established due to the cross-sectional design. The association between PBDE47 and breast cancer warrants further investigation (Holmes et al., 2014).

A case-control study on serum levels of environmental pollutants and risk factors for breast cancer in Inuit (Wielsøe et al., 2017) elucidated the association of serum levels of environmental pollutants such as POPs and breast cancer risk in highly exposed Greenlandic Inuit women. The study included 77 breast cancer cases and 84 controls, with sampling undertaken during 2000–2003 and 2011–2014. Serum levels of 14 PCBs, 11 organochlorine pesticides, 16 PFASs, one polybrominated biphenyl (PBB), and nine PBDEs were determined.

Results showed that the majority of the measured compounds declined significantly from 2000–2003 to 2011–2014. However, for the PFCAs an increase was observed. Serum levels were significantly higher in breast cancer cases compared to controls for the majority of compounds, and after adjusting for age the difference was maintained for ΣOCP, *p,p'*-DDE, ΣPFAS, ΣPFSA, PFHxS, and PFOS. For the lipophilic POPs, high serum levels (middle/highest vs. lowest tertile) of ΣPCB, sum estrogenic PCBs, PCB99, PCB138, PCB153, PCB170, and PCB183 were associated with breast cancer risk; for the amphiphilic PFASs, high serum levels of ΣPFAS, ΣPFCA, ΣPFSA, PFOA, PFNA, PFDA, PFHxS, and PFOS were associated with breast cancer risk.

In summary, significant, positive associations between breast cancer risk and PCBs and PFASs were observed. The associations indicate that environmental exposure to POPs can be a factor that increases risk for breast cancer in Inuit women (Wielsøe et al., 2017).

The receptor activities of persistent pollutant serum mixtures and breast cancer risk were recently analyzed (Wielsøe et al., 2018a). Because studies on associations between POPs and breast cancer risk are inconclusive, most studies have evaluated the effect of single compounds, without considering multiple exposures to and interactions between different POPs. Thus, this study aimed at evaluating breast cancer risk related to combined effects of serum POP mixtures on cellular receptor functions (Wielsøe et al., 2018a).

Data on breast cancer cases (n=77) and controls (n=84) were collected among Greenlandic Inuit women. Serum mixtures of lipophilic POPs, PFASs and dioxin-like POPs were extracted. The effect of the mixture extracts on the estrogen receptor, androgen receptor and aryl hydrocarbon receptor (AhR) was determined using cell culture reporter gene assays. The serum mixtures were analyzed alone and upon co-exposure with natural receptor ligands to determine agonistic and antagonistic/competitive activity.

Results showed that the frequency of lipophilic POP mixtures eliciting a no, or decreasing, or agonistic xeno-androgenic effect differed by breast cancer status. Using lipophilic POP mixtures with no effect on androgen receptor as reference, the POP mixtures with decreasing androgenic effects (XAR) reduced breast cancer risk (OR: 0.30, 95% CI: 0.12–0.76) (Figure 4.4A). The AhR activity (AhR-TEQ) induced by serum POP mixtures was significantly lower in cases than controls, and a reduced breast cancer risk was found when comparing the highest AhR-TEQ (third tertile) to the lowest AhR-TEQ (first tertile) (OR: 0.34, 95% CI: 0.14–0.83) (Figure 4.4B). No association was observed between the xeno-estrogenic activities of lipophilic POPs or PFASs and breast cancer risk (Figure 4.4). Thus, serum lipophilic POP mixtures are hormone disruptive and may influence breast cancer risk, whereas PFASs seem to influence breast cancer risk through other pathways (Wielsøe et al., 2018a).

A study reported blood levels of Cd and Pb in relation to breast cancer risk in three prospective cohorts (Gaudet et al., 2019) by examining the associations of circulating blood levels of Cd and Pb with breast cancer risk in cohorts from the USA, Italy and northern Sweden. Results showed that the northern Swedish women with Cd levels over 2 µg/L had a lower risk of breast cancer and suggested that the anti-estrogenic effect in postmenopausal women might play a role (Gaudet et al., 2019).

4.7.2.3 Contaminant exposure and prostate cancer

Prostate cancer is one of the leading cancer forms in men worldwide. However, no recent data about prostate cancer and environmental exposure in the Arctic region were available after 2015.

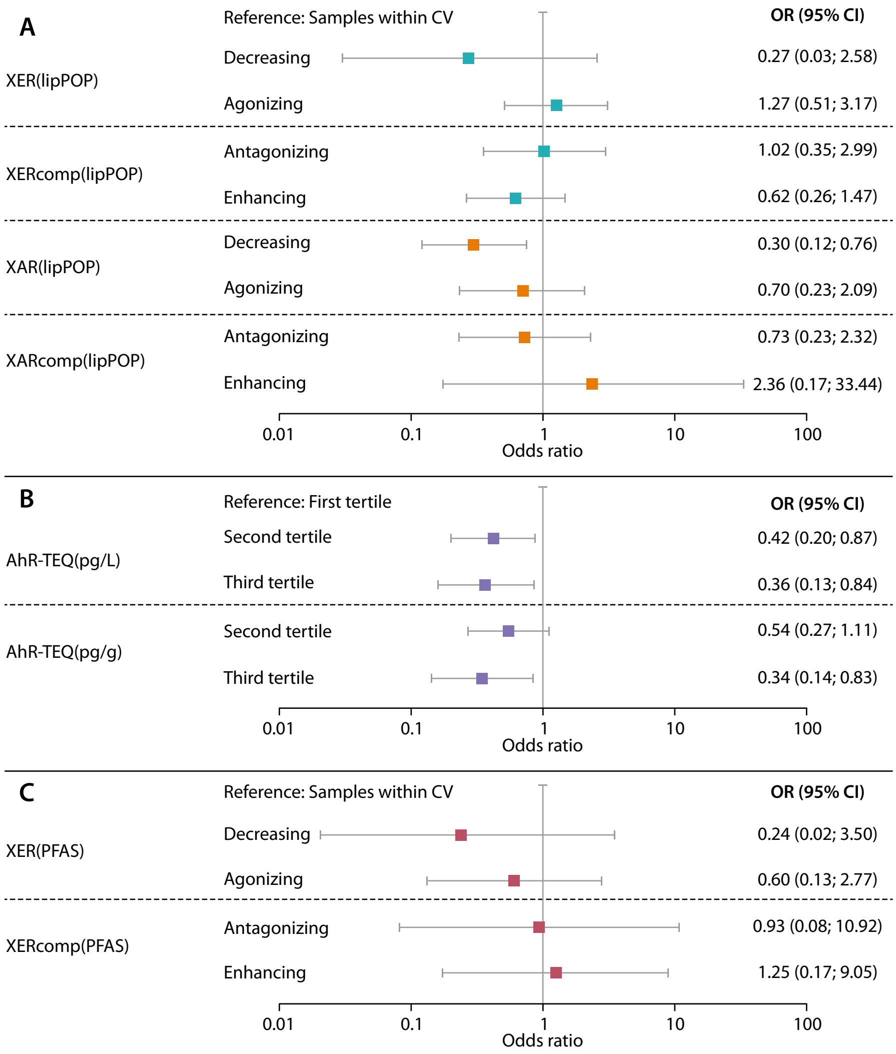


Figure 4.4 Odds ratio estimates from the categorical analyses of xeno-hormone activity and breast cancer risk. Forest plots of associations of xeno-hormone activity of serum-extracted POPs with breast cancer risk. Adjusted odds ratio estimates with 95% CI (as horizontal lines). Age, parity, serum cotinine level, BMI, total serum lipid, and breastfeeding history were considered as confounding factors using the change in estimate principal. OR, odds ratio; CI, confidence interval; XER and XAR, receptor activity of the serum extracts tested alone; XERcomp and XARcomp, competitive receptor activity of the serum extracts tested with co-treatment by potent receptor ligand (Wielsøe et al., 2018a).

Ali et al. (2016) explored the association of exposure to PCBs and prostate cancer using a population-based prospective cohort and experimental studies. The population-based cohort included men aged 45 to 79 years living in central Sweden and dietary PCB153 exposure was found to be positively associated with high-grade prostate cancer (relative risk 1.35, 95% CI: 1.03–1.76) and prostate cancer mortality (RR 1.43, 95% CI: 1.05–1.95). They suggested that PCB153 may stimulate cell invasion and cell migration in human prostate cancer cells and prostate stem cells (Ali et al., 2016).

A nested case-control study including 150 prostate cancer cases and 314 controls was conducted in Norway to analyze the association of prediagnostic serum organochlorine concentrations and metastatic prostate cancer (Koutros et al., 2015). It showed a positive association between the serum level of chlordane metabolite, oxychlordane, and risk of metastatic prostate cancer (OR 2.03, 95% CI: 1.03–4.03). However, PCB44 was negatively associated with metastatic prostate cancer (OR 0.74, 95% CI: 0.56–0.97). This study suggested a possible role of lipophilic POPs in the etiology of prostate cancer (Koutros et al., 2015).

4.7.2.4 Influence of contaminants on liver cancer

The risk of liver cancer in Inuit of Alaska, Nunavik and Greenland is higher than for the populations of the USA, Canada and Denmark, respectively. Although alcohol consumption or other exposures leading to cirrhosis play a role in the high rate of liver cancer in Inuit, hepatitis B virus (HBV) infection is believed to have a causal role (Storm and Nielsen, 1996). The HBV-linked chronic inflammation and hepatocellular carcinomas in Alaska Natives might be stimulated by their elevated body burden of dioxins (Tsyrlov and Konenkov, 2015). The rate of hepatitis B lesions has been high among Alaska Natives and the annual incidence of hepatocellular carcinoma among Alaska Native males was five-fold higher than for white males in the USA (Lanier et al., 1976). Inuit adults from Nunavik (Arctic Quebec) were reported to have a 10- to 25-fold higher body burden of TCDD compared to controls from southern Quebec (Ayotte et al., 1997). 'Xenobiotical virology' is a novel mechanistic concept that hazardous human viruses are up-regulated by body levels of dioxins via the AhR-mediated transcriptional pathway, because HBV possesses multiple 'dioxin-responsive elements' in the virus promoter regulatory regions (Tsyrlov et al., 2012). According to the xenobiotical virology concept, the level in Nunavik Inuit is within the range of TCDD concentrations able to transcriptionally up-regulate HBV. The high incidence of hepatocellular carcinoma among Alaska Natives might be related to their high burden of dioxin, which can stimulate the HBV-linked chronic inflammation (Tsyrlov and Konenkov, 2015).

4.7.2.5 Carcinogenicity of contaminants (mechanisms in cell cultures)

Perfluoroalkylated substances are suspected carcinogens and a potential mode of action is through generation of oxidative stress. In an *in vitro* study exploring the PFAS effect on oxidative stress (Wielsøe et al., 2015), seven long-chained PFASs found in human serum were investigated for the potential to generate reactive oxygen species (ROS), induce DNA damage and disturb the total antioxidant capacity. The tested PFASs were PFHxS, PFOS, PFOA, PFNA, PFDA, PFUnDA, and perfluorododecanoic acid (PFDoDA). Using the human hepatoma cell line (HepG2), with an exposure time of 24 hours, all three endpoints (ROS, DNA damage, total antioxidant capacity) were affected by one or more of the compounds. PFHxS, PFOA, PFOS and PFNA showed a dose-dependent increase in DNA damage in the concentration range 2×10^{-7} to 2×10^{-5} M determined by the comet assay (Figure 4.5).

Except for PFDoDA, all the other PFASs increased ROS generation significantly. For PFHxS and PFUnDA the observed ROS increases were dose-dependent (Figure 4.6). Cells exposed to PFOA were found to have a significant lower total antioxidant capacity compared to the solvent control. A non-significant decreasing trend in total antioxidant capacity was observed for PFOS and PFDoDA and an increasing tendency was observed for PFHxS, PFNA and PFUnDA. The results indicated a possible genotoxic and cytotoxic potential of PFASs in human liver cells (Wielsøe et al., 2015).

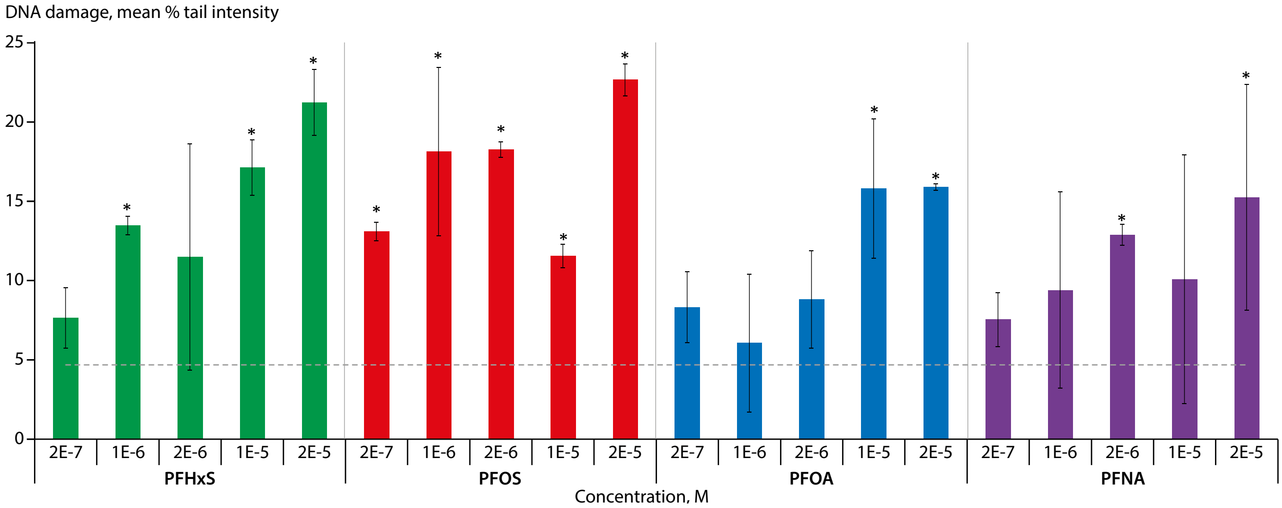


Figure 4.5 Level of DNA damage after PFAS exposure for 24 hours. Cells exposed to PFOS, PFHxS, PFOA and PFNA showed an increase in DNA damage in a dose-dependent manner. Each bar represents the mean % tail intensity SD of three independent experiments each tested in duplicate. The symbol * indicates compound-induced responses significantly different ($p \leq 0.05$) from responses obtained with solvent control (0.04% dimethyl sulfoxide, illustrated by a dashed line) (Wielsøe et al., 2015).

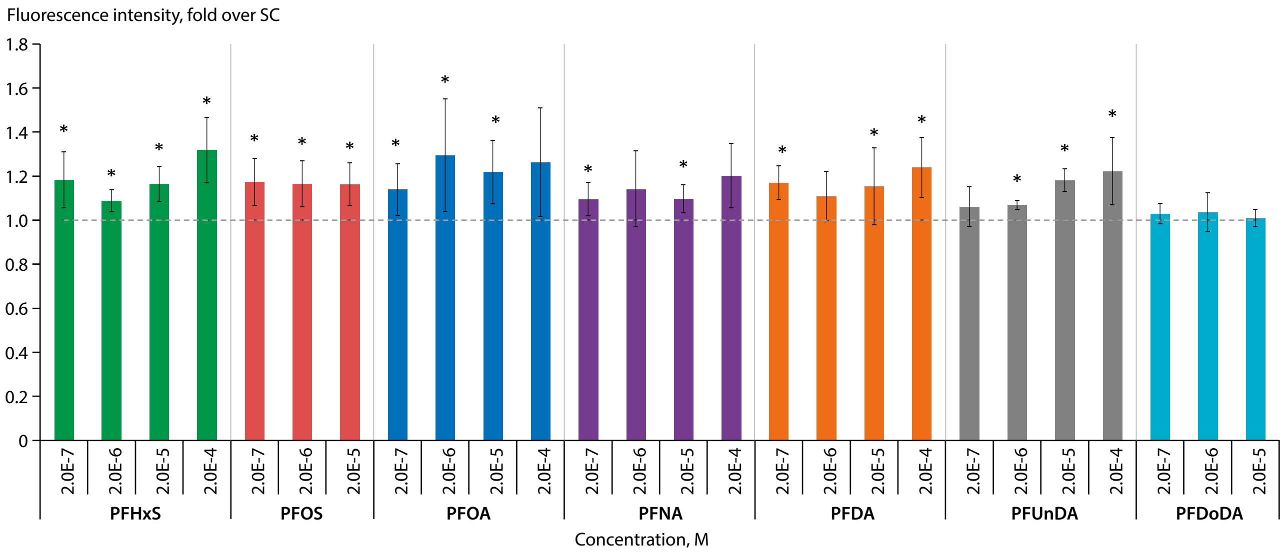


Figure 4.6 Intracellular reactive oxygen species (ROS) generation after exposure to PFASs for 24 hours. The data are reported as fold induction in fluorescence intensity relative to solvent control (SC). The SC was 0.04% dimethyl sulfoxide for PFHxS, PFOS, PFOA, PFNA, PFDA, PFUnDA, and 0.4% ethanol for PFDoDA. The SC was set to 1 and indicated with a dashed line. Data are expressed as mean ± SD of three or four independent experiments, each performed in duplicate. The symbol * indicates statistically different at $p \leq 0.05$ (Wielsøe et al., 2015).

PFOA was reported to inhibit the hepatocyte nuclear factor 4α (HNF4α) protein and HNF4α-dependent gene transcription in HepG2 cells and the inhibition of HNF4α was suggested as a cause of PFOA carcinogenicity (Tsuda, 2016). Beggs et al. (2016) reported that PFOS- and PFOA- induced hepatic effects of human hepatocyte were mediated by HNF4α protein without affecting HNF4α mRNA or causing cell death. They found that PFOA and PFOS could promote cellular dedifferentiation and increase cell proliferation by down regulating positive targets (differentiation genes such as *CYP7A1*) and inducing negative targets of HNF4α (pro-mitogenic genes such as *CCND1*). Furthermore, *in silico* docking simulations indicated that PFOA and PFOS could directly interact with HNF4α in a similar manner to endogenous fatty acids. Hence, HNF4α degradation might be a novel mechanism of PFOA- and PFOS-mediated steatosis and tumorigenesis in human liver (Beggs et al., 2016).

In the human primary hepatocyte HepG2 cells, PFOA was shown to stimulate gene expression of the proto-oncogenes c-Jun and c-Fos, while the PFOA-stimulating cellular proliferation occurs independent of c-Jun and c-Fos (Buhrke et al., 2015). Ma et al. (2016) explored the molecular mechanisms underlying PFOA-induced endometrial cancer cell invasion and migration. PFOA treatment enhanced migration and invasion using human Ishikawa endometrial cancer cells, which correlated with decreased E-cadherin expression, a marker of epithelial-mesenchymal transition. PFOA also induced activation of ERK1/2/mTOR signaling. Treatment with rapamycin, an mTOR inhibitor, antagonized the effects of PFOA and reversed the effects of PFOA activation in a xeno-graft mouse model of endometrial cancer. Consistent with these results, pre-treatment with rapamycin abolished PFOA-induced down-regulation of E-cadherin expression. The study indicated that PFOA is a carcinogen that promotes endometrial cancer cell migration and invasion through activation of ERK/mTOR signaling (Ma et al., 2016).

Pierozan and Karlsson (2018) examined the potentially tumorigenic activity of PFOS in MCF-10A breast cell line. The results showed that PFOS promotes MCF-10A proliferation through accelerating G0/ G1-to-S phase transition of the cell cycle. In addition, PFOS exposure increased CDK4 and decreased p27, p21, and p53 levels in the cells. Longer treatment of PFOS-stimulated MCF-10A cell migration and invasion, which were partially caused by activation of ER. This study suggested that PFOS was capable of transforming the human normal breast epithelial cell line MCF-10A to a malignant profile and exposure to low levels of PFOS might be a potential risk factor in human breast cancer initiation and development.

Environmental and occupational exposures to Cd increase the risk of various cancers, including lung cancer. However, the carcinogenic mechanism of Cd, including its prevention, remains to be investigated.

The roles of ROS, Nrf2, and autophagy in Cd-carcinogenesis and its prevention by sulforaphane were investigated by Wang et al. (2018). They showed that ROS were generated in immortalized lung cells exposed to Cd. Through ROS generation, Cd increased the protein level of TNF-α, which activated NF-κB and its target protein COX-2, creating an inflammatory microenvironment. Cadmium induced the transformation of normal cells into malignant cells. Inhibition of ROS by antioxidants inhibited transformation, showing that ROS were important in the mechanism of this process. The inflammatory microenvironment created by Cd may also contribute to the mechanism of the transformation. Cadmium-transformed cells had a property of autophagy deficiency, resulting in accumulation of autophagosomes and increased p62 protein. The protein p62 upregulated Nrf2 and Nrf2 also upregulated p62 through a positive feedback mechanism. Constitutive Nrf2 activation increased its downstream anti-apoptotic proteins, Bcl-2 and Bcl-xl, resulting in apoptosis resistance.

In untransformed immortalized lung cells, sulforaphane increased autophagy, activated Nrf2, and decreased ROS. In Cd-transformed immortalized lung cells, the natural compound sulforaphane restored autophagy, decreased Nrf2, and decreased apoptosis resistance. In untransformed cells, the sulforaphane induced Nrf2 to decrease ROS and possibly malignant cell transformation. In Cd-transformed cells, sulforaphane decreased constitutive Nrf2 and reduced apoptosis resistance. The dual roles of sulforaphane make this natural compound a valuable agent for preventing Cd-induced carcinogenesis. Wang et al. (2018) showed the Cd-induced carcinogenesis is due to the ability of Cd to induce the transformation of normal cells into malignant cell phenotype. The mechanisms seem to be generation of ROS and decrease of the anti-apoptotic proteins, Bcl-2 and Bcl-xl (Wang et al., 2018), supported by a previous study showing low-level Cd-induced multiple physical and molecular tumor cell characteristics in a human lung epithelial cell (Person et al., 2013).

4.7.3 Summary of latest findings

Cancer is an increasing public health concern, especially lung and colorectal cancer, among some Indigenous People including Inuit in the Arctic. Compared to the world average, Inuit are at extreme high risk for lung and colorectal cancer, and some rare cancers such as nasopharyngeal cancer. A significant increase in cancer incidence in Greenland was observed, with nearly the same incidence level as for the other Nordic countries. Environmental contaminants such as POPs and heavy metals are potentially carcinogenic due to genotoxicity and inducement of oxidative stress. The reported studies show exposure to environmental contaminants such as lipophilic POPs, amphiphilic PFASs and phthalates plays a role in the increase of cancer incidence in the circumpolar region.

The possible biological mechanism of lipophilic POPs on breast cancer may relate to their hormone disruptive property, while PFASs seem to influence breast cancer risk through other pathways such as promotion of cell proliferation through accelerating the transition from G0/G1 phase to S phase of the cell cycle and stimulating migration and invasion of normal breast epithelial cells. *In vitro* studies suggest that the possible mechanisms of carcinogenicity of PFASs were to induce oxidative stress, inhibit HNF4α, and stimulate expression of proto-oncogenes in liver cells.

A study on a non-Inuit population suggested the anti-estrogenic effect of Cd might play a role in breast cancer development. An *in vitro* study showed that Cd induced the transformation of normal lung cells to malignant cells via oxidative stress and anti-apoptosis.

Lipophilic POPs such as PCBs and organochlorine pesticides were observed to play a role in the etiology of prostate cancer in the non-Inuit populations of northern European countries.

Contaminants may interact with microorganisms to influence cancer development. The HBV-linked chronic inflammation and hepatocellular carcinoma in Alaska Natives might be stimulated by elevated body levels of dioxins.

A US study indicated that cold environments (north of 36.5°N) were associated with higher cancer incidence in females compared to south of this latitude. The combined effect of environmental contaminant exposure and cold environment in terms of the increasing trend of cancer incidence in Arctic regions merits study.

4.8 Genetic modifiers

4.8.1 AMAP Assessment 2015: conclusions

There is an interaction between genotype and environmental exposure in relation to cancer risk. The metabolic gene polymorphism associated with POPs observed in Greenlandic Inuit might support elucidating the role of these gene variants in susceptibility to environmental contaminants. The *BRCA1* founder mutation and polymorphisms in *CYP1A1* and *CYP17* can increase breast cancer risk among Inuit women and the risk increased with higher levels of PFOS and PFOA.

In vitro and *in vivo* studies showed that the androgen receptor gene nucleotide CAG repeat length could influence the effects of endocrine-disrupting chemicals on androgen receptor activity. The association between some markers of male reproductive function and androgen receptor CAG or GGN repeat length was curvilinear. The curvilinear relationships between AR repeat lengths and male reproductive outcomes suggested a segmented association, where a linear association flattens either below or above a certain threshold and effects disappear or become saturated.

Genetic variation in *CYP2A6* can alter smoking quantity and lung cancer risk in heavy smokers. *CYP2A6* metabolizes nicotine to cotinine, which is an inactive metabolite. On the other hand, *CYP2A6* activates pro-carcinogenic tobacco-specific nitrosamines. A study of Alaska Natives showed that genetic variation in *CYP2A6* resulting in slower enzyme activity reduced the tobacco consumption by, for example, inhaling less deeply. The slow *CYP2A6* metabolizers had lower pro-carcinogen levels and bio-activation, which is consistent with a lower risk of developing smoking-related cancers. This demonstrates the importance of *CYP2A6* in the regulation of tobacco consumption behaviors.

Differing mutational profiles and genetic variability were observed among the different HBV genotypes predominating in circumpolar Indigenous hepatitis patients.

Animal studies mimicking human exposure showed that the interaction of chemical mixtures played a role in toxicology, and a life-long intake of a high-fat diet containing low doses of environmental contaminants could aggravate metabolic disorders induced by obesity itself. The increased hepatic T4 glucuronidations via hepatic uridine diphospholgucuronosyl transferases and increased thyroidal conversion of T4 to T3 via hepatic type 1 deiodinase were partly responsible for PFOS-induced hypothyroxinemia in rats.

Global DNA methylation levels refer to the level of 5-methylcytosine (5mC) relative to total cytosine (for further details see Vryer and Saffery, 2017). This represents the changes in several common repetitive elements, such as long interspersed nuclear elements (LINE) or arthrobacter luteus (Alu) elements. An inverse association between Global DNA methylation and blood plasma levels of several POPs was reported for Greenlandic Inuit.

There was an association between several biologically relevant epigenetic markers related to metabolic health and long-term intake of marine-derived omega-3 PUFAs in Alaska Natives.

In a British population with low MeHg exposure, associations between MeHg exposure and adverse neuropsychological outcomes were equivocal. Heterogeneities in several relevant genes suggested possible genetic predisposition to MeHg neurotoxicity in a substantial proportion of the population.

4.8.2 New peer-reviewed literature

4.8.2.1 Genetic adaption

Greenlandic Inuit have lived for a long time in the extreme conditions of the Arctic, including low annual temperatures, and with a specialized diet rich in protein and beneficial fatty acids, particularly omega-3 PUFAs. A recent study reported that Greenlandic Inuit have developed genetic adaptations associated with diet and climate (Fumagalli et al., 2015). The genetic signatures of diet and climate adaption in Greenlandic Inuit was evidenced, because a scan of Inuit genomes for signatures of adaptation revealed signals at several loci, with the strongest signal located in a cluster of fatty acid desaturases. These fatty acid desaturases are the rate-limiting steps in the conversion of linoleic acid (omega-6) and α-linolenic acid (omega-3) to the longer, more unsaturated and biologically active eicosapentaenoic acid (omega-3), docosahexaenoic acid (omega-3), and arachidonic acid (omega-6) and thus determine the PUFA levels. This study also found that the selected alleles were associated with multiple metabolic and anthropometric phenotypes and had large effect sizes for weight and height. The study found that the selected alleles modulated fatty acid composition. Because of the negative feedback loop between plasma fatty acids and human growth hormone secretion, the change in composition and level of fatty acids may affect the regulation of growth hormones (Quabbe et al., 1972). Thus, the Inuit have genetic and physiological adaptations to a diet rich in PUFAs (Fumagalli et al., 2015).

4.8.2.2 Genetic polymorphisms and contaminants

A Faroese birth cohort study reported that specific chemicals in cord blood could help to identify sex-specific DNA methylation changes (Leung et al., 2018). Faroese consume marine foods contaminated with MeHg, PCBs, and other toxicants associated with chronic disease risks. Differential DNA methylation at specific CpG sites in cord blood may serve as a surrogate biomarker of health impacts from chemical exposures.

To identify key environmental chemicals in cord blood associated with DNA methylation and changes, 72 participants recruited from a Faroese birth cohort between 1986 and 1987 were followed until adulthood (Leung et al., 2018). The cord blood DNA methylome was profiled and associations were evaluated between CpG site changes and concentrations of 16 compounds, including MeHg, PCBs, other organochlorine compounds (HCB; *p,p'*-DDE; and *p,p'*-dichlorodiphenyltrichloroethane, *p,p'*-DDT), and PFASs. Results showed that in a combined sex analysis, PCB105 exposure was associated with the majority of differentially methylated CpG sites (214 out of a total of 250). In females, only 73 CpG sites with significant methylation changes were associated with PCB105. Among 73 CpG sites, 44 were mapped to 33 genes in the Embryonic Lethal, Abnormal Vision, Drosophila, Homolog-Like 1 (ELAVL1) gene-associated cancer network. The dysregulation of the ELAVL1 gene was shown to play an important role in cancer progression (Wang et al., 2016b). In males, high numbers of methylation changes were seen for exposure to PFOS (10598 CpG), HCB (1238 CpG), and *p,p'*-DDE (1473 CpG sites). Among these CpG sites, 15% were enriched in cytogenetic bands of the X-chromosome associated with neurological disorders. The data showed chemical- and sex-specific methylation changes in cord white blood cell DNA located in genes associated with networks of reproductive, cardiovascular, and neural/behavioral disruption. Significantly, more methylome changes were found in male infant DNA samples, with enrichment in the X-chromosome (Figure 4.7). This multiple-pollutant and genome-wide study served to identify the key epigenetic toxicants, mainly POPs. The significant enrichment of specific X-chromosome sites in males implies potential sex-specific epigenome responses to prenatal chemical exposures (Leung et al., 2018).

Genetic polymorphisms were reported associated with exposure biomarkers for metals and POPs among Inuit from the Inuvialuit Settlement Region, Canada (Parajuli et al., 2018). As described in several AMAP assessment reports, Inuit are exposed to some of the highest levels of contaminants such as POPs and heavy metals, which are linked to adverse health effects. Studies suggest that several of the genes that mediate the metabolism of these contaminants are polymorphic. This study explored whether single nucleotide polymorphisms (SNPs) in such genes may underline differences in biomarker concentrations and/or modify exposure-biomarker associations in residents from the Canada Inuvialuit Settlement Region. Blood concentrations of Hg, Cd, Pb, DDE, and PCB153 were measured. The data from 112 SNPs in genes involving pathways such as glutathione, metallothionein, oxidative stress, xenobiotic transport and metal response were genotyped in 281 participants. The results showed that biomarker levels significantly differed by genotype: four SNPs for Hg, three for Cd, four for Pb, three for DDE, and three for PCB153. In multivariable analyses (for Pb, DDE, PCB153) adjusting for age, sex and BMI, only two associations (Pb, DDE) remained significant. In multivariable analyses accounting for sources of Hg or Cd exposure, 24 SNPs (nine for Hg, 15 for Cd with four overlapping) had significant main effects on biomarker levels and/or modified exposure-biomarker associations. Hence, the findings suggested that polymorphisms in key environmentally responsive genes could influence biomarker levels and/or modify exposure-biomarker associations for contaminants of concern to Arctic Inuit populations and so could influence the health effects of these contaminants. The gene-environment results may help improve and better conduct exposure and risk assessments of country foods and Inuit health (Parajuli et al., 2018).

PFASs are substrates for organic anion transporter (OAT) and OAT4 is expressed in human placenta. Pregnant women are exposed to PFASs, and the presence of PFASs in umbilical cord blood represents fetal exposure. To evaluate the contribution of OAT4 and ATP-binding cassette transporter G2 (ABCG2) proteins in the trans-placental transfer of PFOS and PFOA, an *ex vivo* dual recirculating human placental perfusion from healthy Finnish mothers with uncomplicated pregnancies was used (Kummu et al., 2015). The study showed that both PFOS and PFOA crossed the placenta. The expression of OAT4 showed a negative correlation with the transfer index (TI%) of PFOA ($R^{(2)}$=0.92, p=0.043) and PFOS ($R^{(2)}$=0.99, p=0.007) at 120 minutes, while at 240 minutes the correlation was statistically significant only with PFOA. The expression of ABCG2 did not correlate with the TI% of PFOS or PFOA. This study suggests the involvement of the organic anion transporter OAT4 in placental passage of PFASs. Placental passage of PFOS and PFOA was modified by the transporter protein OAT4 but not by ATP-binding cassette transporter ABCG2 proteins. OAT4 may decrease fetal exposure to PFASs and protect the fetus after maternal exposure to PFASs (Kummu et al., 2015).

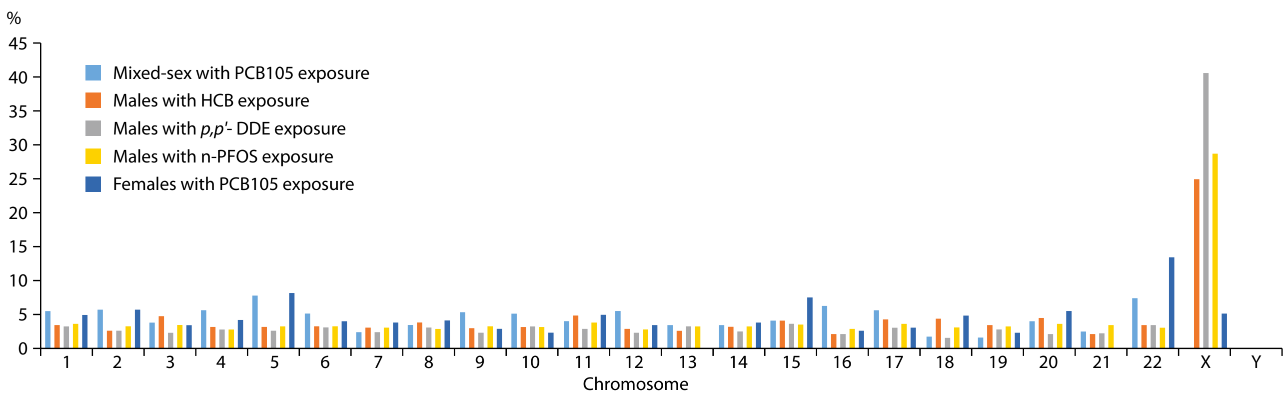
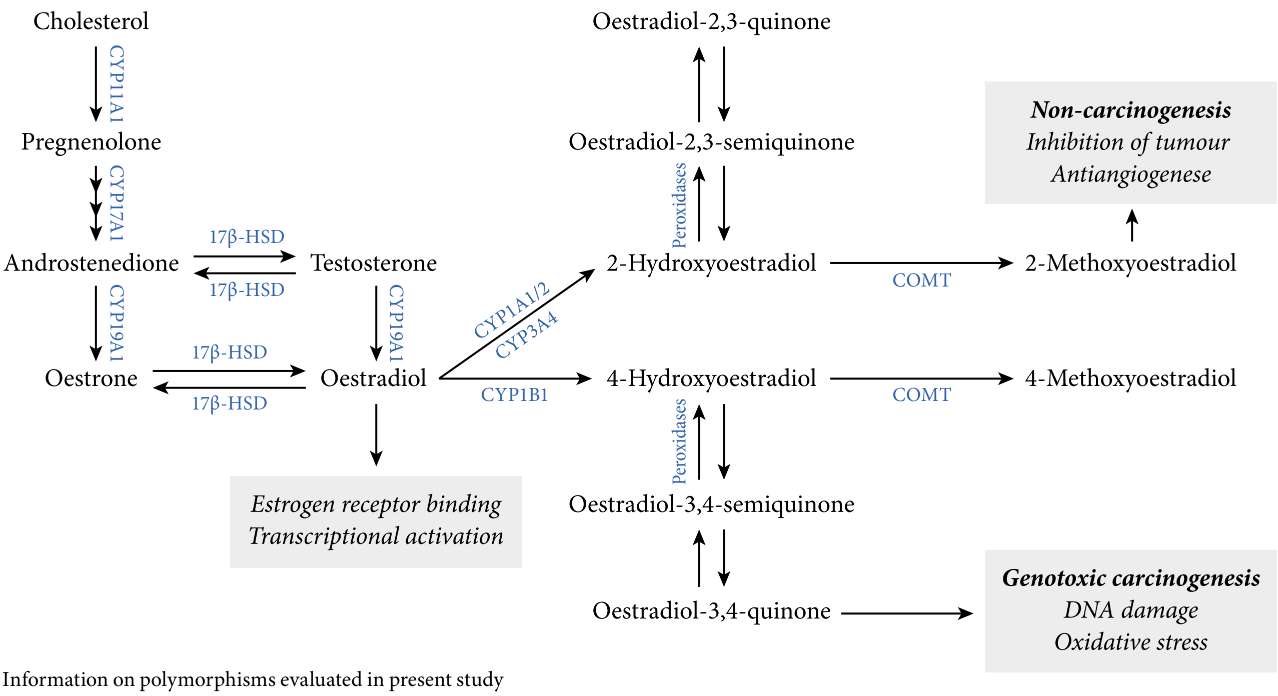


Figure 4.7 Chromosomal locations of the significant CpG sites. The percentage of the number of CpG sites with significant methylation change against each exposure (PCB105, HCB, *p,p'*-DDE, PFOS) per chromosome was calculated. (Leung et al., 2018).

4.8.2.3 Genetics in relation to cancer risk

Analysis of GLOBOCAN-2012 data (Global Cancer Observatory, no date) showed that cancer incidence worldwide was highly related to low average annual temperatures and extreme low temperatures. This applied for all cancers together or separately for many frequent or rare cancer types (all cancers p=9.49x10^{-18}) (Voskarides, 2018). A supporting fact was that Inuit living at extreme low temperatures had the highest cancer rates for some cancers today. To test the hypothesis of an evolutionary relationship between adaptation at extreme environmental conditions and increased cancer risk in humans, 240 cancer genome-wide association studies, and seven genome-wide association studies for cold and high-altitude adaptation were combined. A list of 1377 cancer-associated genes was created to investigate whether cold-selected genes were enriched with cancer-associated genes. The study of Voskarides (2018) showed that a statistically significant number of cancer-associated genes have undergone selection procedures in Native Americans, Inuit and Siberian Eskimos; the highest association was observed for Native Americans. Selection for tumor suppressor genes including *BRCA1* and *p53* in cold conditions was observed, and many cancers that rank high in populations living in extreme cold are associated with tumor suppressor genes (Voskarides, 2018). The Voskarides (2018) study indicated that genetic variants selected for adaptation to the extreme environmental conditions can increase cancer risk late in life. This is in accordance with the antagonistic pleiotropy hypothesis where genetic variants that predispose to a disease could have been selected by natural selection if offering a survival advantage (Nesse, 2011).

A Greenlandic case-control study (Wielsøe et al., 2018b) investigated the effects of SNPs in xenobiotic and steroid hormone-metabolizing genes in relation to breast cancer risk, and explored possible effect modifications (analyzed by ratio of odds ratio (ROR) for alleles on the specific site) on POPs and breast cancer associations. The study also assessed the effects of Greenlandic *BRCA1* founder mutations. Greenlandic Inuit women (77 cases and 84 controls) were included in this study. Two founder mutations in *BRCA1* were determined: Cys39Gly (rs80357164) and 4684delCC, and five SNPs in xenobiotic and estrogen-metabolizing genes: CYP17A1 -34T>C (rs743572), CYP19A1 *19C>T (rs10046), CYP1A1 Ile462Val (rs1048943), CYP1B Leu432Val (rs1056836) and COMT Val158Met (rs4680) (Figure 4.8). The results showed that the variant allele of *BRCA1* Cys39Gly increased breast cancer risk 12-fold (Gly/Cys versus Cys/Cys, OR: 12.2, 95% CI: 1.53–98.1), and carriers of the variant allele of *CYP17A1* -34T>C had reduced risk (CT+CC versus TT, OR: 0.44, 95% CI: 0.21–0.93). *CYP17A1* -34T>C was an effect modifier on the association between PFASs and breast cancer risk (ΣPFAS, ROR: 0.18, 95% CI: 0.03–0.97).



Information on polymorphisms evaluated in present study

Gene	Position	SNP rs number	Amino acid change	Common allele	Enzyme expression/ activity of variant allele[1]
CYP17A1	10q24.3	rs743572	-34T>C (5'UTR)	T	High
CYP19A1	15q21.1	rs10046	*19C>T (3'UTR)	C	High
CYP1A1	15q24.1	rs1048943	Ile462Val	Ile	High
CYB1B1	2p22.2	rs1056836	Leu432Val	Leu	High
COMT	22q11.21	rs4680	Val158Met	Val	Low

Figure 4.8 Cytochrome P450-mediated metabolic pathways of estradiol and SNP information. CYP11A1, CYP17A1, CYP19A1 and 17b-hydroxysteroid dehydrogenase (17b-HSD) convert cholesterol to estradiol through several steps. Estrogen is transformed into 2-hydroxyoestradiol by CYP1A1, CYP1A2 and CYP3A4 or into 4-hydroxyoestradiol by CYP1B1. The catechol metabolite is *O*-methylated by catechol *O*-methyltransferase (COMT); alternatively they can be oxidized into semiquinone and quinone generating free radicals. [1]Reported or expected enzyme expression or activity of the minor allele protein relative to the major allele (Wielsøe et al., 2018b).

Non-significant modifying tendencies were seen for the other SNPs on the effect of PCBs, organochlorine pesticides and PFASs. In summary, the genetic variations of *BRCA1* Cys39Gly and substitution of T to C in position -34 of the *CYP17A1* gene (CYP17A1 -34T>C) genetic variations were associated with breast cancer risk. The results suggest that the genetic variants evaluated modify the effects of POP exposure on breast cancer risk; however, due to the relatively small sample size in this study, further studies are needed (Wielsøe et al., 2018b).

4.8.2.4 Genetics in relation to reproduction and development

How human semen quality can be affected by interactions between polymorphisms in the AhR signaling pathway and exposure to POPs was studied by Brokken et al. (2014). Many dioxin-like POPs exert effects by activating the AhR signaling pathway. A study analyzed whether gene–environment interactions between polymorphisms in AhR (R554K) and AhR repressor (AhRR, P185A) and serum levels of markers of POP exposure *p,p'*-DDE and PCB153 were associated with 21 parameters of male reproductive function in 581 proven-fertile European and Greenlandic men (Brokken et al., 2014). It was observed that in Greenlandic men, AhR variants significantly modified the association between serum levels of both *p,p'*-DDE and PCB153 and inhibin B levels, sperm chromatin integrity, and seminal Zn levels. In the total cohort including populations from Greenland, Poland and Ukraine, interactions between AhRR variants and serum levels of PCB153 were associated with sperm chromatin integrity and the expression of the pro-apoptotic marker protein Fas. Brokken et al. (2014) concluded that susceptibility to adverse effects of POP exposure on male reproductive function was dependent on polymorphisms in genes involved in AhR signaling.

In a cross-sectional study, Consales et al. (2016) assessed the relationship between serum POP concentrations and DNA methylation levels in sperm of non-occupationally exposed fertile men from Greenland, Warsaw (Poland), and Kharkiv (Ukraine). Serum levels of PCB153, as a proxy for the total PCB body burden, and *p,p'*-DDE, the main metabolite of DDT were measured. Sperm DNA methylation level was assessed globally by flow cytometry. Multivariate linear regression analysis was applied to investigate correlations between serum POP concentrations and DNA methylation of sperm. Consales et al. (2016) found no consistent associations between exposure to POPs and sperm DNA methylation at repetitive DNA sequences. Flow cytometric analysis showed a statistically significant global decrease in methylation was associated with exposure to PCB153 and *p,p'*-DDE. They concluded that although lipophilic POP exposure appears to have a limited negative impact on sperm DNA methylation levels in adult males, the global hypomethylation detected in sperm suggests that further investigation is warranted.

Leter et al. (2014) investigated the association between exposure to PFASs and sperm DNA global methylation of fertile men from the Arctic and Europe. The levels of PFASs in serum from 262 partners of pregnant women from Greenland, Poland and Ukraine were determined. PFOS, PFOA, PFHxS, and PFNA were detected in 97% of blood samples. Two surrogate markers were used to assess DNA global methylation levels in semen samples from the same men: average DNA methylation level in repetitive DNA sequences (Alu, LINE-1, Sata) and flow cytometric DNA methylation level. The data showed no consistent major associations between PFAS exposure and sperm DNA global methylation endpoints after multivariate linear regression analysis. However, weak but statistically inversely significant associations of PFHxS with DNA methylation were found for Greenlanders. The effects of PFASs on sperm epigenetic processes cannot be completely excluded, and this issue warrants further investigation (Leter et al., 2014).

Because the association of exposure to endocrine-disrupting chemicals in the peripubertal period with subsequent sperm DNA methylation is unknown, the relation of peripubertal serum dioxin (TCDD) concentrations and subsequent sperm methylome profiles of young Russian adults was studied (Pilsner et al., 2018). The Russian young adults had serum TCDD concentration measured at 8 to 9 years old and provided a semen sample at 18 to 19 years of age. Whole-genome bisulfite sequencing of sperm was conducted to identify differentially methylated regions (DMRs) between groups having the highest (n=4) and lowest (n=4) peripubertal serum TCDD concentration. The results showed that 52 sperm DMRs were associated with peripubertal serum TCDD concentrations. The distribution of methylation differed between the two groups. In the highest peripubertal serum TCDD group, 75% of the identified 52 sperm DMRs displayed hypomethylation while 25% displayed hypermethylation. The study further showed the estrogen receptor alpha playing a central regulator under the function of multiple biological networks associated with cellular assembly and organization, cellular function and maintenance, and carbohydrate metabolism. From this limited sample size the study suggested that peripubertal environmental exposures were associated with sperm DNA methylation in young adults (Pilsner et al., 2018).

A study reported *CPT1A* missense mutation associated with fatty acid metabolism and reduced height in Greenlanders (Skotte et al., 2017). Inuit have lived for thousands of years in an extremely cold environment on a diet dominated by marine-derived fat. To investigate how this selective pressure has affected the genetic regulation of fatty acid metabolism, 233 serum metabolic phenotypes in a population-based sample of 1570 Greenlanders were assessed. The *CPTA* gene regulates mitochondrial long-chained fatty acid oxidation. The study found the following: (i) the Pro479Leu variant in the *CPT1A* gene (rs80356779) was strongly associated with markers of omega-3 fatty acid metabolism, such as degree of unsaturation ($p = 1.16 \times 10^{-34}$); (ii) the ratio of polyunsaturated fatty acids to total fatty acids ($p = 2.35 \times 10^{-15}$); (iii) the ratio of omega-3 fatty acids to total fatty acids ($p = 4.02 \times 10^{-19}$); and (iv) the ratio of DHA to total fatty acid ($p = 7.92 \times 10^{-27}$). The derived allele of rs80356779 (L479) occurred at a frequency of 76.2% in the Greenlanders while being absent in most other populations, and the strong signatures of positive selection were observed at the locus. Furthermore, each copy of L479 was observed to reduce height by an average of 2.1 cm ($p = 1.04 \times 10^{-9}$). In exome sequencing data from a sister population (Nunavik Inuit), no other likely causal candidate than rs80356779 was found, which supports rs80356779 being the likely causative variant. This study has shown that a common *CPT1A* missense mutation was strongly associated with a range of fatty acid metabolic phenotypes and so possibly influenced attained height of Greenlanders (Skotte et al., 2017).

4.8.2.5 Genetics in relation to nervous system disorder

The organochlorine pesticides such as DDE have been found to be associated with Parkinson's disease in Arctic Inuit (Koldkjaer et al., 2004). Variants in xenobiotic metabolizing genes were inconsistently associated with Parkinson's disease risk. Genetic modification of the association of organochlorine compounds and Parkinson's disease by a xenobiotic membrane transporter is biologically plausible, but few data have been published. Recently, genetic and gene-environment associations with Parkinson's disease were reported in a case-control study of Alaska Native people (Goldman et al., 2015). This study aimed to determine the association of variants in the gene of ATP-binding cassette sub-family B member 1 (*ABCB1*) and Parkinson's disease in Alaska Native people. *ABCB1* is also known as transporter p-glycoprotein (p-gp) or multidrug resistance protein 1 (MDR1) and is an important protein of the cell membrane that pumps many foreign substances out of cells. The study also explored whether variants modify the associations with persistent organochlorine compounds (Goldman et al., 2015). Single nucleotide polymorphic variants in *ABCB1* were tested and organochlorine compounds measured in serum, and minor allele dominant associations were tested in logistic regression models adjusted for age and gender. Multiplicative interaction was tested by including a product term for SNPs by organochlorine compounds. Seven out of nine *ABCB1* SNPs with a minor allele frequency >5% were observed to be significantly associated with Parkinson's disease, including rs10276036 (OR 2.7, 95% CI 1.5–4.9), rs2032582 (G2677A/T) (OR 2.4, 95% CI 1.3–4.5) and rs2235040 (OR 2.3, 95% CI 1.02–5.3). *ABCB1* SNPs modified associations between organochlorine compounds and Parkinson's disease, with HCB having the greatest modification effect. The study showed variants in the p-glycoprotein gene were associated with Parkinson's disease in Alaska Native people who were exposed to environmentally persistent organochlorine compounds. The *ABCB1* genotype affected the associations between organochlorine compounds and Parkinson's disease. People with altered activity of xenobiotic efflux pumps may be more susceptible to Parkinson's disease, especially in combination with exposure to organochlorine compounds (Goldman et al., 2015).

Another case-control study assessed PCBs and Parkinson's disease, and whether the membrane transporter variants had a modification effect in a Caucasian population (Goldman et al., 2016). *ABCB1* SNPs were genotyped, and 15 PCB congeners were measured in serum of Parkinson's disease cases. The results showed that all PCB levels were higher in Parkinson's disease cases than in controls. *ABCB1* coding variant rs9282564 modified the associations between PCBs and Parkinson's disease: a high level of PCBs was associated with a 1.4-fold (95% CI: 0.7–2.8) greater risk in those with AA genotype, but an 11.4-fold (95% CI: 2.8–45) greater risk in those with AG or GG genotype (p-interaction 0.008). Goldman et al. (2016) concluded that PCB levels were higher in Parkinson's disease cases than in controls for both Alaska Native and Caucasian populations. Risk was markedly increased in people with both higher PCB levels and variants in *ABCB1*, suggesting a gene-environment interaction.

4.8.2.6 Genetics in relation to endocrine diseases

The Greenlandic population has experienced a dramatic increase in the prevalence of Type 2 diabetes over the past 25 years due to lifestyle and dietary transition (Jørgensen et al., 2002). One study reported that a common Greenlandic *TBC1D4* variant conferred muscle insulin resistance and Type 2 diabetes (Moltke et al., 2014). The study involved association mapping of Type 2 diabetes-related quantitative traits in up to 2575 Greenlandic individuals without known diabetes and discovered a nonsense p.Arg684Ter variant (in which arginine is replaced by a termination codon) in the gene *TBC1* domain family member 4 (*TBC1D4*) with an allele frequency of 17%. *TBC1D4* plays an important role in glucose homeostasis. The homozygous carriers of this variant had a 3.8 mmol/L higher plasma glucose level and 165 pmol/L higher serum insulin level 2 hours after an oral glucose load, compared with individuals with other genotypes (both non-carriers and heterozygous carriers). Furthermore, homozygous carriers had an 0.18 mmol/L lower concentration of fasting plasma glucose and 8.3 pmol/L lower level of fasting serum insulin. The homozygous carriers had a high risk of Type 2 diabetes (OR 10.3, $p=1.6\times10^{-24}$). Heterozygous carriers had an 0.43 mmol/L higher plasma glucose concentration 2 hours after an oral glucose load than non-carriers. Analyses of skeletal muscle biopsies showed lower messenger RNA and protein levels of the long isoform of *TBC1D4*, and lower muscle protein levels of the glucose transporter GLUT4, with increasing number of p.Arg684Ter alleles. These findings indicated that the p.Arg684Ter *TBC1D4* variant conferred increased risk of a subset of diabetes that features deterioration of postprandial glucose homeostasis. Moltke et al. (2014) concluded that these findings were concomitant with a severely decreased insulin-stimulated glucose uptake in muscle, leading to postprandial hyperglycemia, impaired glucose tolerance and Type 2 diabetes.

4.8.3 Summary of latest findings

In multifactorial diseases such as cancer, environmental variables and gene variants shape the risk per population. The genetic variants found to be under selection for cold environments can also predispose for cancer.

Prenatal exposure to contaminants such as POPs can cause changes in sex-specific DNA methylation of genes associated with networks of reproductive, cardiovascular and neural/behavioral disruption. Genetic polymorphisms in the key genes involved in metabolism of xenobiotic chemicals could influence the levels of POPs and heavy metals and modify the association between exposure and contaminant levels in the Arctic population. This can in turn influence the human health effects of these contaminants.

The organic anion transporter 4 (OAT4) expressed in human placenta can modify the transfer of PFASs through placenta. OAT4 may protect the fetus by decreasing fetal exposure to PFASs.

Dietary and lifestyle transition and the genetic variants selected for adaptation at extreme cold conditions might increase cancer risk in later life. The genetic variants of genes involved in the synthesis and metabolism of estrogens, especially *CYP17A1*, can modify the effects of POP exposure on breast cancer risk. Adverse effects of POP exposure on male reproductive function are dependent on polymorphisms in the genes involved in AhR signaling. For the Arctic population, POPs exposure is associated with global DNA methylation in the sperm.

The Inuit have genetic and physiological adaptions to a diet rich in PUFAs. Mutation in genes regulating mitochondrial long-chained fatty acid oxidation was strongly associated with a range of metabolic phenotypes in Greenlanders and may influence attained height in Greenlanders.

The xenobiotic efflux membrane p-glycoprotein gene (*ABCB1*) modified the associations of exposure to lipophilic POPs and Parkinson's disease. People with variants of membrane transporter *ABCB1* may be more susceptible to Parkinson's disease.

A genetic variant in a gene involved in glucose homeostasis is associated with glucose homeostasis and Type 2 diabetes in the Greenlandic population (also briefly mentioned in Section 4.6.2).

4.9 Effect modifiers

4.9.1 AMAP Assessment 2015: conclusions

Different chemical substances can interact and induce similar effects in an additive, synergistic or non-additive way and may target the same organ. Because most studies concern human exposure to single chemicals rather than chemical mixtures and ignore potentially confounding effects introduced by the presence of other factors, the association between a specific exposure and its outcome may be underestimated. Negative confounding could result in underestimation of those chemicals causing toxicity (e.g., MeHg and PCBs in seafood) and those having benefits (e.g., long-chain omega-3 PUFAs in seafood).

4.9.2 New peer-reviewed literature

Prenatal exposure to PCB153, *p,p*'-DDE and birth outcomes and the exposure-response relationship and factors modifying this relationship were reported by Casas et al. (2015). The study explored whether modifier and susceptible subgroups exist. A pooled dataset was used comprising 9377 mother–child pairs enrolled in 14 study populations from 11 European birth cohorts including cohorts from the Faroe Islands. The study observed an inverse linear exposure–response relationship between prenatal exposure to PCB153 and birth weight over the entire exposure range, including at low levels. The effect of reduced birth weight owing to PCB153 exposure seemed to be stronger among children of mothers who were non-Caucasian or who had smoked during pregnancy. The most susceptible subgroup was girls whose mothers smoked during pregnancy. This study suggested that an inverse association between low-level exposure to PCB153 and birth weight exists and that both maternal smoking and ethnicity modify this association (Casas et al., 2015).

Yary et al. (2017) evaluated the links between serum omega-6 PUFAs, serum Zn, delta-5- and delta-6-desaturase activities and incident metabolic syndrome. This study aimed to investigate the associations between serum omega-6 PUFA and the activities of enzymes involved in PUFA metabolism such as delta-5-desaturase and delta-6-desaturase with risk of incident metabolic syndrome, and investigated whether Zn, a cofactor for these enzymes, modifies these associations. This prospective follow-up study of an eastern Finland Kuopio population included 661 men who were between 42 and 60 years old at baseline in the period 1984–1989 and who were re-examined in the period 1998–2001. The results showed that compared to the lowest tertile of serum total omega-6 PUFAs, men in the highest omega-6 PUFA tertile had a 70% lower multivariate-adjusted risk of incident metabolic syndrome (OR 0.30; 95% CI: 0.18–0.51, p trend <0.001). Inverse associations were also observed for linoleic acid, arachidonic acid and delta-5-desaturase activity. By contrast, men in the highest tertile of delta-6-desaturase activity had an 84% higher risk of metabolic syndrome (OR 1.84; 95% CI: 1.15-2.94, p trend = 0.008). Similar associations were observed with many of the metabolic syndrome components at the re-examinations. Most associations were attenuated after adjustment for BMI. Finally, the associations of delta-6-desaturase and omega-6 PUFA such as linoleic acid with the risk of metabolic syndrome were stronger among those with a higher serum Zn concentration. The conclusion of this study was that higher serum total omega-6 PUFA, linoleic acid and arachidonic acid concentrations and delta-5-desaturase activity were associated with a lower risk of incident metabolic syndrome and higher delta-6-desaturase activity was associated with a higher risk of metabolic syndrome in middle-aged and older men from eastern Finland. The modification role of Zn needs further investigation in other populations (Yary et al., 2017).

4.9.3 Summary of latest findings

Maternal smoking and ethnicity modify the association of prenatal exposure to PCBs and birth weight. Nutrition status can influence metabolic syndrome risk and Zn may modify the association of incident metabolic syndrome with omega-6 PUFAs and PUFA metabolism enzymes.

4.10 Summary on health effects

In birth cohort studies, prenatal exposure to MeHg can explain most of the neurodevelopmental deficits. However, postnatal MeHg exposure also appears to contribute, especially in relation to visuospatial processing and memory. Marine fatty acids appear to diminish the MeHg effect on the central nervous system. Moreover, prenatal exposure to PFASs and organochlorine compounds seems to have a negative effect on child behavior, that is, parent-reported behavioral problems at preschool age.

Studies in the circumpolar area indicate that dietary exposure to environmental contaminants has a negative impact on the immune system, such as demonstrated by inhibition of antibody formation to child vaccines. Further study is needed on pre- and postnatal windows of vulnerability and identification of the most immunotoxic substances.

The prevalence of intestinal bowl disease is high in the Faroe Islands. However, the excess risk seems to disappear over time when immigrating to Denmark, indicating a gene-environment interplay.

Environmental toxins might influence vitamin D deficiency and people with autism spectrum disease had lower vitamin D levels than people without the diagnosis. Reports show that low habitual iodine intake in pregnant women, that is, lower than the recommended intake for non-pregnant women, is associated with mothers reporting poorer child language, poorer school performance, and increased likelihood of special educational needs at the age of 8 years.

The protective effect of EPA and DHA in Inuit diets on myocardial infarctions is diminished by the adverse effect of exposure to MeHg in the diet. Therefore, promoting the increased consumption of fish species with high EPA+DHA levels and low MeHg levels may help to prevent myocardial infarctions among Inuit.

No significant associations were observed between PCBs, organochlorine pesticides and blood pressure among Greenlanders. Most remarkable is a recent prospective study of Inuit in Greenland showing no association between blood Hg and risk of developing cardiovascular diseases.

Transition from a traditional marine diet to imported western food is evident in Greenlandic pregnant women. Currently, traditional marine foods represent 12% of the diet with imported western foods responsible for the remaining 88%. However, despite a decrease in the intake of traditional foods, POP levels in pregnant Inuit women are still higher than in Caucasian women (e.g., Danish women) and occur at a level shown to affect fetal growth and development in Greenlandic Inuit. Although lower than in the past, smoking frequency for pregnant women in Greenland is still high (36%), and affects fetal growth. The high rate of tobacco smoking during pregnancy and impacts on fetal growth are of concern and require action.

Mean BMI of pregnant women in Greenland is increasing as also seen for the rest of the Greenlandic population. Transition from a traditional marine diet to a higher intake of imported Western food may be an explanatory factor. Thus, dietary recommendations are important for the intake of healthy food, including more intake from the lower levels of the marine food chain (e.g. fish) and less intake from marine mammals.

Reproductive health is affected by POP exposure. PFASs (PFOSA, PFNA) exposure may impair female fertility and high exposure to some environmental organochlorines/ metals/ phthalates may affect the male reproductive system. POPs interfere with the reproductive system as demonstrated with the following data: inverse association with semen quality/motility (e.g., dioxins, PCB153), positive associations with reproductive hormones (e.g., HCB and Cd vs testosterone), inverse associations between testosterone and DINP metabolites, positive associations between POPs and reproductive parameters (Hg vs inhibin B, HCB vs sex hormone-binding globulin), and sperm aneuploidy/disomy in adulthood (e.g., *p,p'*-DDE, total PCB vs XX, XY, and total disomy). However, further studies are needed to confirm these findings.

POPs are endocrine-disrupting chemicals that mimic the function of endogenous hormones, such as by eliciting xeno-estrogenic and xeno-androgenic activities. The combined xeno-estrogenic activity of PFAS serum mixtures in pregnant women is inversely associated with fetal growth indices.

POPs, PFASs and PBDEs can interfere with thyroid hormone homeostasis. Early-life exposure to POPs affects newborn thyroid hormone levels, and may increase risk of neurological disorders (e.g., ADHD).

Some studies suggest that maternal exposure to endocrine-disrupting chemicals can increase risk of childhood obesity. Exposure to POPs affects diabetic parameters, such as beta cell function and may be a risk factor for developing Type 2 diabetes.

Cancer among certain Indigenous Arctic Peoples is of increasing concern. The circumpolar Inuit have rates for several cancer sites that exceed all other regions in the world. From 1989 to 2008, a marked increase in lung, colorectal and female breast cancers linked to a western lifestyle has been shown, while cervical cancer has declined. Endocrine-disrupting chemicals such as some POPs (e.g., PCBs, PFASs), heavy metals (e.g., Cd), and phthalates are potential carcinogens and may play a role in the increased incidence of breast, prostate and lung cancers. These contaminants might interact with microorganisms to influence the development of liver cancer.

The genetic polymorphisms of key genes involving metabolism of xenobiotic chemicals could influence the levels of POPs and heavy metals in humans, and modify the association between exposure and contaminants in the Arctic population and in turn influence the health effects of these contaminants. Genetic variants emerging as an adaptation to extreme environmental conditions can increase cancer risk as an interaction with transition to Western life-style and diet. A genetic variant in a gene involved in glucose homeostasis is associated with glucose homeostasis and Type 2 diabetes in the Greenlandic population. Exposure to POPs increases risk of Parkinson's disease for humans carrying variants of membrane transporter *ABCB1* gene.

DNA methylation is a genetic modification that can influence gene expression. Prenatal exposure to POPs can cause changes in sex-specific DNA methylation of genes associated with reproductive, cardiovascular and neural/behavioral disruption. DNA methylation can increase and/or decrease gene expression and DNA methylation relates to the risk of breast cancer. Genetic variants involved in the synthesis and metabolism of estrogens can increase risk of breast cancer. Exposure to POPs such as PCBs, dioxin, and PFASs can affect sperm DNA methylation and polymorphisms and thus might adversely influence male reproductive function.

Effect modifiers are other factors that can affect the association between a specific exposure and its outcome. Maternal smoking and ethnicity modify prenatal POP exposure and lower birth weight, and non-Caucasian women that had smoked during pregnancy had a higher risk having offspring with low birth weight. Zinc may modify the association between incident metabolic syndrome and omega-6 PUFAs and PUFA metabolism enzymes. The protective effect of omega-6 PUFAs such as linoleic acid on metabolic syndrome and the positive association between serum delta-6-desaturase and risk of metabolic syndrome were stronger for the middle-aged and older men from eastern Finland with higher serum Zn concentrations.

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5. Human health risks associated with contaminants in the Arctic

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Key findings

- *Different jurisdictions set different guidance values for persistent organic pollutants and metals designed to protect health. The guidance values can differ based on, among others, estimated dietary intakes, approaches to uncertainty, population to be protected, purpose of the guidance, and the mandate of the organization issuing the guidance.*
- *Guidance values can vary in complexity, from a maximum level in a food item, to a recommended maximum dietary intake, to a level measured in human matrices below which effects are unlikely to be observed. These guidance values can be based on epidemiological, experimental and/or modeling studies.*
- *Since the 1990s, there has been a trend of decreasing mercury and lead exposure, resulting in fewer exceedances of guidelines. The regions where mercury and lead guidelines were exceeded are Nunavik and Greenland.*
- *Indigenous Arctic populations were identified as a population in need of improved contaminant exposure estimation tools.*
- *Future studies are necessary in order to reduce uncertainties in the estimates of health risks from exposure to environmental contaminants by better identifying the sources of contaminants; deriving and/or updating reference values for key contaminants; exploring risk assessment methods to address risks associated with mixtures; and improving the overall process of health risk assessment, including harmonizing reference values where possible.*

5.1 Introduction

A human health risk assessment describes both the nature of a health impact and the probability that it will occur. Guidance on conducting such assessments is available from national and international programs (e.g., IPCS, 2010). Studies on the impact of contaminants on human health are challenging to undertake owing to the effects of confounding factors simultaneously influencing health. Nevertheless, risk assessment is an essential part of safeguarding populations against adverse effects of exposure to contaminants.

Risk assessment in the Arctic deserves particular attention because the primary route of exposure for many contaminants is through traditional foods, and these foods are also important nutritionally and culturally (see Chapter 2). Risk may be affected by underlying conditions (see Chapter 4). Understanding risk assessment, as well as its strengths and limitations is important to being able to communicate risks (see Chapter 6). Risk assessment in the Arctic must consider inputs specific to particular regions or communities (e.g., food intake, seasonal intake), unique exposure mixtures and underlying factors. Many of these issues are being addressed by advances in risk assessment (e.g., IOM, 2013; US EPA, 2019; Sprong et al., 2020); however, examples of risk assessment in the Arctic are limited.

This chapter reports on the utility and related challenges of estimating human health risks associated with exposure to environmental contaminants in the circumpolar Arctic, specifically via the consumption of traditional/country and local foods. It describes how food-based, dietary intake-based and human tissue-based contaminant data can be compared against different types of reference values to estimate risk. This is the first time that these approaches have been examined together in an AMAP human health assessment. Reference and guidance values are described that are applicable to AMAP work, especially dietary exposure to contaminants. Other values, such as inhalation or dermal guidance values, are outside the scope of this work. This chapter also provides examples of how guidance values are used in an Arctic circumpolar context, and details the challenges and limitations of using these values to interpret the type of information derived from human health research in the Arctic.

5.2 General principles of human health risk assessment

The conventional risk assessment process, which incorporates hazard assessment, exposure assessment, and risk characterization, is used to quantify the probability of harmful and adverse effects on human health.

Hazard assessment involves identifying and characterizing the hazards associated with a contaminant. Evidence is available from epidemiological studies, *in vitro* or *in vivo* toxicological studies and modeling research. Many risk assessments are based on toxicological data and these may be supported by toxicokinetic modeling, and quantitative structure-activity relationships, among others. Use of epidemiological studies may address the issue of multiple-contaminants, interaction between chemical and nonchemical stressors, and may decrease the need to apply uncertainty factors (Hoek et al., 2018). More detailed information on the results of health effects studies in the Arctic can be found in Chapter 4.

Exposure assessment is used to estimate the exposure of a population to a contaminant or contaminants. Many methods are available for assessing exposure. For example, in terms of dietary information, food frequency questionnaires or recall surveys collect information on possible sources of exposure. These data can then be combined with contaminant levels measured or modeled in food items to estimate dietary exposure. Total exposure may be estimated through human biomonitoring data, i.e., the measurement of a chemical in a biological matrix, such as blood. This chapter focuses on levels of metals and persistent organic pollutants (POPs) in blood because, in the context of the AMAP Human Health Assessment Group circumpolar collaboration since the 1990s, all participating countries have collected blood samples for international comparison. Breastmilk, urine, and other matrices are not discussed here as they are collected less frequently. More detailed information on exposure studies in the Arctic can be found in Chapter 3.

Risk characterization combines the results of the hazard and exposure assessments to describe the risk of effects given exposure. Approaches to characterize risk from dietary exposure to environmental chemicals include comparing contaminant levels in foodstuffs to food safety limits; comparing estimated daily intakes (EDIs) to acceptable daily intakes (ADIs) or tolerable daily intakes (TDIs); comparing contaminant levels in blood (human exposure levels) to blood guidance values; and modeling to describe human exposure.

Risk assessments often focus on a specific chemical or stressor. However, individuals are exposed to multiple chemicals and stressors. It is possible to combine risks associated with multiple sources of exposure or across multiple chemicals with similar effects to estimate hazard quotients (HQs) for non-cancer effects or excess lifetime cancer risks.

5.2.1 Dietary-based guidance values

5.2.1.1 Contaminant limits in food items (food safety limits)

Codex Alimentarius, formed in 1962 by the United Nations World Health Organization (WHO) and the Food and Agriculture Organization (FAO), currently unites over 180 countries worldwide as Codex members. The Codex Alimentarius Commission (CAC) is an intergovernmental body which develops and adopts international food standards. Maximum residue level (MRL) is the maximum concentration of a pesticide residue (expressed as mg/kg), recommended by the CAC to be legally permitted in food, food commodities and animal feeds. Codex MRLs are derived from estimations based on comprehensive toxicological assessments of pesticides and their residues and residue data (FAO/WHO, 2020a). MRLs for contaminants in food are not a direct human health risk assessment parameter, but do represent a level below which there is no concern for human health.

Other national and international authorities, including the European Food Safety Authority (EFSA), Health Canada, and the Russian Federal Service for Supervision of Consumer Rights Protection and Human Welfare (Rospotrebnadzor), establish allowable limits for residual pesticides present in food items (MRLs or maximum allowable levels; MALs). Maximum levels (MLs) are set for other contaminants, including some metals, and contaminants not purposefully applied to food items. Rospotrebnadzor sets federal sanitary-epidemiological rules, norms and regulations, and hygiene standards that are state regulatory legal acts approved by a decree of the Chief State Sanitary Physician and are valid throughout the country. Violations of the rules lead to administrative and criminal liability (Russian Federation, 1999). Most of these MRLs and MALs are available online (Health Canada, 2012; European Commission, 2016; FAO/WHO, 2020b).

Table 5.1 Comparison of maximum allowable levels (MALs) and maximum residue levels (MRLs) of POPs in raw foods of animal origin, mg/kg ww.

		ΣDDTs				ΣHCHs	γ-HCH	
		MAL	MRL			MAL	MRL	
Food group	Foodstuff	Russian[1]	Codex[2]	HC[3]	EU[4]	Russian[1]	Codex[2]	EU[4]
Land mammals	Meat	0.1	5.0[a]	-	0.05[a]	0.1	0.01[a]	0.01[a]
Marine mammals	Meat	0.2	-	-	-	0.2	-	
	Blubber	0.1	-	-	-	0.2	-	
Fowl	Muscle	0.1	0.3[a]	1.0	1.0[a]	0.1	0.005[a]	0.01[a]
	Eggs	0.1	-	0.5	0.05[a]	0.1	0.001	0.01[a]
Fish	Muscle (all species)	-	-	5.0	-	-	-	
	Muscle (freshwater species)	0.3	-	-	-	0.03	0.01	
	Muscle (marine species)	0.2	-	-	-	0.2	0.01	
	Caviar	2.0	-	-	-	0.2	-	
	Liver	3.0	-	-	-	1.0	-	

- Not established; [a]applies to the fat of meat or 'fat soluble'.
Sources: [1]Russian Federation (2011); [2]FAO/WHO (2020b); [3]Health Canada (2012); [4]European Commission (2016).

A comparison of MRL and MAL values for selected POPs in a range of raw food items of animal origin (relevant to AMAP's work) is presented in Table 5.1, with a similar comparison of MALs for selected metals in Table 5.2. MRLs in some jurisdictions (such as Canada) are intended to be applied to retail products, and are not relevant to country foods. They are presented here for comparison purposes only.

As Table 5.1 shows, MRLs are most common for POPs, but do not cover all POPs, particularly 'new' POPs, such as brominated and fluorinated compounds. Russia has the most comprehensive list of MALs, and the only values for marine mammal tissue (DDT, hexachlorocyclohexane [HCH], polychlorinated biphenyls [PCBs]). Values may differ between jurisdictions based on many factors, including available data, estimated exposure, analytical measurements, sampling method and different approaches to uncertainty. For some POPs this difference is 50- to 100-fold.

As seen in Table 5.2, there are only MALs for lead (Pb), arsenic (As), cadmium (Cd) and mercury (Hg) in raw foods. Compared to other jurisdictions, Russian hygienic regulations for metals in foods cover almost the entire suite of species, both fauna and flora. The USSR MALs for copper (Cu), zinc (Zn), nickel (Ni), chromium (Cr) and aluminum (Al), presented in Table 5.2, were established in the 1980s for several food groups. These MALs have not been revised, but are still in use in Russia owing to the lack of any other standards for these metals worldwide (see Section 5.4.5).

5.2.1.2 Oral/dietary contaminant intake guidance values

This section is limited to oral or dietary guidance values, because the primary route of exposure to contaminants relevant to this AMAP assessment is from food consumption (see Chapter 2). Similarly, only contaminants relevant to the work of AMAP's Human Health Assessment Group are included in this section.

Estimated daily intakes

Estimated daily intakes describe the intake of a contaminant for different receptors (e.g., different age groups). The general equation for calculating an EDI, in the case of chronic oral exposure to a contaminant, is the following:

$$EDI = C \times IR / BW$$

Where: EDI is the amount (in mg) of daily contaminant consumption with food per kg bw (mg/kg bw/day), C is the concentration of a contaminant in a food item (mg/kg ww); IR is the daily food ingestion rate (kg/person/day); and BW is average body weight (usually 60 or 70 kg).

Estimates of exposure can be compared to reference or guidance values (described in subsequent sections). A sum of EDIs calculated for individual food items analyzed for a specific contaminant, which represents the total EDI for a contaminant from all food sources, can also be compared to an oral daily intake for a contaminant. If the calculated total EDI is higher than the TDI or ADI, then the human non-cancer health risk associated with oral intake of this contaminant could be considered as increased.

Non-carcinogenic risk

The concept of 'acceptable daily intake' was first introduced in 1961 by the Council of Europe. Later, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) defined it as "the daily intake which, during the entire lifetime, appears to be without appreciable risk to the health of the consumer on the basis of all the known facts at the time of the evaluation of the chemical by the Joint FAO/WHO Meeting on Pesticide Residues" (FAO/WHO, 2020a). For contaminants and other chemicals not used intentionally, the term 'tolerable daily intake' is often preferred, but the terms ADI and TDI are frequently used interchangeably. TDI is an estimate of the quantity of a

Table 5.1 Continued

α-HCH	β-HCH	ΣPCBs	HCB	ΣChlordanes			Heptachlor			
MRL	MRL	MAL	MRL	MAL	MRL		MAL	MRL		
EU[4]	EU[4]	Russian[1]	EU[4]	Russian[1]	Codex[2]	EU[4]	Russian[1]	Codex[2]	HC[3]	EU[4]
0.01[a]	0.01[a]	-	0.01 [a]	0.05[a]	0.05[a]	0.005[a]	0.2	0.2[a]	0.2	0.01[a]
-	-	2.0	-	-	-	-	-	-	-	-
-	-	3.0	-	-	-	-	-	-	-	-
0.01[a]	0.01[a]	-	0.01[a]	0.5[a]	0.05[a]	0.05[a]	0.2	0.2[a]	0.2	0.2[a]
0.01[a]	0.01[a]	-	0.01[a]	0.02	0.02	0.005[a]	0.05	0.05	-	0.02[a]
-	-	2.0	-	-	-	-	-	-	-	-
-	-	2.0	-	-	-	-	-	-	-	-
-	-	2.0	-	-	-	-	-	-	-	-
-	-	2.0	-	-	-	-	-	-	-	-
-	-	5.0	-	-	-	-	-	-	-	-

Table 5.2 Comparison of maximum allowable levels (MALs), maximum levels (MLs) and maximum residue limits (MRLs) of metals in raw foods, mg/kg ww.

Food group	Foodstuff	Pb		As		Cd		Hg[a]		Cu[4]	Zn[4]	Ni[5]	Cr[5]	Al[5]
		MAL	ML	MAL	ML	MAL	ML	MAL	MRL	MAL				
		Russian[1]	Codex[2]	Russian[1]	Codex[2]	Russian[1]	Codex[2]	Russian[1]	EU[3]	Russian[b]				
Land mammals	Meat	0.5	0.1	0.1	-	0.05	-	0.03	0.04	5.0	70.0	0.5	0.2	10.0
	Liver	0.6	0.1-0.2	1.0	-	0.3	-	0.1	0.02	-	-	-	-	-
	Kidney	1.0	0.1-0.2	1.0	-	1.0	-	0.2	0.02	-	-	-	-	-
Marine mammals	Meat	1.0	-	5.0	-	0.2	-	0.5	-	-	-	-	-	-
	Blubber	1.0	-	1.0	-	0.2	-	0.3	-	-	-	-	-	-
Fowl	Meat	0.5	0.1	0.1	-	0.05	-	0.03	0.01	-	-	-	-	-
	Egg	0.3	-	0.1	-	0.01	-	0.02	0.01	-	-	-	-	-
Fish	Muscle (all species)	1.0	0.3	-	-	0.2	-	-	-	10.0	40.0	0.5	0.3	30.0
	Muscle (freshwater species)	-	-	1.0	-	-	-	0.6	-	-	-	-	-	-
	Muscle (marine species)	-	-	5.0	-	-	-	0.5	-	-	-	-	-	-
	Caviar, Milt	1.0	-	1.0	-	1.0	-	0.2	-	-	-	-	-	-
	Liver	1.0	-	-	-	0.7	-	0.5	-	-	-	-	-	-
Seafood	Invertebrates	10.0	-	5.0	-	2.0	2.0	0.2	-	-	-	-	-	-
	Seaweed, Alga	0.5	-	5.0	-	1.0	-	0.1	-	-	-	-	-	-
Vegetables	All species	0.5	0.05–0.3	0.2	-	0.03	0.05–0.2	0.02	0.01	5.0	10.0	0.5	0.2	30.0
Berries	All species	0.4	0.1–0.2	0.2	-	0.03	-	0.02	0.01	5.0	10.0	0.5	0.1	20.0
Mushrooms	All species	0.5	0.3	0.5	-	0.1	-	0.05	0.5	10.0	20.0	0.5	-	-

- Not established; [a]sum of mercury compounds expressed as mercury; [b]not revised since the collapse of the USSR but still in use in Russia owing to the lack of any other standards for these metals worldwide.
Sources: [1]Russian Federation (2011); [2]FAO/WHO (2019); [3]European Commission (2016); [4]Russian Federation (1989); [5]Russian Federation (1981).

non-cancer causing chemical that humans can be exposed to every day for their whole life without threatening their health. The TDI, or similarly the tolerable weekly intake (TWI) or tolerable monthly intake (TMI), in the case of substances with longer biological half-lives, can also apply to carcinogenic compounds that do not have a genotoxic mode of action or to indirect genotoxic compounds (i.e., those with a threshold). ADIs or TDIs are expressed in milligrams of chemical per kilogram of body weight per day (mg/kg bw/day).

Equivalent terms have been developed by other organizations. The United States Environmental Protection Agency (US EPA) has offered an ADI modification with the name 'reference dose' (RfD) as the acceptable safety level for chronic non-carcinogenic and developmental effects. In essence, the US EPA has replaced ADI and TDI with the single term RfD, also expressed in mg/kg bw/day. The primary modification was that the uncertainty factors in multiples of 10 – traditionally applied to the no observed adverse effect level (NOAEL) approach derived from animal studies – may be lower than 10, such as 1 or 3, based on scientific judgment. The Agency for Toxic Substances and Disease Registry (ATSDR) has established national values analogous to TDIs, called minimal risk levels (ATSDR-MRLs). It is noted that this abbreviation is identical to the Codex Alimentarius MRLs but the meaning is different, which caused a confusion in terminology that still exists today. In the context of this chapter, chronic ATSDR-MRLs (365 days and longer) are of most interest, but intermediate ATSDR-MRLs (15 to 364 days) are also presented.

The TDIs, ADIs, RfDs and ATSDR-MRLs are usually based on studies carried out on laboratory animals, but can be based on epidemiological studies. First, a 'point of departure' (POD) is determined. Dose–response modeling approaches, specifically benchmark dose (BMD)-methods, are now generally regarded by many international health organizations as the method of choice for deriving PODs. However, the lowest observed adverse effect level (LOAEL)/ NOAEL approach has been the standard methodology (familiar to most risk assessors) for deriving PODs for decades. The POD is divided by an uncertainty factor to calculate the TDI, ADI, RfD or ATSDR-MRL. Depending on many conditions, the uncertainty factor may range from 10 to several thousand. Guidance on the selection of uncertainty factors has been published by different jurisdictions (e.g., EFSA, 2012; IOM, 2013).

To calculate the lifetime non-carcinogenic risk, the EDI of a non-carcinogenic chemical can be divided by the RfD (TDI or ADI or ATSDR-MRL). The resulting target hazard quotient (THQ) is a unitless risk estimate. A summation of THQs for all non-carcinogenic contaminants to which an individual is orally exposed was proposed to calculate the total hazard index (THI) as the total non-carcinogenic risk. In general, the site-specific THI for contaminants with reference doses based on the same toxic endpoint should not exceed a value of 1.0 (calculated by summing the HQs for individual contaminants). A value greater than 1.0 indicates an increased risk of non-cancer health effects.

Table 5.3 presents a comparison of reference values for POPs and metals from national organizations from AMAP countries and international bodies (ATSDR, Health Canada, JECFA, EFSA, Codex Alimentarius, Russian Rospotrebnadzor and US EPA).

It is evident from Table 5.3 that reference values for POPs have been derived primarily by ATSDR, Codex and Russia, whereas values for metals are more commonly presented from ATSDR, Health Canada and JECFA. The reason for the discrepancies between values may be the use of different uncertainty factors, the window of exposure (e.g., intermediate vs chronic) and the date of assessment, among other influences. Interestingly, ATSDR has derived values for some newer chemical classes, including polybrominated diphenyl ethers (PBDEs) and per- and polyfluoroalkyl substances (PFASs).

Carcinogenic risk

The International Agency for Research on Cancer (IARC) classifies an agent according to its carcinogenicity to humans based on the weight of evidence to: Group 1 "sufficient evidence of carcinogenicity to humans", Group 2A "probably carcinogenic to humans", Group 2B "possibly carcinogenic to humans", Group 3 "not classifiable as to its carcinogenicity to humans" (Table 5.4).

Carcinogens may exert their effects via genotoxic or non-genotoxic mechanisms. Genotoxic carcinogens can be labelled non-threshold carcinogens as there is thought to be no safe exposure threshold owing to their interactions with DNA. In contrast, a threshold below which effects would not be expected to occur can be derived for non-genotoxic carcinogens, which act via other mechanisms, such as hormonal effects, cytotoxicity, cell proliferation, or epigenetic changes (Nohmi, 2018).

Current scientific knowledge shows no reliable evidence of genotoxicity for environmental persistent contaminants studied in the Arctic. Many POPs are xenoestrogens, which act as hormone disruptors. Some POPs and some metals could be classified as non-genotoxic carcinogens, which are assumed to have a threshold below which carcinogenicity is not observed. Similar to non-carcinogenic chemicals, TDIs (ADI, RfD or ATSDR-MRL) based on the NOAEL-approach and/or BMD can be derived for these chemicals.

The key risk assessment parameter derived from the US EPA carcinogenic risk assessment is the cancer oral slope factor, for which there may be different abbreviations (CSF, CFS, OSF, SFO, CPSo). Cancer slope factor is a plausible upper-bound estimate of the probability that an individual will develop cancer if exposed to a carcinogenic or potentially carcinogenic chemical for a lifetime. The cancer oral slope factor is expressed as (mg/kg bw/day)$^{-1}$; it is an estimate of the increased cancer risk from oral exposure to a dose of 1 mg/kg bw/day for a lifetime.

To calculate the lifetime cancer risk, the EDI of a carcinogenic chemical can be multiplied by a cancer slope factor, and then compared to the level of acceptable cancer risk. A target cancer risk (TCR) is a unitless value. A summation of TCRs for all carcinogenic contaminants to which an individual is orally exposed was proposed to calculate the total target cancer risk (TTCR).

Acceptable cancer risk is defined by respective jurisdictions. For example, in Russia, the estimated individual lifetime carcinogenic risk equal to or less than 10^{-6} (corresponding to one additional case of cancer per one million exposed persons) is considered minimal to the general population; risk in the range 10^{-6} to 10^{-4} is considered acceptable; risk in the range 10^{-4} to 10^{-3} is considered unacceptable to the general population; while risk equal to or greater than 10^{-3} is considered high, requiring measures to reduce it (Russian Federation, 2004).

While recognizing that jurisdictional policy differences can have significant impacts on the development of these values, the US EPA has the most robust set of cancer slope factors. Table 5.4 presents the cancer slope factors from the US EPA and some other jurisdictions, as well as the IARC classifications for POPs and metals used to estimate risk in Section 5.3.1.

5.2.2 Human biomonitoring

Human biomonitoring of contaminants is the measurement, in people, of a chemical or the products a chemical makes when it breaks down. This measurement is usually made in blood or urine and sometimes in other tissues and fluids such as hair, nails, and breastmilk. Biomonitoring provides an estimate of exposure to a chemical; the 'internal dose' of a chemical resulting from integrated exposures from all routes. Human biomonitoring is used increasingly as a tool for quantifying human exposure to chemicals in order to inform public health, risk assessment, and risk management decisions. Tools are available to interpret the data in different contexts. There are three primary tools that are, in order of increasing complexity, reference values, biomonitoring equivalents, and tissue-based guidance values.

5.2.2.1 Reference values

Reference values (RV95s) for environmental chemicals indicate the upper bound of background exposure of the general population to a given substance at a given time. They are defined by the German HBM Commission as, "the 95th percentile of the measured pollutant concentration levels in the relevant matrix of the reference population. To derive it, it is rounded off within the 95% confidence interval" (HBM Commission, 2016). RV95s can be computed based on population-representative human biomonitoring data sets. They are statistical reference values. They are not health-based and as such are not risk-based values, but do allow exposure in an individual or population to be compared to other populations.

Development of RV95s requires a sufficiently large population. RV95s are based on general population exposure, or a reference population. For example, individuals with high fish or seafood consumption may be excluded from an RV95 for Hg because these are known sources of this contaminant and would skew the background value for a general population. Therefore, the utility of comparison to these limits for many exposures in the Arctic driven by known sources, such as diet, may not be relevant. The reference population can be partitioned by age or sex if significant differences exist between groups. RV95s developed for one data set can be compared to other similar data sets and can be used to identify individuals or sub-populations with increased exposures, to follow changes in

Table 5.3 Comparison of oral non-cancer ATSDR minimal risk levels (ATSDR-MRLs), acceptable daily intake values (ADIs), tolerable daily intake values (TDIs), and US EPA reference doses (RfDs) for persistent organic pollutants and metals.

Substance	ATSDR-MRL, mg/kg bw /day	ADI, mg/kg bw /day	
	ATSDR[1]	Codex[2]	Russia[3]
ΣDDT	0.0005 – int[a]	0.01	0.01
HCHs	0.008 (α-HCH) 0.0006 – int (β-HCH) 0.00001 – int (γ-HCH)	0.005	0.01 (ΣHCH)
HCB	0.00007	-	0.0006
PentaCB	-	-	-
ΣChlordanes	0.0006	0.0005	0.0005
Heptachlor + Heptachlor epoxide	0.0001- int (heptachlor)	0.0001	0.0001
Mirex	0.0003	-	-
Toxaphene	0.002 – int	-	-
PCBs	0.00002 (Arochlor 1254)	-	-
PBBs	-	-	-
PBDEs (lower brominated)	0.000003 – int	-	-
PBDEs (deca brominated)	0.0002 – int	-	-
PFHxS	0.00002 – int	-	-
PFNA	0.000003 – int	-	-
PFOA	0.000003 – int	-	-
PFOS	0.000002 – int	-	-
Pb	-	-	-
As	0.0003	-	-
Cd	0.0001	-	-
Hg inorganic	-	-	-
MeHg	0.0003	-	-
Cu	0.01 – int	-	-
Zn	0.3	-	-
Ni	-	-	-
Cr	0.0009 (vi)	-	-
Al	1.0	-	-
Mn		-	-
Ba	0.2	-	-
Be	0.002	-	-
B	0.2 – int	-	-
Co	0.01 – int	-	-
Mo	0.008 – int	-	-
Sb	0.0006 – int	-	-
Sr	2.0 – int	-	-
Sn	0.3 – int	-	-
V	0.01 – int	-	-
Ag	-	-	-
W	-	-	-

- Not established; prov. provisional; [a]intermediate exposure duration (15–364 days); all other values are chronic exposure duration (365 days and longer); [b]Health Canada guidance on PCBs has been revised from specific numerical values to guidance "to be evaluated with dioxins, using appropriate toxic equivalent factors (TEFs)". Health Canada (2010).

Sources: [1]ATSDR (2019); [2]FAO/WHO (2020b); [3]Russian Federation (2018); [4]US EPA (2020); [5]Environment Canada and Health Canada (1993b); [6]IPCS (1997); [7]Environment Canada and Health Canada (1993a); [8]WHO (2006); [9]WHO (2003); [10]Health Canada (2010); [11]Health Canada (2018); [12]JECFA (2011b); [13]EFSA (2011); [14]JFECA (2011a); [15]TERA (2020); [16]JECFA (2007); [17]JECFA (1982); [18]EFSA (2020); [19]EFSA (2014); [20]JECFA (2011c).

Table 5.3 Continued

TDI, PTWI, PTMI, mg/kg bw /day				RfD, mg/kg bw /day
Health Canada	JECFA	EFSA	IPCS	US EPA[4]
-	-	-	-	0.0005 (DDT) 0.0003 (*p,p'*DDE)
-	-	-	-	α – 0.008 (α-HCH) - (β-HCH) 0.0003 (γ-HCH)
0.00005[5]	-	-	0.00017[6]	0.0008
0.0005[7]	-	-	-	0.0008
-	-	-	-	0.0005
-	-	-	0.0001[8]	0.0005 (heptachlor) 0.000013 (heptachlor epoxide)
-	-	-	-	0.0002
-	-	-	-	0.00009
[b]	-	-	0.00002 (Aroclor 1254)[9]	7×10^{-9} – 0.00002 (different congeners and Arochlors)
-	-	-	-	0.000007
-	-	-	-	0.0001 (TetraBDE47) 0.002 (PentaBDE) 0.0001 (PentaBDE99)
-	-	-	-	0.007 (DecaBDE209)
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
-	-	-	-	0.0003
0.025 (PTMI)[11] (diet)	0.025 (PTMI)[12]	0.0025 (TWI)[13]	-	0.001 (diet) 0.0005 (water)
0.0003[10]	0.004 (PTWI)[14]	-	0.002[15]	0.0003
0.00047 (adult)[10]	0.0016 (PTWI)[16]	-	-	0.0001
0.141 (adult)[10]	0.5 (prov.)[17]	-	-	0.04
0.57 (adult)[10]	1.0 (prov.)[17]	-		0.3
-	-	0.013[18]	-	- (metallic Ni) 0.011 (Ni compounds and oxide) 0.02 (Ni soluble salts)
0.001 (total)[10]	-	0.3 (iii)[19]	-	0.003 (vi) 1.5 (iii)
-	2 (PTWI)[20]	-	-	1.0
0.156 (adult)[10]	-	-	-	0.14
0.2[10]	-	-	0.02[15]	0.2
-	-	-	0.002[15]	0.002
0.0175[10]	-	-	-	0.2
-	-	-	-	0.0003
28 (adult)[10]	-	-	-	0.005
-	-	-	-	0.0004
-	-	-	0.13[15]	0.6
-	-	-	-	0.6
-	-	-	-	0.005
-	-	-	-	0.005
-	-	-	-	0.0008

Table 5.4 Oral cancer slope factors and IARC classifications for relevant chemicals.

	Oral cancer slope factor		IARC group
	mg/kg bw /day	Source	
DDTs	0.34 (DDT)	US EPA (2020)	2A
	0.34 (*p,p'*DDE)	US EPA (2020)	-
HCHs	6.3 (α-HCH)	US EPA (2020)	2B
	1.8 (β-HCH)	US EPA (2020)	2B
	1.1 (γ-HCH)	US EPA (2020)	1
HCB	1.6	US EPA (2020)	2B
Chlordanes	0.35	US EPA (2020)	2B
Heptachlor	4.5 (heptachlor)	US EPA (2020)	2B
	9.1 (heptachlor epoxide)	US EPA (2020)	-
Mirex	18	US EPA (2020)	2B
Toxaphene	1.1	US EPA (2020)	2B
PCBs	0.07–13000 (different congeners and Arochlors)	US EPA (2020)	1
PBBs	30	US EPA (2020)	2A
DecaBDE209	0.0007	US EPA (2020)	-
PFOA	-		2B
Pb	0.0085	OEHHA (2015)	2B
As	1.5	US EPA (2020)	1 (As and inorganic compounds)
Cd	0.38	Russian Federation (2004)	1 (Cd and compounds)
Hg	-		3 (Hg and inorganic compounds)
			2B (MeHg compounds)
Ni	-		2B (metallic Ni)
	1.7 (Ni subsulfide)	Russian Federation (2004)	1 (Ni compounds)
Cr	-		3 (metallic Cr)
	0.5 (Crvi)	US EPA (2020)	1 (Crvi compounds)
Be	4.3	Russian Federation (2004)	1 (Be and compounds)
Co	-		2B (Co and compounds)

- Not established

exposure over time or to determine the effectiveness of actions to reduce exposures. However, they cannot be used to describe risk, because they are not health-based.

The most comprehensive sets of RV95s are from Germany and Canada (Table 5.5). Data from the population-representative German Environmental Surveys were used to derive reference values for Hg in blood, as well as urine (not reported here). The reference values derived were 0.8 µg/L and 2.0 µg/L for Hg in child's blood (3–14 years) with fish consumption ≤3 times/month and adults' blood (18–69 years) with fish consumption ≤3 times/month, respectively (Apel et al., 2017). In Canada, RV95s for total Hg in blood are 1.5 µg/L (provisional; 3–5 year-olds), 1.2 µg/L (6–19 year-olds) and 2.3 µg/L (provisional; 20–79 year-olds) based on data from the cross-sectional Canadian Health Measures Survey, 2012–2013 (Saravanabhavan et al., 2017).

5.2.2.2 Biomonitoring equivalents

A biomonitoring equivalent is the concentration of a chemical or metabolite in a biological medium (such as blood or urine) consistent with a reference value (such as TDI). Development of biomonitoring equivalents draws on exposure guidance values and available information on pharmacokinetics in animals or humans. The derivation of biomonitoring equivalents consists of relating the toxicological 'point of departure' (POD) in animals to a critical dose metric (the tissue concentration of the active chemical form causing the toxicity) that is then scaled to humans. HBM-I values, derived by the German HBM Commission, are conceptually identical to biomonitoring equivalent values. An HBM-I represents the concentration in a human tissue or fluid below which no risk of adverse health effects are expected (Apel et al., 2017).

Biomonitoring equivalents are principally intended as screening values to assist in the evaluation of general population or specific population biomonitoring data. Comparing biomonitoring equivalents to human biomonitoring data allows for quick interpretation of human biomonitoring data in a risk-based context; priority setting; and evaluating the need for further refinement or exploration of the associated risks of a chemical. Biomonitoring equivalents cannot be used to assess individual health risks or be interpreted as thresholds for action.

Table 5.5 Selected RV95s from Germany (Apel et al., 2017) and Canada (POPs: Haines et al., 2017; metals: Saravanabhavan et al., 2017).

Parameter	Germany		Canada	
	Age group in years (year of study)	RV95	Age group in years (year of study)	RV95
PCB138 men/women, µg/L[a]	7–14 (2003/2006)	0.3		
	18–19 (2010)	0.13		
	20–29 (2010)	0.20	20–39 (2007–2009)	0.096
	30–39 (2010)	0.45		
	40–49 (2010)	0.70	40–59 (2007–2009)	0.25
	50–59 (2010)	0.85		
	60–69 (2010)	1.10	60–79 (2007–2009)	0.4
PCB153 men/women, µg/L[a]	7–14 (2003/2006)	0.4		
	18–19 (2010)	0.20		
	20–29 (2010)	0.30	20–39 (2007–2009)	0.17
	30–39 (2010)	0.80		
	40–49 (2010)	1.10	40–59 (2007–2009)	0.47
	50–59 (2010)	1.40		
	60–69 (2010)	1.65	60–79 (2007–2009)	0.81
PCB180 men/women, µg/L[a]	7–14 (2003/2006)	0.30		
	18–19 (2010)	0.10		
	20–29 (2010)	0.20	20–39 (2007–2009)	0.098[b]
	30–39 (2010)	0.50		
	40–49 (2010)	0.80	40–59 (2007–2009)	0.35
	50–59 (2010)	1.05		
	60–69 (2010)	1.2	60–79 (2007–2009)	0.81
ΣPCB (138+153+180) men/women, µg/L[a]	7–14 (2003/2006)	1.0		
	18–19 (2010)	0.37		
	20–29 (2010)	0.67	20–39 (2007–2009)	0.37
	30–39 (2010)	1.6		
	40–49 (2010)	2.6	40–59 (2007–2009)	1.1[b]
	50–59 (2010)	3.2		
	60–69 (2010)	3.9	60–79 (2007–2009)	2.0
Total arsenic whole blood, µg/L			6–19 (2007–2009)	1.4
			20–79 (2007–2009)	2.0
Lead whole blood, µg/L	Children, 3–14 (2003–2006)	35	3–5 (2012–2013)	20
	Women, 18–69 (1997–1999)	70	6–19 (2012–2013)	15
	Men, 18–69 (1997–1999)	90	20–79 (2012–2013)	33
Mercury whole blood, µg/L	Children, fish ≤3 times/month, 3–14 (2003–2006)	0.8	Total, seafood <3 times/month, 3–5 (2012–2013)	1.5[b]
	Adults, fish ≤3 times/month, 18–69 (1997–1999)	2.0	Total, seafood <3 times/month, 6–19 (2012–2013)	1.2
			Total, 20–79 (2012–2013)	2.3[b]
PFOS plasma, µg/L	Women (2003–2007)[c]	20	12–19 (2009–2011)	11
	Men (2003–2007)[c]	25	20–39 (2009–2011)	17[b]
	Children, <10 (2003–2007)[c]	10	40–59 (2009–2011)	16
			60–79 (2009–2011)	21[b]
PFOA plasma, µg/L	Women, men, children, <10 (2003–2007)[c]	10	12–19 (2009–2011)	4.0
			20–39 (2009–2011)	5.8
			40–59 (2009–2011)	4.4
			60–79 (2009–2011)	6.4

[a]Whole blood (Germany) and plasma (Canada); [b]provisional reference values as RV95s were derived from estimates with coefficients of variation between 16.6% and 33.3%; [c]not a strictly representative sample.

Table 5.6 Tissue-based guidance values.

Contaminant	Target population	Guidance value		Source
		Type of value	Value	
Total PCBs	Pregnant women, WCBA[a], Breastfeeding women, Young girls, Teenage girls, Children (<3 years)	Guidance value	0.7 µg/g plasma lipids	AFSSA (2010)
	Boys (> 3 years), Adult men, Women over childbearing age	Guidance value	1.8 µg/g plasma lipids	AFSSA(2010)
Pb	Pregnant women, Children	Intervention level	50 µg/L blood	CDC (2010, 2012)
	All	Intervention level	100 µg/L blood[b]	CEOH (1994)
Hg	Children, Pregnant women, WCBA	Provisional guideline	8 µg/L blood = 2 µg/g hair	Legrand et al. (2010), Pirkle et al. (2016)
		Action level	40 µg/L blood =10 µg/g hair	
	Women (≥50 years), Men (>18 years)	Guidance value	20 µg/L blood = 5 µg/g hair	
		Action level	100 µg/L blood = 25 µg/g hair	
	All	Reference dose equivalent	5.8 µg/L blood = 1 µg/g hair	US NRC (2000)

[a]The term 'women of childbearing age' is an approximate age range meant to capture those women who may become pregnant; [b]currently under review by the federal, provincial, and territorial Council of Chief Medical Officers of Health (Health Canada, 2019).

5.2.2.3 Tissue-based guidance values

Blood reference values are employed as toxicological cut-off points for evaluating potential health outcomes. For a select number of chemicals, such as Hg, Pb and PCBs, there are sufficient data to support the development of tissue-based guidance values that relate human biomonitoring data directly to health outcomes (Abass et al., 2016). Tissue-based guidance values in blood are summarized in Table 5.6. The German HBM Commission also derives HBM-II values, which are action levels for interpreting individual biomonitoring data. HBM-II values represent the concentration in a human tissue or fluid above which there is an increased risk for adverse health effects and an urgent need to reduce exposure and provide individual biomedical care (Apel et al., 2017).

Tissue-based guidance values are based on extensive scientific databases. For such chemicals, epidemiological studies have shown direct links between biomonitoring data and health effects, and these results are supported by other types of study, such as toxicological studies. Tissue-based guidance values can be used to compare to measurements from an individual; can be used by researchers and clinicians to evaluate individual, community and population risk and guide public health action when necessary; and can be employed as toxicological cut-off points for evaluating potential health outcomes.

5.2.3 Modeling exposures

Toxicokinetic modeling is a useful complementary tool in quantifying human exposure to environmental pollutants based on their levels in human biological matrices, which represents a sum of multiple exposure routes and thus improves the accuracy of the estimate of the level in human tissue for comparison with risk values (Breivik et al., 2010; Čupr et al., 2011; Abass et al., 2013; Dede et al., 2018). A toxicokinetic modeling approach depends mainly on the burden of contaminant in different body compartments as well as the transfer coefficient between different body compartments. Several factors determine the contaminant's body burden, including dietary exposure (frequency, quantity and contaminant content of fish eaten for instance), human variability in toxicokinetics, and the state of pregnancy, lactation, and overall health.

Several mechanistic models have been published that focus on Arctic Indigenous human population exposure to environmental contaminants. The human food-chain bioaccumulation model ACC-HUMAN was combined with the environmental fate model CoZMoPOP2 (Undeman et al., 2010) or the global fate and transport model GloboPOP (Czub et al., 2008; Binnington et al., 2016a,b) to simulate PCB exposure in Arctic populations. In addition, several studies have developed physiologically-based pharmacokinetic (PBPK) models to assess lifetime internal exposure in Arctic populations. Some of these are described in Section 5.3.3.

5.3 Application of risk assessment principles

5.3.1 Comparison to non-cancer and cancer guidance values

Calculation of the EDIs of different contaminants for different food items provides an opportunity to evaluate the 'structure' of dietary exposure to contaminants for the study population, that is, to assess the input of each food item to the total EDI for each contaminant. This approach was used in the Russian component of the of EU Kolarctic KO467 project 'Food and health security in the Norwegian, Finnish and Russian border region, 2013-2016' in the Pechenga district of Murmansk Oblast and in coastal Chukotka (Dudarev et al., 2015a,b). Figures 5.1 to 5.3 show the percentage contribution of various food items to total metal intake in the Pechenga district of Murmansk Oblast in 2013 and to metals and POPs intake in coastal Chukotka in 2016. Mushrooms and fish were the primary contributors to metal intake in the Pechenga district of Murmansk Oblast. In contrast, in coastal Chukotka, the metals intake was mainly driven by seafood consumption, while the POPs intake was from consumption of marine mammal blubber.

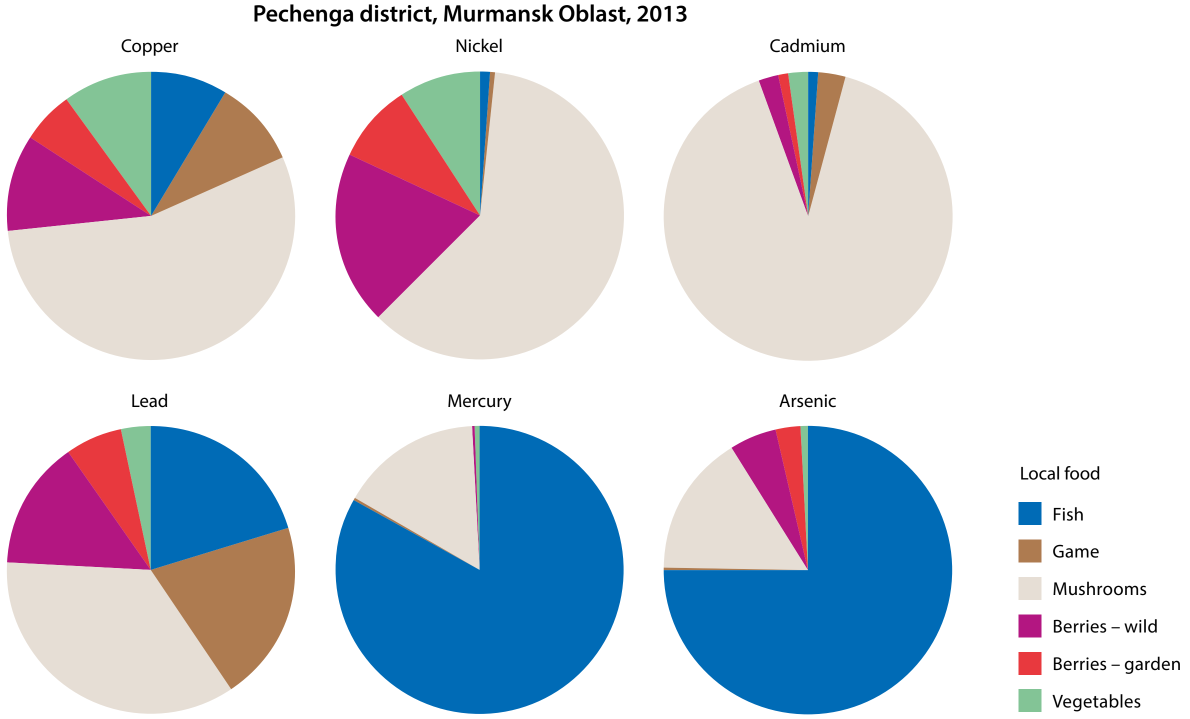

Figure 5.1 Percentage contribution of different local foods to the estimated daily dietary exposure to metals in the population of the Pechenga district of Murmansk Oblast in 2013 (Dudarev et al., 2015b).

Contaminant concentrations in food items were compared to MALs (see Section 5.2.1.1). In the Pechenga district of Murmansk Oblast, exceedances (Dudarev et al., 2015b) of the Russian MALs (see Table 5.2) were identified for Cd in mushrooms (laminar and tubular; 1.5- to 2-fold higher) and for Hg in orange-cap mushrooms (up to 3-fold higher). Exceedances of the old USSR MALs were found for Cu in milk-cap mushrooms (1.5-fold higher), and for Ni in wild berries (up to 4.5-fold higher), garden berries (up to 2.5-fold higher), potatoes (up to 2-fold higher) and mushrooms (2.5- to 30-fold higher).

A similar approach was taken using data from the USA-Russia project 'Food Security and Lactic Bacteria Use in Alaska and the Bering Strait Region', 2015–2018. A comparison of results to Russian MALs for As and Cd concentrations in local foods in coastal Chukotka is presented in Table 5.7 (Dudarev et al., 2019b).

Table 5.7 Exceedances of the highest concentrations of arsenic and cadmium in food samples from coastal Chukotka over the Russian MALs, 2015–2018 (Dudarev et al., 2019b).

Food item	Exceedance, %	
	As	Cd
Walrus blubber	270	-
Fermented walrus blubber	130	-
Bearded seal blubber	230	-
Ringed and spotted seal blubber	140	-
Reindeer meat	140	-
Hare meat	160	140
Seaweed	280	-
Mussels	-	45
Berries	-	230

In addition to describing the contribution of different food items to the EDIs of metals and POPs, researchers also calculated non-cancer and cancer risks caused by metals in local foods and drinking water as part of the EU Kolarctic project 2013–2016 in the Pechenga district of Murmansk Oblast. For calculations of non-cancer risk (Table 5.8), the US EPA RfD for As; the JECFA TDIs for Cd, Pb, Hg and Cu; and the UK TDI for Ni were used. The high THI of 3.11 was associated mainly with Ni in mushrooms, wild berries and drinking water, Cd in mushrooms, Hg in fish and As in fish and mushrooms. For cancer risk (Table 5.9) oral slope factors from the Office of Environmental Health Hazard Assessment (OEHHA) of the California Environmental Protection Agency (for As and Pb), and Russian SFO for Cd and Ni were applied. The TTCR of 1.25×10^{-2} was associated mainly with Ni in mushrooms, wild berries and drinking water, and partly to As in fish and mushrooms.

5.3.2 Comparison to biological-based guidance values

The routes of exposure and health effects of Hg and Pb have been well described (AMAP, 1998, 2003, 2009, 2011, 2015; AMAP/ UN Environment, 2019). This section compares biomonitoring results to blood-based guidance values for Hg and Pb, and hair-based guidance values for Hg.

For the Hg blood guidelines listed in Table 5.6, blood Hg concentrations below 20 µg/L are considered acceptable for the general population, while concentrations above 20 µg/L are considered an 'increasing risk', and concentrations above 100 µg/L indicate an 'at risk' range. The 8 µg/L provisional guideline was designed to be a more protective guideline for pregnant women, due to the developmental sensitivity of the fetus, and 40 µg/L is the proposed action level guideline for this population (Legrand et al., 2010).

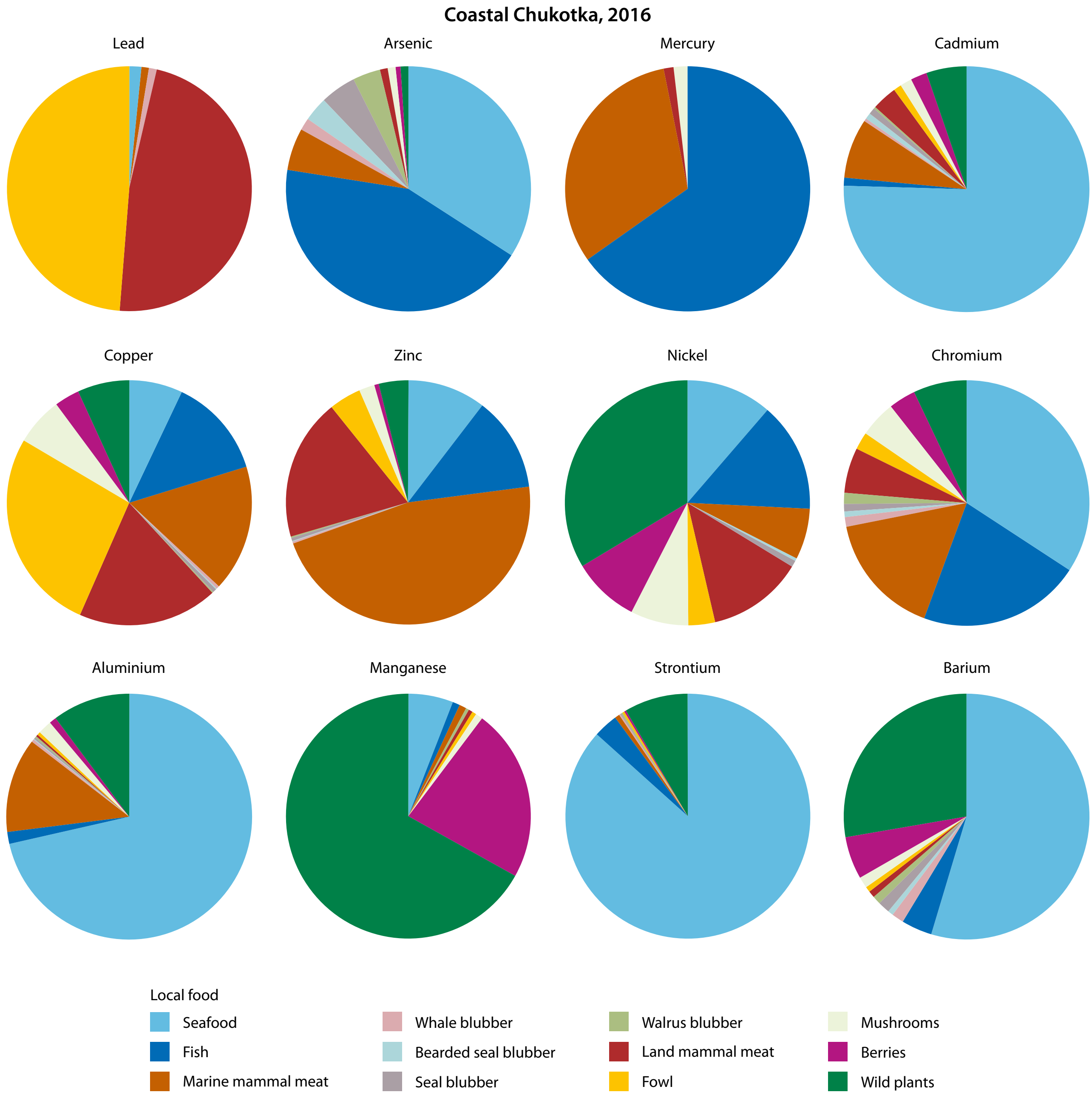

Figure 5.2 Percentage contribution of different local foods to the estimated daily dietary exposure to metals of the Indigenous population of coastal Chukotka in 2016 (Dudarev et al., 2019b).

Table 5.8 Estimated individual lifetime non-cancer risk for selected metals through consumption of local foods in the Pechenga district of Murmansk Oblast in 2013 (Dudarev et al., 2015a).

	Target hazard quotient (THQ)						Total hazard index (THI)
	Cu	Ni	Cd	Pb	Hg	As	
Fish	0.0016	0.0083	0.0028	0.0123	0.3240	1.1682	1.52
Game	0.0018	0.0042	0.0063	0.0125	0.0011	0.0049	0.03
Mushrooms	0.0104	0.3983	0.1996	0.0215	0.0611	0.2494	0.94
Berries, wild	0.0020	0.1296	0.0046	0.0087	0.0010	0.0828	0.23
Berries, garden	0.0011	0.0582	0.0022	0.0039	0.0009	0.0429	0.11
Vegetables	0.0019	0.0586	0.0037	0.0020	0.0010	0.0091	0.08
All local foods	0.02	0.66	0.22	0.06	0.39	1.56	2.9
Drinking water	0.0007	0.15	0.0008	0.0006	-	0.0566	0.21
All foods + drinking water	0.02	0.81	0.22	0.06	0.39	1.62	3.11

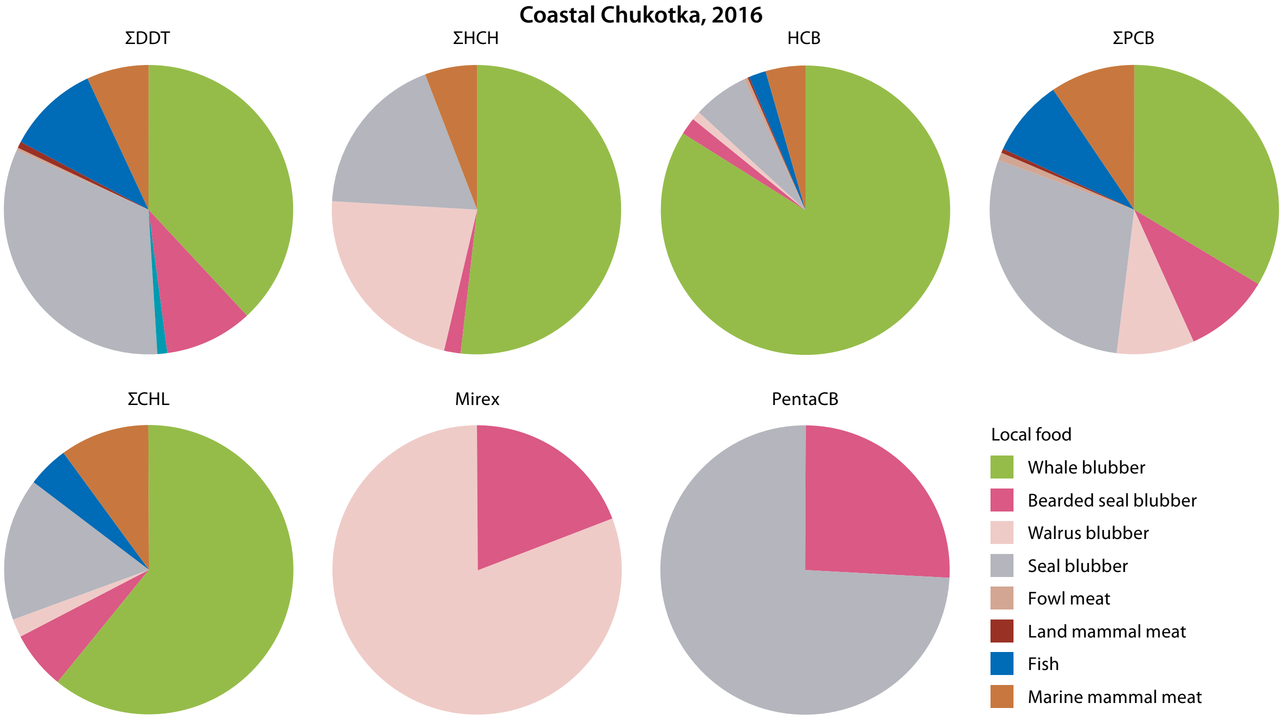

Figure 5.3 Percentage contribution of different local foods to the estimated daily dietary exposure to POPs of the Indigenous population of coastal Chukotka in 2016 (Dudarev et al. 2019a).

Data are available for men, women including women of childbearing age (WCBA), pregnant women, and children from Canada, Greenland, Iceland, Sweden, Faroe Islands, Finland and Russia (Table 5.10). As shown in Table 5.10, very few men and women exceeded Hg guidelines in many regions of the Arctic, the exception being Nunavik and Greenland which are the two regions with the highest mean concentrations of blood Hg (see Chapter 3). In the western Canadian Arctic there were very few exceedances of the guideline, and only in men. In Nunavik (eastern Canadian Arctic), data are presented for both WCBA and pregnant women, with pregnant women treated as a distinct group separate from WCBA. While the percentage of WCBA above 8 µg/L in 2017 was much higher than among pregnant women in 2017 (57.3% and 37.7%, respectively), it should be noted that the sample of WCBA was older (mean age 31 years) than the pregnant women (mean age 24 years). Seasonality is also an important factor as the pregnant women were sampled in winter, while the adult men and women were sampled in autumn, and so Hg exceedances may be higher in adult men and women due to closer proximity to the summer hunting season and peak beluga whale consumption (beluga meat is a major dietary source of Hg). In Greenland, exceedances of blood guidelines have also been broken down by region in Table 5.10, and large regional differences can be seen. Exceedances of the 8 µg/L blood guideline in pregnant women were highest in the northern and eastern Greenlandic communities (34.4% and 68.4%, respectively), while the lowest exceedances were in western and southern Greenlandic communities where consumption of country foods is typically lower. In Faroe Islands Cohort 1, exceedances among children appeared to decline, but once in adulthood, exceedances increased slightly from 1.4% to 5.7% between 2008–2009 and 2013–2016. In Faroe Islands Cohort 5, exceedances among children were highest at age 5 years in 2012–2014 (10.6% above 8 µg/L), but decreased

Table 5.9 Estimated individual lifetime cancer risk for selected metals through consumption of local foods in the Pechenga district of Murmansk Oblast in 2013 (Dudarev et al., 2015a).

	Target cancer risk (TCR)				Total target cancer risk (TTCR)
	Ni	Cd	Pb	As	
Fish	1.2×10^{-4}	8.6×10^{-7}	4×10^{-7}	5.2×10^{-4}	6.5×10^{-4}
Game	1×10^{-5}	1.9×10^{-6}	4.1×10^{-7}	2.2×10^{-6}	1.5×10^{-5}
Mushrooms	5.7×10^{-3}	6.1×10^{-5}	7×10^{-7}	1.1×10^{-4}	5.9×10^{-3}
Berries, wild	2.1×10^{-3}	1.4×10^{-6}	2.8×10^{-7}	3.7×10^{-5}	2.2×10^{-3}
Berries, garden	3.6×10^{-4}	6.6×10^{-7}	1.3×10^{-7}	1.9×10^{-5}	3.8×10^{-4}
Vegetables	3.7×10^{-4}	1.1×10^{-6}	6×10^{-8}	4.1×10^{-6}	3.7×10^{-4}
All local foods	8.7×10^{-3}	6.7×10^{-5}	2×10^{-6}	7×10^{-4}	9.5×10^{-3}
Drinking water	3×10^{-3}	2.5×10^{-7}	2×10^{-8}	2.6×10^{-5}	3×10^{-3}
All foods + drinking water	1.17×10^{-2}	6.73×10^{-5}	2×10^{-6}	7.3×10^{-4}	1.25×10^{-2}

Table 5.10 Exceedance of blood guidelines for total mercury and lead in populations from several Arctic regions. Data presented as a percentage of the study population above given guidance values for each target population group (Abass pers. comm., 2019; Bonefeld-Jørgensen and Long pers. comm., 2020; Drysdale et al. pers. comm., 2020; Dudarev pers. comm., 2020; Laird and Ratelle pers. comm., 2020; Lemire and Blanchette pers. comm., 2020; Ólafsdóttir pers. comm., 2020; Petersen pers. comm., 2019; Wennberg pers. comm., 2019).

Country	Region/cohort	Target population (age)	Year(s)	n	Exceedance, %			
					Hg		Pb	
					≥8 µg/L	≥20 µg/L	>50 µg/L	>100 µg/L
Canada	Old Crow, Yukon	WCBA (20–47)	2019	17	0			0
		Women (54–72)	2019	11		0		9.1
		Men (21–75)	2019	26		0		3.8
	Dehcho and Sahtú, NWT	WCBA (18–49)	2016–2018	68	0			0
		Women (50+)	2016–2018	44		0		4.5
		Men (18–88)	2016–2018	128		0.78		0.78
		Children (8–17)	2016–2018	26	0		0	
	Nunavik	Pregnant women	1996–1997	78	71.8		60.3	
		Pregnant women	1998–1999	43	51.2		48.8	
		Pregnant women	2000–2001	47	61.7		38.3	
		Pregnant women	2004	31	51.6		6.4	
		Pregnant women	2007	42	16.7		4.8	
		Pregnant women	2011–2012	111	36		3.6	
		Pregnant women	2013	95	37.9		1	
		Pregnant women	2017	123	37.7		6.7	
		Youth (16–17)	2017	127	36.0		8.7	0.4
		Men (18+)	2017	407		21.4		3.6
		Women (18+)	2017	790				4.7
		WCBA (18–49)	2017	557	57.3			3.7
		Women (50+)	2017	233		36.5		7.5
Greenland	All regions	Pregnant women	2002–2004	184	28		0.5	
		Pregnant women	2010–2015	497	19.7		0.6	
	North	Pregnant women	2010–2015	32	34.4		0	
	Disko Bay	Pregnant women	2010–2015	120	20.8		0	
	West	Pregnant women	2010–2015	282	15.3		0.7	
	South	Pregnant women	2010–2015	44	13.6		0	
	East	Pregnant women	2010–2015	19	68.4		5.3	
	All regions	Children	2012–2015	333	14.41		-	
	Nuuk	Children	2012–2016	81	1.23		-	
	Disko Bay	Children	2012–2017	128	23.4		-	
	West	Children	2012–2018	100	8		-	
	East	Children	2012–2015	24	37.5		-	
Iceland		Pregnant women	1995	40	0		-	
		Pregnant women	2014–2015	50	0		-	
Faroe Islands	Cohort 1	Pregnant women	1986–1987	1022	88.4		-	
		Children (7)	1993–1994	922	54.5		-	
		Children (14)	2000–2001	792	22.5		-	
		Adults (22)	2008–2009	849		1.4		-
		Adults (28)	2013–2016	703		5.7		-
	Cohort 5	Pregnant women	2007–2009	500	7		-	
		Children (1.5)	2009–2011	363	1.9		-	
		Children (5)	2012–2014	347	10.6		-	
		Children (9)	2016–2018	381	5.1		-	

Table 5.10 Continued

Country	Region/cohort	Target population (age)	Year(s)	n	Exceedance, %			
					Hg		Pb	
					≥8 μg/L	≥20 μg/L	>50 μg/L	>100 μg/L
Sweden		Men (all)	1990–1999	299		0.6		1.7
		WCBA (25–35)	1990–1999	74	1.4			1.4
		Women (50–60)	1990–1999	77	5.2	1.3		0
		WCBA (26–35)	2004	164	0			0
		Women (50–60)	2004	123		0		0
		Men (25–35)	2009	68		0		0
		Men (50–59)	2009	82		0		0
		WCBA (26–35)	2009	91	0			0
		Women (50–59)	2009	86		0		0
		Men (25–35)	2014	84		-		1.2
		Men (50–59)	2014	86		-		0
		WCBA (25–35)	2014	70	-			0
		Women (50–64)	2014	93		-		0
Finland		Men (31)	1997	126		0		1.6
		WCBA (31)	1997	123	3.2		1.6	
Russia	Pechenga	Men (27–54)	2013	18		6		0
		Women (26–65)	2013	32		0		3
		Pregnant women	2013–2014	50	0		2	

- Data not available.

by 2016–2018 in children at age 9 years (5.1% above 8 μg/L). In Icelandic pregnant women and Swedish men and women (from 2004 onwards) there were no exceedances of either the 8 or 20 μg/L guidelines, while a very small proportion of WCBA in Finland exceeded 8 μg/L (3.2%), and a small proportion of men in the Russian Pechenga district exceeded the 20 μg/L guideline (0.78% and 6%, respectively).

Blood Hg exceedances have declined in Nunavik and Greenland, with exceedance of the provisional guideline value (8 μg/L) among pregnant women from Nunavik falling from 71.8% in 1996–1997 to 37.7% in 2017, and for pregnant women from Greenland from 28% in 2002–2004 to 19.7% in 2010–2015.

For Pb blood guidelines, Health Canada has adopted 100 μg/L as an intervention level for the general population (CEOH, 1994), while the US CDC has set a guideline value of 50 μg/L, which is intended to be a more protective intervention level for pregnant women and children (CDC, 2020). As shown in Table 5.10, only a small proportion of Arctic populations exceeded either the 50 or 100 μg/L guidelines, and in regions with multiple time points there appears to be a declining trend of exceedances. In Sweden, exceedances of 100 μg/L have fallen from 1.7% among men (1990–1999) to 1.2% and 0% among younger and older men, respectively (2014). Swedish women had fewer exceedances with only 1.3% of women above 100 μg/L in 1990–1999. In the Canadian Arctic, Pb exceedances among WCBA were low in Nunavik, and there were no exceedances in the Yukon and the Northwest Territories (NWT); there was however, a small percentage of men and women over 50 years of age that exceeded 100 μg/L in all three regions. The most exceedances observed were in the Yukon (9.1%) and Nunavik (7.5%) among women over 50 years of age.

The regions with the highest Pb exceedances among pregnant women were Nunavik and Greenland, although exceedances of the 50 μg/L guideline among pregnant women in Nunavik declined from 60.3% in the late 1990s to 6.7% in 2017, this was probably due more to dietary shifts than declining levels in food items (see Chapter 2 for more details on dietary habits in Arctic populations).

Exceedances of Hg hair guidelines among men and women, pregnant women, WCBA and children are presented in Table 5.11 for the few regions where hair data are available. The Canadian hair guidelines presented in Table 5.6 are equivalent to their corresponding blood guidelines; how these guidelines are used to assess Hg exposure and determine required action are described by Pirkle et al. (2016). While blood Hg levels provide an indication of short-term exposure (<3 months), hair Hg levels indicate longer-term Hg exposure, depending on the length of the hair samples. Hair Hg exceedances in the Canadian territories of Yukon and the NWT were low. In Old Crow, Yukon there were no exceedances of hair guidelines among men or women. Exceedances of the Canadian guidelines of 2 and 5 μg/g in the Dehcho and Sahtú regions of the NWT, were 1.3% in WCBA and 2.2% and 1.1% in men and women (over 46 years of age), respectively. No hair Hg exceedances of the action levels were observed for any group.

Table 5.11 Exceedance of hair mercury guidelines in populations from Canadian Arctic regions. Data presented as a percentage of the study population above given guidance values for each targeted population group (Drysdale et al. pers. comm., 2020; Laird and Ratelle pers. comm., 2020).

Region	Target population	Year(s)	n	Hg exceedances, %	
				>2 µg/g	>5 µg/g
Old Crow, Yukon	Men (18+)	2019	31		0
	WCBA (18–49)	2019	23	0	
	Women (50+)	2019	17		0
Dehcho and Sahtú, NWT	Men (18–88)	2016–2018	184		2.2
	WCBA (18–45)	2016–2018	78	1.3	
	Women (46–81)	2016–2018	93		1.1

5.3.3 Toxicokinetic modeling for describing human exposure

Indigenous Arctic populations were identified as a population in need of improved contaminant exposure estimation tools (AMAP, 2015; Wania et al., 2017). Published mechanistic models have been grouped into four disciplines, as stated by Wania (2017), to achieve the following:

> "Identify the properties of contaminants capable of accumulating in Arctic human food chains and to identify chemicals used in commerce that may have such properties.
>
> Enhance the understanding of human biomonitoring studies conducted in the Canadian Arctic by aiming to reconcile measured concentrations of POPs with recall estimates of dietary intake.
>
> Understand the impact of dietary change on human contaminant exposures, including dietary transitions that may be either permanent or temporary.
>
> Characterize infant exposure to POPs during epidemiological studies and identify age periods of increased susceptibility to adverse effects."

Several mechanistic models have been published that focus on the exposure of Arctic Indigenous human populations to environmental contaminants. The human food-chain bioaccumulation model ACC-HUMAN was combined with either the environmental fate model CoZMoPOP2 (Undeman et al., 2010) or the global fate and transport model GloboPOP (Czub et al., 2008; Binnington et al., 2016a,b) to simulate PCB exposure in Arctic populations.

The ACC-HUMAN model is employed to simulate organic contaminant transfer from the physical environment to humans and bioaccumulation in humans. Application of the model to predict dietary exposure of Arctic Indigenous People necessitated a restructuring of the underlying food chain. Czub et al. (2008) modified ACC-HUMAN by introducing a mammal sub-model into the marine food chain. The model was parameterized for ringed seal (*Phoca hispida*), one of the dominant seal species in the traditional diet of Greenlandic Inuit (Czub et al., 2008). In addition, several other reparameterizations were defined to reflect the body properties and dietary habits of Inuit. Inuit children were assumed to have similar lipid masses as European children up to the age of 9 years. The increase in lipid mass was thereafter less than for Europeans. The lipid mass of adult Inuit men was estimated to be equal to 66% of the lipid mass of European men. For Inuit women, the lipid mass was set to 80% of that of Inuit men. Inuit women were assumed to give birth to three children: the first child at 20 years of age, the second and third at 25 and 30 years, respectively. The lactation period was assumed to last six months for each child (Czub et al., 2008).

The same fate and transport model and food chain bioaccumulation model was used to calculate PCB exposures and daily dietary intake of nutrients and Hg (Binnington et al., 2016a). Consumption of certain tissues in caribou (heart, liver, tongue, meat, bone marrow), ringed seal (liver, meat, blubber), beluga whale/narwhal (meat, blubber) and Canada goose (meat, eggs) for Hg intake was differentiated. However, for POPs a distinction was made between meat and blubber intake only. This lack of differentiation was justified as POPs are retained predominantly in adipose tissue, typically resulting in minimal lipid-normalized concentration differences among the organs and meat of the same traditional food species (Binnington et al., 2016a).

Several studies have developed PBPK models to assess lifetime internal exposure in Arctic populations. These PBPK models have been applied to Arctic Indigenous women for different POPs, based on the physiology and reproductive history of the subjects (Verner et al., 2008), or on blood concentrations (Abass et al., 2013). A PBPK model was employed to assess exposure in children, based on physiological parameters, breastfeeding duration, and levels of POPs measured in maternal blood at delivery, cord blood, or breastmilk (Verner et al., 2013) or based on maternal blood levels at the time of delivery.

5.3.3.1 PCBs

Undeman et al. (2018) introduced a modeling approach to identify populations highly exposed to PCB153 based on a dynamic simulation of both global environmental fate (using the model BETR-Global) and human food chain bioaccumulation (using the model ACC-HUMAN). This approach can be used to explore the combined effect of source proximity, global transport, human food web structure and dietary habits on human exposure to POPs. Undeman et al. (2018) predicted that the inclusion of a warm-blooded carnivore in the diet is

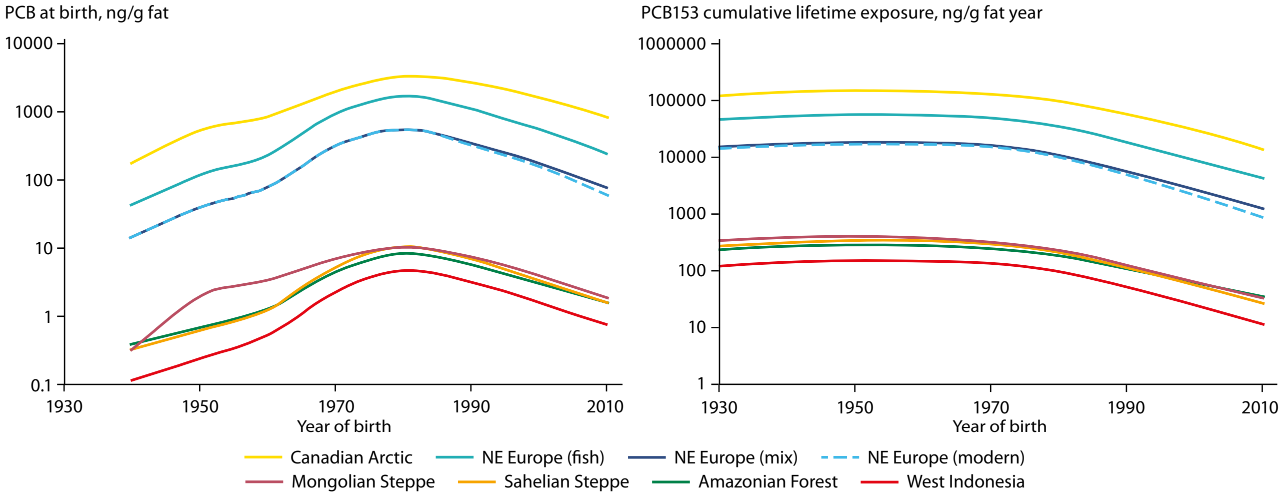

Figure 5.4 Concentration of PCB153 at birth (left) and cumulative life-time exposure to PCB153 (right) for different female birth cohorts from eight global human subpopulations calculated with the BETR Global and ACC-HUMAN models (Underman et al., 2018). NE Europe (fish) refers to a diet dominated by fish; NE Europe (mix) refers to a mixed diet with locally sourced fish; NE Europe (modern) refers to a mixed diet with internationally sourced fish.

the factor most responsible for elevated PCB exposure in a human subpopulation. Populations eating seals, such as the Inuit (Canadian Arctic) or subsistence fishermen on Lake Baikal (Mongolian Steppe), are thus among the most PCB-exposed populations worldwide, see Table 5.12 and Figure 5.4.

5.3.3.2 Mercury

Abass et al. (2018b) has developed a modeling system consisting of three linear toxicokinetic models for describing the fate of methylmercury (MeHg), inorganic Hg, and metallic Hg in the body, in order to estimate daily intake of Hg as measured through total Hg concentrations in the blood.

The population data were based on the 2003–2004 Norwegian Fish and Game Study (Jenssen et al., 2012). One of the aims of the original study was to measure total Hg in blood and urine and estimate the dietary exposure of Norwegians with a diversity of seafood and game consumption (Knutsen et al., 2008; Kvalem et al., 2009). Participants provided blood samples, and dietary information for the preceding 12 months was obtained using a detailed semi-quantitative food frequency questionnaire (FFQ). The FFQ had been designed and validated for the Norwegian Mother and Child Cohort Study and contained 340 questions covering 255 different food items (Brantsæter et al., 2008; Meltzer et al., 2008).

Table 5.12 Comparison of emissions and concentrations of PCB153 as predicted by the BETR-Global model for selected regions (Underman et al., 2018).

Region	Grid cell number in the BETR-Global model	Hosting	Cumulative emissions to grid cell for 1930–2090, kg		Concentration in the lowest air compartment of the grid cell averaged over 1930–2090, pg/m³		Concentration in the seawater compartment of the grid cell averaged over 1930–2090, pg/L	
			Absolute emissions, kg	Relative to NE-Europe (factor difference)	Absolute concentrations, pg/m³	Relative to NE-Europe (factor difference within parentheses)	Absolute concentrations, pg/L	Relative to NE-Europe (factor difference within parentheses)
NE Europe	62	Swede, Baltic fishermen	142,763	1	7.71	1	5.39	1
Central Asia	68	Mongolian herder	4421	0.031 (32)	0.48	0.06	-	-
Sahel	109	Sahel herder	2948	0.021 (48)	2.93	0.38	-	-
Brazilian Amazon	153	Amazon fisherman	8337	0.058 (17)	0.79	0.10	0.07[a]	0.013
Eastern Indian Ocean	163	Indonesian fisherman	3414	0.024 (42)	0.35	0.05	0.04	0.007
Canadian Arctic Archipelago	31	Canadian Inuit	64	0.0005 (2221)	0.13	0.02	0.27	0.049
International fishing grounds	14, 15, 37, 39, 151, 176, 62[b]	Modern Swede	-	-	-	-	4.72[c]	0.875

- Not applicable. [a]Freshwater was used instead of seawater to indicate contamination of the aquatic food chain; [b]average of multiple cells, weighted based on the contribution to internationally sourced fish sold in Sweden; [c]average for international fishing grounds relative to the average for NE Europe between 1980 and 2010 is 0.7 and this ratio is 0.1 in 2010 when locally-sourced fish in the modern diet was phased out.

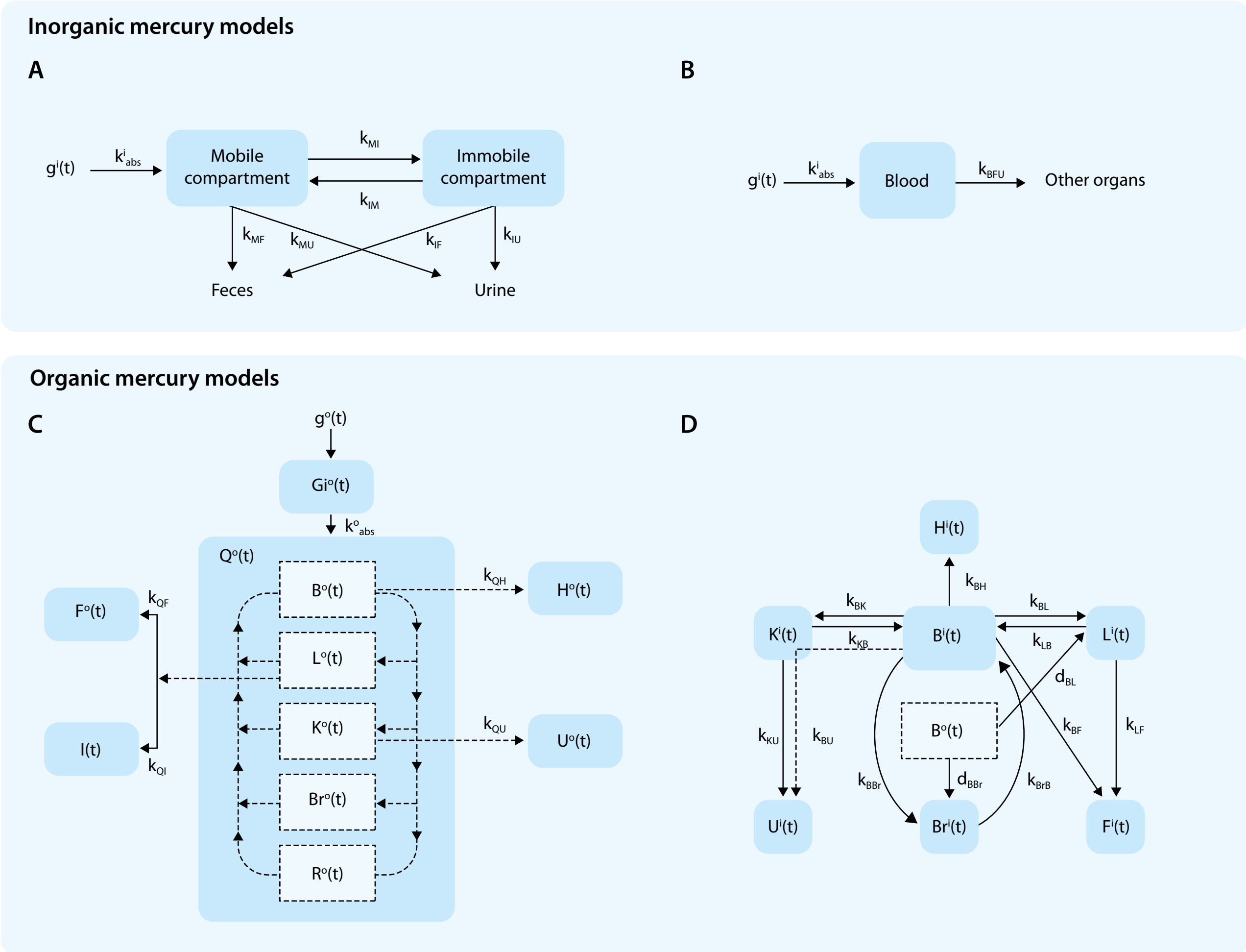

Figure 5.5 The modeling system used to estimate daily intake of Hg as measured through total Hg concentrations in the blood (Abass et al., 2018). The two-compartment model of Farris et al. (2008) (model A) was employed to simulate the fate of inorganic Hg in the body, while the one-compartment model of inorganic Hg in blood (model B) was utilized to link the models together. The fate of metabolized organic Hg (along with the change into inorganic Hg in the body) is simulated by the multi-compartment model of Carrier et al. (2001a,b) for biologically-based toxicokinetics. This model is divided into blocks of organic and inorganic Hg (models C and D) that are linked through the concentration of organic Hg in the blood (see compartment $B^o(t)$ in both blocks).

During the course of the study a linear toxicokinetic model based on the total Hg level in blood for describing the fate of MeHg, inorganic Hg, and metallic Hg in the body was used to estimate daily intake of Hg from food based on data provided by the Norwegian Fish and Game Study (part C) (Jenssen et al., 2012). While the published literature includes several multi-compartmental models for Hg (Farris et al., 1993; Smith et al., 1994), the models of Carrier et al. (2001a,b) and Farris et al. (2008) stand out as being well-documented and for having been utilized in different studies (Noisel et al., 2011). Thus, they were both applied in constructing a new combined model. The linear toxicokinetic model by Carrier et al. (2001a,b) was used for modeling the fate of MeHg in the body, and the model of Farris et al. (2008) for modeling the fate of inorganic Hg in the body. The models are connected through a blood circulation model and organic blood compartment. Because the models are linear and do not overlap, the concurrent use of all three was justified. The block diagrams of the toxicokinetic modeling system are presented in Figure 5.5.

The results indicate that toxicokinetic modeling based on blood levels gave higher daily intake values of Hg compared to those of the FFQ. The bias was minimal in terms of the estimates between the median daily intake of Hg, being 0.043 µg Hg/kg bw/day as estimated by the FFQ and 0.050 µg Hg/kg bw/day as estimated by the toxicokinetic model. That said, the values for the intake of MeHg by the FFQ and the toxicokinetic modeling had a correlation of only 0.38. There was also an intra-class correlation coefficient of 0.298 between the FFQ and the toxicokinetic model.

Limitations and strengths of the present model should be noted. The main strengths are utilizing a modeling system comprising a validated two-compartmental model to simulate the fate of inorganic Hg, a validated multi-compartmental model to simulate the fate of organic Hg, and an independent blood compartment for linking the main models together. In addition, data employed in the modeling system were based on detailed information about dietary sources and demographic factors in addition to accurate Hg measurements in blood (Jenssen et al., 2012). In modeling, there are certain limitations that may lead to under- or overestimation of the actual exposure, such as the estimated shares for MeHg and inorganic Hg, the concentration of Hg in foods other than fish, the lack of precise Hg intake information for the study participants, significant variations in the dietary exposure estimates between individuals and data on inorganic Hg, and dental amalgam fillings in the Norwegian Fish and Game Study. The proportions of different forms of Hg in blood need to be addressed in order to construct a complete model. However, it should be emphasized that the levels of total Hg measured from blood provide a firm basis for the future development of toxicokinetic modeling, enabling better estimates of health impacts associated with exposures.

5.3.4 Risk assessment to inform risk management

The risk management actions that follow a risk assessment depend on the jurisdiction, the purpose of the risk assessment and the risk identified. In this section two case studies highlight the use of local information to drive specific guidance for a region. They also highlight differences in terminology in different jurisdictions. Recommended food daily intake limits (RFDILs) are derived in the Russian case study, whereas a similarly derived recommended maximum intake (RMI) is used in the Canadian case study.

5.3.4.1 Coastal Chukotka, Russia

A risk management approach to locally harvested foods was applied in coastal Chukotka (Dudarev et al., 2019c). RFDILs were set for locally harvested foods, which represents one of several possible approaches. The guidelines were developed based on the results of the analysis of POPs and metals found in samples of locally harvested food collected in 2016. The aim of the study was to expand the toolset for dealing with the challenges of: (1) setting dietary recommendations when assessing multiple contaminants in a variety of foods (RFDIL calculations are an example of one possible approach) and (2) managing the real-life circumstances when many types of food are mixed in many dishes regularly and the concentrations of contaminants in these mixed dishes become uncertain.

To calculate the RFDILs, Dudarev et al. (2019c) used established Russian and international ADIs and TDIs (see Table 5.3), and the highest concentrations of POPs and metals in the analyzed food samples (each specific contaminant in each specific food item) using the following formula:

$$RFDIL = (TDI \times BW) / C$$

Where: RFDIL is the recommended food daily intake limit (kg ww of food/person/day); TDI is the tolerable daily intake of contaminant (mg/kg bw/day); BW is body weight (kg); and C is the concentration of contaminant (mg/kg ww of food).

All calculations were made for an adult human weighing 60 kg regardless of gender and age and the RFDILs for selected food items for the population of Providensky district of Chukotka are presented in Table 5.13.

As presented in Section 5.3.1, both non-cancer and cancer risks associated with the totality of metals in the totality of foods and drinking water were high in the Pechenga district of Murmansk Oblast. It was concluded that recommendations are required for reducing consumption of certain local food products in the local population. Clean alternatives to the local Ni-contaminated drinking water sources should also be identified. If this is not possible, bottled water should be imported for the local population (Doushkina et al., 2015).

5.3.4.2 Canadian case study

Caribou are important sources of food in the North. The Canadian Arctic Caribou Contaminant Monitoring Program monitors levels of various environmental contaminants in caribou herds to determine whether contaminant levels in the caribou populations are changing over time and whether caribou remain a safe and healthy food choice for Northerners.

Results show that caribou meat (muscle) does not accumulate high levels of trace elements. Most trace elements measured in caribou organs are also not of concern for human health although kidney does appear to accumulate higher levels of Hg and Cd compared to other caribou tissues (Gamberg et al., 2005). Based on these observations, upon request, Health Canada's Food Directorate can provide a health risk opinion on concentrations of trace elements in caribou kidney to the responsible Regional Health Authority.

Health-based guidance values can be used to calculate RMIs. These represent an amount of food or tissue that can be safely consumed over a period of time and can be used by the responsible health authority to determine if risk management is needed, such as consumption advice for the traditional food in question. The RMI, for a given scenario, is calculated using the following equation:

$$RMI = (HBGV \times BW)/C$$

Where: RMI is the recommended maximum intake (grams of tissue per day, week or month); HBGV is the health-based guidance value (nano- or micrograms per kilogram body weight per day, week or month); BW is body weight (kg); and C is contaminant concentration (nano- or micrograms per gram tissue).

Several key factors inform the calculation of RMIs for environmental contaminants in traditional foods. The average body weights used in the assessment should be representative of actual consumers in the population of the food in question. The concentration of the environmental contaminant present in the traditional food (e.g., caribou) should reflect levels typically present in those foods and tissues (e.g., kidney) that are being consumed in the population. If there are other known and quantifiable sources of exposure to the contaminant in question from other food sources, this can also be taken into consideration. RMI calculations can help identify the greatest source of the contaminant in the diet and inform risk management considerations by the responsible authority. When assessing multiple contaminants in the same traditional food, the contaminant that results in the most restrictive consumption advice, that is, the lowest RMI value, is selected as the basis of the recommendation.

This case study focuses on data from two barren-ground caribou herds: one from the eastern (Porcupine) and one from the western (Qamanirjuaq) Canadian Arctic, which are designated for annual sampling as a key species for monitoring contaminants in the terrestrial Arctic ecosystem (NCP, 2019). In caribou kidney, Cd concentrations result in the most restrictive RMIs and, as a result, Cd in caribou kidney is the focus of the health risk opinion. More detailed discussion on how the Food Directorate calculates RMIs and how these should be interpreted is provided below.

Table 5.13 Calculated recommended food daily intake limits (RFDILs) for selected food items for the population of the Providensky district in Chukotka (Dudarev et al., 2019c).

Contaminant	Fish			Marine mammal	
	Freshwater	Migratory	Marine	Meat	Blubber
ΣHCH	NL	NL	NL	NL	NL
ΣCHL	NL	NL	NL	NL	420g whale *mantak*[a]
ΣDDT	NL	NL	NL	NL	NL
HCB	NL	NL	NL	NL	180g whale blubber and *mantak*
ΣPCB	NL	NL	NL	NL	400g ringed and spotted seals 430g whale *mantak*
Pb	NL	NL	NL	NL	NL
As	NL	NL	60g	300g walrus and bearded seal	50g walrus and bearded seal, 70g ringed and spotted seals and walrus *kopalkhen*[b], 300g whale, 180g whale *mantak*
Cd	NL	NL	NL	NL	NL
Hg	360g	360g	180g flounder	450g whale and walrus, 230g bearded, ringed and spotted seals	NL
Cu	NL	NL	NL	NL	NL
Zn	NL	NL	NL	450g walrus	NL
Ni	NL	NL	NL	NL	NL
Cr	NL	NL	NL	400g	NL
Al	NL	NL	NL	430g whale and bearded seal	NL
Mn	NL	NL	NL	NL	NL
Ba	NL	NL	NL	NL	NL
POPs + metals	360g	360g	60g	230g bearded, ringed and spotted seals, 300g walrus, 400g whale	50g walrus and bearded seal, 70g ringed and spotted seals and walrus *kopalkhen*, 180g whale, 180g whale *mantak*

- No data; NL no limit to consumption. [a]*mantak* is the original Siberian Yupik (Chukotkan Eskimo) term for the layer of whale skin with a thin layer of adjacent blubber; *mantak* has the same meaning as *muktak* or *muktuk* in Alaska, Canada or Greenland: [b]*kopalkhen* is a traditional food (meat roll) made from fermented walrus meat.

Human-based guidance values

Human-based guidance values are chemical-specific and derived from either experimental animal studies or human epidemiological data. Nephrotoxicity (kidney toxicity), characterized by renal dysfunction and damage is considered the critical health effect associated with long-term dietary exposure to Cd in humans. The provisional tolerable monthly intake for Cd derived by the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011b) is 25 μg/kg bw/month. This value is based on epidemiological data from populations living in areas with high environmental levels of Cd. These studies use urinary Cd concentrations as a biomarker of exposure and specific urinary proteins as biomarkers of toxic effects on kidneys in humans. Given that Cd accumulates over time in the kidney, urinary concentrations are considered the best biomarker of an individual's chronic exposure to Cd (Health Canada, 2018).

Body weights. Average body weights for consumers of the traditional foods in question are typically not readily available to inform the Food Directorate's health risk opinions. Therefore, RMIs are calculated using an assumed average body weight of 70 kg for adults (default mean body weight for adults ≥20 years of age from the Canadian Community Health Survey – Cycle 2.2 on Nutrition; Statistics Canada, 2004). The RMI estimates would be lower for younger age groups based on differences in the assumed average body weights.

Contaminant concentration. The concentration used for the RMI calculation should reflect the levels typically present in the traditional food or food tissue that is consumed by the local population. Average kidney Cd concentrations for each caribou herd are calculated. If more than one year of sampling data is available, the averages are compared across sampling years for that specific herd. To increase the total sample number (i.e., the representativeness of the data), a total average of the data for each herd is used to calculate the RMI if averages are considered comparable across sampling years. If averages are not comparable across sampling years or an increasing or decreasing trend is observed, the average from the most recent sampling year, which would be considered the most relevant for current consumption, is used to calculate the RMI. Table 5.14 provides a summary of the average and range of Cd concentrations calculated in the kidney samples for the two caribou herds.

In the absence of information on other dietary sources of Cd, the RMI calculation for caribou kidney assumes that

Table 5.13 Continued

Reindeer, hare, goose meat	Mushrooms	Berries	Wild plants	Seaweed	Ascidians	Mussels
NL	-	-	-	-	-	-
NL	-	-	-	-	-	-
NL	-	-	-	-	-	-
NL	-	-	-	-	-	-
NL	-	-	-	-	-	-
NL	NL	NL	NL	NL	NL	NL
NL	NL	NL	NL	20g	220g	90g
NL	NL	NL	NL	300g	300g	20g
NL	NL	NL	NL	NL	NL	NL
NL	NL	NL	NL	NL	NL	NL
NL	NL	NL	NL	NL	NL	NL
NL	NL	NL	NL	NL	NL	NL
NL	NL	NL	NL	200g	60g	150g
NL	NL	NL	170g (120g *Rhodiola* leaves)	350g	20g	60g
NL	NL	300g	200g (50g *Rhodiola* leaves)	NL	NL	NL
NL	NL	NL	NL	NL	NL	NL
NL	NL	300g	170g (50g *Rhodiola* leaves)	20g	20g	20g

consumption of this tissue represents the only source of Cd intake from the diet. In providing a health risk opinion to the responsible authority, the Food Directorate will point out that this scenario is unlikely and that the authority should consider this uncertainty when determining if consumption advice is warranted.

In making this determination, the responsible authority may wish to consider the following: For example, if the estimated RMI is greater than the quantity of the traditional food the local populations are actually consuming then consumption advice may not be needed. For the responsible authority, accurate information and knowledge of typical consumption patterns of traditional foods is key when considering potential risk management measures, such as consumption advice or advisories. It is recommended that the authority identifies the traditional foods consumed, quantifies the amount of each food consumed per eating occasion or serving, and determines the frequency of consumption (i.e., is the food in question a staple in the diet of the local population or only consumed on an occasional or seasonal basis). The seasonality of the consumption is important in the context of caribou kidney. For example, if caribou are normally hunted in autumn, this could be the period during which kidney is likely to be consumed. The RMIs should also be expressed in a way that makes sense to the local populations consuming the food in question. For example, the RMI can be expressed on a 'meals' per week or monthly basis, or in the context of caribou kidney on a yearly basis; it is then important to communicate what is considered to be the typical size of a 'meal' (e.g., where X g represents a meal per week, month or year). In the case of caribou kidney it can be useful to know the average weight of a kidney for the herd because depending on the consumption patterns of the local population a recommendation of the maximum number of kidneys per year may be the most relatable context. Based on available data, consumption advice or advisories have not been issued for caribou kidney by Regional Health Authorities.

5.4 Challenges for risk assessment in an Arctic context

5.4.1 Estimating dietary exposure

Several national biomonitoring programs (Kim and Lee, 2012; Statistics Canada, 2019; UBA, 2019; CDC, 2020) include a food frequency questionnaire, among other dietary assessment

Table 5.14 Summary of caribou kidney data for cadmium for two barren-ground caribou herds, one from the eastern (Porcupine) and one from the western (Qamanirjuaq) Canadian Arctic (Gamberg pers. comm., 2017).

Herd	Sampling years	Total average Cd concentration (range), µg Cd/g wet wt	Recommended maximum adult intake, g kidney/month
Porcupine	1990–2013, 2015	8.15 (5.02–12.82)	215
Qamanirjuaq	1992, 2006–2015	5.61 (3.49–7.59)	312

methods, to estimate dietary exposure to chemicals. Estimated dietary exposure using FFQs has some limitations. Dietary exposure is estimated by combining data on consumption and average contaminant concentration in specific food items, while the contaminant content in food items may vary a lot between geographical areas and types of fish, for instance. FFQs are relatively imprecise instruments for estimating contaminant intake (Meltzer et al., 2008), and participants' ability to recall and average their habitual diet correctly can be limited. Very detailed questions (e.g., species-by-species) may lead to over-reporting of particular food items, whereas grouping of food items can lead to under-reporting (Lincoln et al., 2011). On the other hand, toxicokinetic modeling can overcome the limitations of dietary information from FFQs, such as recall error. For example, toxicokinetic modeling depends mainly on the burden of contaminant in different body compartments, as well as the transfer coefficient between different body compartments. One contaminant for which modeling has been extensively applied is MeHg. Several factors determine the contaminant body burden of MeHg. These include dietary exposure (frequency, quantity and MeHg content of fish eaten), the individual's 'absorption, distribution, metabolism and excretion (ADME)' kinetics, and the state of pregnancy, lactation, and overall health. Many studies reported not only wide inter-individual variability in MeHg elimination rates, but also MeHg half-life variation within an individual over time, indicating significant variations in the biological process of MeHg elimination (Rand et al., 2016; Caito et al., 2018). This variation can result in MeHg levels exceeding the US EPA reference dose and can influence the derivation of a meaningful reference dose for MeHg applicable to all individuals in a population (Rand and Caito, 2019).

5.4.2 Characterizing exposure

The profile of exposure to contaminants in many Arctic populations differs from those of reference populations used to derive many guidance values. Even across the Arctic, differences in diet (including differences in type of species consumed) can have a dramatic effect on contaminant intake, resulting in regional differences across countries. Exposures in other areas, as a result of similar dietary patterns, may be homogenous across populations. See Chapters 2 and 3 for more details on dietary habits and contaminant levels in Arctic populations. As a result, when conducting a risk assessment, the inputs and assumptions required to characterize exposure must be carefully considered, to avoid mischaracterizing risk for a given population. Conducting cumulative risk assessments that address the mixture to which Arctic populations are exposed could better characterize risks to these populations. Methods to conduct cumulative risk assessments have been described (e.g., WHO, 2009) and could be applied in this context.

Exposures may be transient or seasonal. Exposure to contaminants may mirror consumption of country foods that are readily available at specific times of the year. Risk assessment methods that address intermittent exposures could more accurately characterize risks from contaminants. For example, peak exposures may relate to hunting seasons. It is also necessary to consider exposures dependent on storage (e.g., community freezer programs) or sharing (e.g., sharing of items between regions). This is particularly important for populations, such as pregnant women, when timing of exposure changes the associated risk of exposure.

Cultural practices may affect exposure patterns, and different consumption patterns may result in different exposure profiles. For example, Little et al. (2019) documented gender differences in beluga consumption. Traditionally, it is women rather than men that consume the tail of a beluga. Differences in contaminant or nutrient levels based on which part of an animal is consumed could influence inputs to risk assessments.

Among Indigenous groups in several Arctic regions, consumption of traditional foods represents the primary route of exposure to POPs and Hg, while also representing a significant proportion of nutrient intake (see Chapter 2). Science-based risk assessments that balance risk from contaminants with benefits from nutrients are difficult to perform. In addition, risk-benefit analyses require information from other knowledge holders to address sociological, spiritual and community considerations.

5.4.3 Characterizing effects

Several epidemiological studies have been established in the circumpolar area to examine the relationship between exposure to contaminants and health outcomes (see Chapter 4). Figure 5.6 shows findings from Arctic cohort studies which reported a link between exposure and human health outcomes (see Abass et al., 2018a for details and references).

Few guidance values have been based on effects observed in Arctic research studies. However, there are very strong databases for Hg in the Arctic and these have been used in Hg risk assessments worldwide (e.g., JECFA, 2007; Legrand et al., 2010; AMAP / UN Environment 2019). Using Arctic-specific data aids in the development of risk communication in Arctic countries (see Chapter 6).

5.4.4 Choosing the correct biomarker

Much has been written about the relevance of different matrices (e.g., blood, urine, hair, nails, teeth, umbilical cord blood, meconium) to actual exposures (Ha et al., 2017). A chosen biomarker must be relevant to the exposure of interest, otherwise it cannot be used in a risk assessment without introducing uncertainty into the outcome of the assessment.

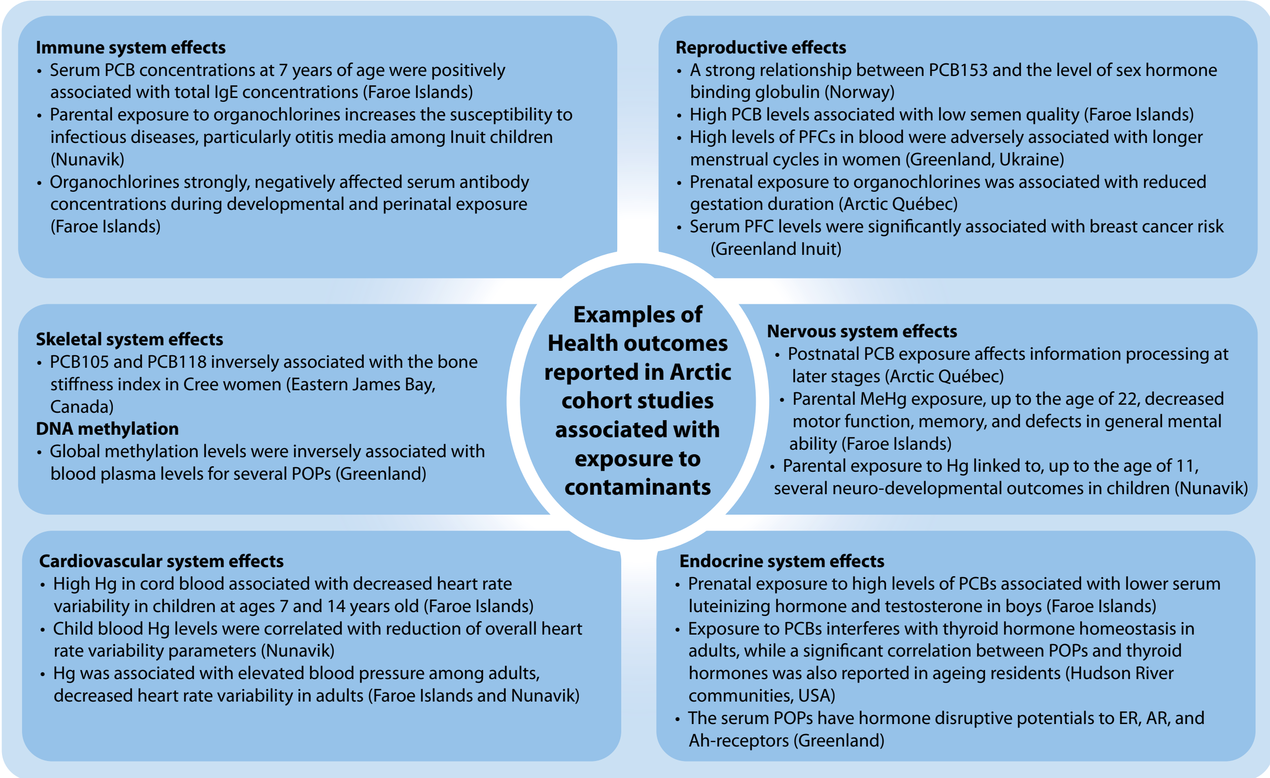

Figure 5.6 Examples of health outcomes reported in published Arctic cohort studies associated with exposure to contaminants. See Chapter 4 for more detailed information and references.

There are a few key characteristics to consider when identifying the right biomarker, including ubiquity, natural presence, metabolism, and specificity. If a substance is environmentally pervasive it may create an overestimation of exposure (Kolossa-Gehring et al., 2017). Exposure discrepancies may happen when a chemical is being formed naturally in a body and is excreted in either very high and/or very low concentrations, or if a substance breaks down into many metabolites which may decrease the overall specificity during detection (Kolossa-Gehring et al., 2017). Pharmacokinetic characteristics of a chemical and its tendency to accumulate in certain tissues should be considered, as some chemicals may accumulate in fat issues (e.g., most POPs) or in the meat and organs of mammals (e.g., Hg, PFASs). A biomarker that lacks specificity (e.g., is a metabolite of several compounds) will be of limited use in describing exposures. These considerations and others are important when choosing a biomarker for any study. In an Arctic context they must be considered in conjunction with other issues.

Identifying the best biomarker may not identify the most feasible biomarker. Other factors must be considered, such as sample viability, temperature, level of expertise required to collect samples and required equipment. These may be critical considerations if the sampling location is remote, temperatures are extreme, the study team is small, and/or samples need to be shipped to a laboratory within a strict time period. Sampling must also be culturally sensitive. Acceptance for giving different matrices (e.g., breastmilk, hair, blood, nails) may differ between and within communities. Furthermore, standardization of methods across studies makes comparison of data possible and may need to be considered. Hence, the most valid biomarker may not be the most appropriate biomarker.

It is critical that contaminants are measured in matrices that are relevant to the exposure of interest. For example, measuring total Hg levels in body tissues such as blood, urine and hair can help in estimating Hg exposure (Berglund et al., 2005; Björkman et al., 2007; Needham et al., 2011; Sheehan et al., 2014) because these provide an indication of the internal dose, although it is necessary to take great care in choosing the correct biomarker to accurately anticipate internal exposure (Berglund et al., 2005). According to the literature, currently the best proxy for long-term MeHg exposure in individuals is the concentration of Hg in hair (Sheehan et al., 2014). Using hair to assess Hg exposure has many advantages compared to other matrices. Collection is less invasive, more cost-effective, does not require any major equipment, and hair samples are easy to transport and store (Liberda et al., 2014). In general, the ratio of Hg in hair to Hg in blood is 250 (WHO, 1990). However, there are concerns over the inter-individual variability in this ratio, and it has been recommended that whole blood Hg is also used, especially when providing individual advice (Liberda et al., 2014; Ha et al., 2017). Other matrices are considered excellent biomarkers for inorganic Hg, such as urine (Berglund et al., 2005) or bile and feces (Canuel et al., 2006), thanks to renal and hepatic clearance, respectively. Urine is commonly used; while bile and feces are rarely used.

5.4.5 Lack of guidance values

As reported in Section 5.2 there are a limited number of chemical-specific guidance values. There may be several reasons for this. In general, reference levels exist when there is a strong database and weight of evidence to support a derivation. For contaminants of emerging concern there may be few hazard or exposure data on which to base a guidance value. For well-regulated chemicals with a strong hazard base, an alternative to a guidance value may be to suggest that levels be kept as low as possible. If exposures are expected to be limited, guidance values may be seen to be of minimal value. Changes in risk assessment approaches may also affect the availability of guidance values. Regardless, the lack of chemical-specific guidance values can limit the ability to carry out human health risk assessments.

Guidance values must be updated to ensure they remain valid. This is not always done. For example, USSR MALs (Standards of 1989 and 1981) were very helpful in carrying out the EU Kolarctic KO467 project aimed at the study of local food contamination by the nickel-copper smelter in the Pechenga district of Murmansk Oblast. Interpreting the project's results was made difficult by the absence of internationally established food contamination standards for Ni and Cu in foods, which were the key pollutants in the study area. Given the lack of updated reference points for Ni and Cu, a decision was made to focus on the contaminants with internationally agreed reference points, namely Pb, Hg, Cd and As, even though their levels were low in local foods. The only joint international publication (Hansen et al., 2017) covering all data from all countries (Norway, Finland, Russia) only briefly considered the risk of consuming wild food. Hansen et al. (2017) concluded that the elevated Ni and Cu concentrations observed in some mushroom samples could pose a risk to people who frequently consume mushrooms. These people should avoid collecting mushrooms near the smelter and in other areas showing high concentrations of toxic elements in mushroom species. Several Russian publications (Doushkina et al, 2015; Dudarev et al, 2015a,b) have discussed in detail the Ni-Cu dietary exposure (including local water) and the related human health risks.

When guidance values are not available to conduct a human health risk assessment other approaches may be necessary. In lieu of guidance values, exposures in one study may be compared to exposures in other populations. A margin-of-exposure approach may be used to compare known or suspected health effects with observed exposures. Provisional guidance values, specific to a given project, may be developed based on studies in the literature. These approaches do not take the place of guidance values but do allow for some interpretation of results.

5.4.6 Susceptibility and variability

Genetic variations and polymorphisms may play a significant role in MeHg body burden disparities between populations and among individuals within a population; however, a review on this topic suggested more research is necessary to identify major gene(s) modifying the kinetics or toxicity of Hg (LIop et al., 2015). Forming a conjugation between MeHg and tripeptide glutathione (GSH) is a crucial step for MeHg elimination in the bile via the ATP-binding cassette (ABC) transporter system. Genetic polymorphisms in genes involved in GSH synthesis, *GCLC*, *GCLM* and *GSTP1*, have been linked to MeHg retention and body burden in adults in a prospective study of the Seychelles population with a diet rich in fish. MeHg metabolism may be influenced by maternal differences in genes involved in GSH synthesis. Maternal variation in these genes may also affect the association between exposure to MeHg and neurodevelopmental outcomes (Wahlberg et al., 2018). Genetic polymorphisms in cytochrome *CYP3A* genes may modify MeHg body burden during early life development. Polymorphisms in *CYP3A7* and *CYP3A5* genes modified the magnitude of the association between prenatal exposure to MeHg and child neuropsychological development, with those expressing a high activity allele having higher developmental test scores. No *CYP3A* polymorphisms were shown to influence MeHg toxicokinetics in the fetus (Llop et al., 2017).

Additionally, polymorphisms in ABC transporter genes were associated with maternal hair Hg concentrations in mother-infant pairs in the Seychelles Child Development Study. Of fifteen ABC single nucleotide polymorphisms (SNPs) identified, seven (*ABCC1* rs11075290, rs212093, and rs215088; *ABCC2* rs717620; *ABCB1* rs10276499, rs1202169, and rs2032582) were associated with Hg concentration in maternal hair, while only one (*ABCC1* rs11075290) was significantly associated with negative neurodevelopmental testing outcome (Engström et al., 2016). Polymorphisms in ABC transporters may also influence MeHg body burden in both mother and fetus during pregnancy. In a study of participants from two European birth cohorts, researchers identified child SNPs in three ABC transporter genes that modified the association between maternal fish consumption and cord blood Hg levels (Llop et al., 2014). Expression of ABC transporters may be related to ethnicity, as was shown by Matsson et al. (2012) who observed nineteen genes that were differentially expressed among individuals of African, Asian and European descent.

Differential expression of other genes has also been reported across different groups. Indigenous populations of North America have unique genetic variation profiles that may critically impact their response to the body burden of xenobiotics. With regard to *CYP3A5* in the Yup'ik Alaska Native Confederated Salish and Kootenai Tribes population, *CYP3A5*1* was detected at a frequency of 7.5%, *CYP3A5*3* at 92.5%, while *CYP3A5*6* and *CYP3A5*7* were not detected. These data suggest that 14.9% of Yup'ik Alaska Native Confederated Salish and Kootenai Tribes individuals express *CYP3A5*, contributing to their total *CYP3A* metabolic activity (Henderson et al., 2018). Functional *CYP3A5* is expressed in approximately 20% of Caucasians and about 67% of African-Americans (Kuehl et al., 2001). Indigenous populations of North America may also have novel *P450* gene variations not seen in other populations of the world that can potentially influence the body burden of xenobiotics, including Hg (Henderson et al., 2018). Additionally, genetic variation profiles were reported within populations in Denmark, the Faroe Islands, and Greenland. The frequency of *CYP2D6* poor metabolizers is 2–3% in Greenlanders and nearly 15% in the Faroese population. The frequency of *CYP2C19* poor metabolizers in eastern Greenlanders is approximately 10% (Brosen, 2015).

It is clear that employing a general Hg model for humans is insufficient (Llop et al., 2015). Indeed, unique genetic backgrounds, among other factors, may have a significant role in individual/population susceptibility to MeHg body burden (Figure 5.7).

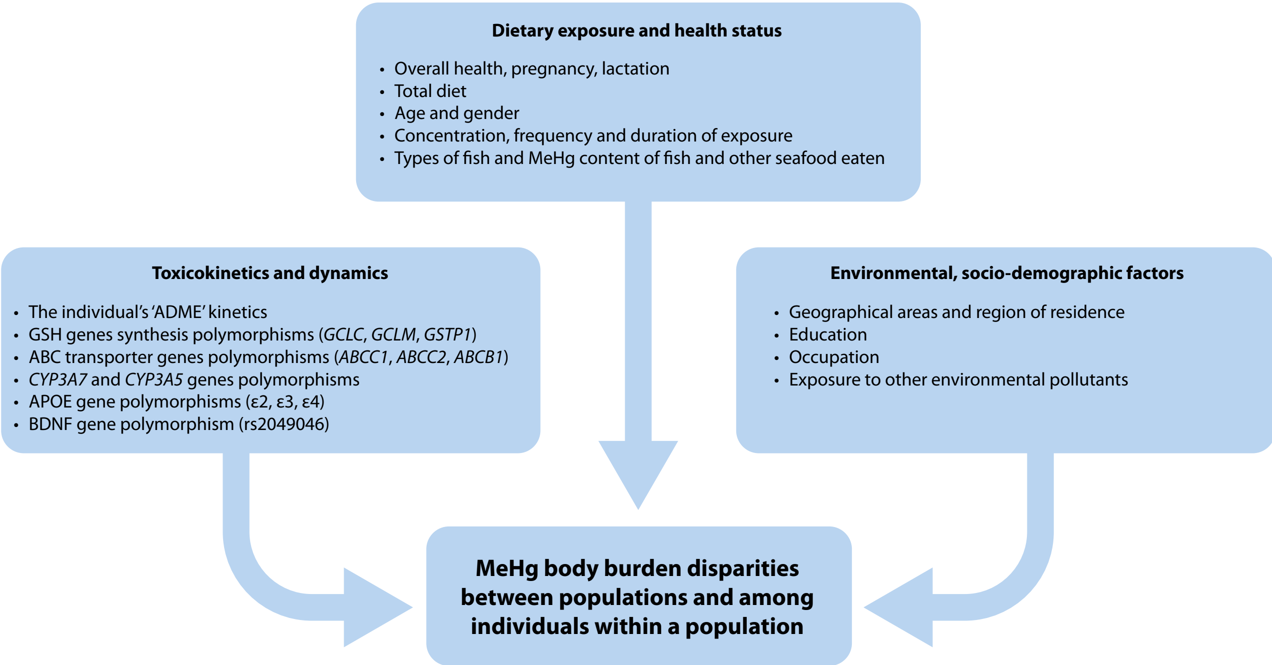

Figure 5.7 Factors determining variations in human body burden of methylmercury.

5.5 Conclusion

Conclusions drawn in previous AMAP assessments on risk assessment remain valid today, including the need to understand the health effects of Hg at low levels; the need to identify vulnerable populations and the need for robust inputs to create meaningful toxicokinetic models (AMAP, 2015); the importance of epidemiological studies and cumulative exposures (AMAP, 2003); and the importance of risk-benefit considerations (AMAP, 2003, 2009). Risk assessment in the Arctic must consider inputs that are specific to regions or communities (e.g., food intake, seasonal intake), unique exposure mixtures and underlying factors.

Different jurisdictions set different reference values for POPs and metals. The values can differ based on estimated dietary intakes, approaches to uncertainty and organizational mandate, among others. Reference levels can vary in complexity, from a maximum level in a food item, to a recommended maximum dietary intake, to a level measured in human matrices below which effects are unlikely to be observed. These can be based on epidemiological, toxicological and/or modeling studies.

Tools are available to interpret human biomonitoring data in different contexts. Reference values are not health-based values, but do allow exposure in an individual or population to be compared to other populations. Biomonitoring equivalents are principally intended as screening values for quick interpretation of human biomonitoring data in a risk-based context. Only a few tissue-based guidelines have been established by different organizations as health-related biological exposure limit values for metals (Hg, Pb) and PCBs. There is a trend of decreasing Hg exposure and this has resulted in far fewer exceedances of health-based blood Hg guidelines in areas that have historically higher levels of Hg, such as the eastern Canadian Arctic and Greenland.

Dietary and seasonality patterns, cultural practices, environmental and sociodemographic variables, and genetic variations and polymorphisms, among other factors, may play a significant role in the susceptibility of Arctic Indigenous populations to environmental contaminants. Further work in this area could greatly improve risk assessment.

Indigenous Arctic populations were identified as a population in need of improved contaminant exposure estimation tools. Several mechanistic models and physiologically-based pharmacokinetic modeling have been developed to assess Arctic Indigenous human population exposure to environmental contaminants.

Future studies are necessary in order to reduce uncertainties and better characterize health risks associated with environmental contaminants by better identifying sources of contamination; deriving and/or updating reference values for key contaminants; exploring risk assessment methods to address risks associated with mixtures; and improving the overall process of health risk assessment, including harmonization of reference values where possible.

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6. Contaminant risk communication update

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Key findings

- *Current risk communication activities in most Arctic countries emphasize the importance of a nutritious diet. Contaminant-related restrictions are mostly based on mercury; a limited amount of dietary advice is also based on other contaminants.*
- *Specific data on effectiveness evaluation is limited to a few regions in Canada and a few other countries. Only Sweden has provided information on the effectiveness of their national dietary advice. More health communication and risk perception data are important in order to compare results to other regions and countries across the circumpolar Arctic.*
- *There is a lack of information on risk communication specifically for Indigenous Peoples in Arctic countries other than Canada (such as Saami in Europe).*
- *Risk communication with Arctic Indigenous Peoples should be developed in full partnership with the affected people (regions and/or communities) and needs to involve regional health authorities and local clinicians (nurses, physicians, Indigenous midwives).*
- *In risk communication activities, trusted relationships between all involved parties (particularly between communicators and recipients of the messages) are crucial for the success of the communication. This trust is difficult to build and very easily damaged or destroyed.*
- *Very targeted, regular, clear communication, and timely and personalized messaging is required to ensure retention of messages and to enable reduced contaminant exposure.*
- *Risk communication needs to be well-balanced, and should take into account cultural aspects and benefits of traditional country foods.*
- *Sensationalized and alarmist messages that contradict cultural values of local audiences can result in confusion, fear, or 'inoculation effects', and thus can threaten the success of future communication.*
- *Social media, when properly managed, may be a useful tool in risk communication. It enables two-way communication, may help to better reach target audiences, and may help build relationships. Information on its use in risk communication (especially in the Arctic) is still very limited.*
- *Communication of contaminant risk is a very complex undertaking. Risk communication is a tool available to protect populations under current conditions, however, it is not a sustainable solution to ensure low levels of contaminant exposures in human populations. It is therefore crucial that regulatory actions to lower contaminants in the environment are implemented effectively.*

6.1 Introduction

As described in previous chapters of this assessment, the main exposure pathway for most persistent organic pollutants (POPs) and metals in Arctic populations is through the diet. For Arctic Indigenous Peoples, the diet consists of traditional country food items and includes top predators of the Arctic food chain, such as marine mammals and/or predatory fish. Arctic Indigenous Peoples rely on their traditional country foods for food security, for their general health and wellbeing, and as part of their spiritual and cultural identity. If high contaminant levels are found in Arctic biota forming part of the traditional diet, then communication of information about contaminant risks and benefits of the diet is an important and immediate means by which public health officials and clinicians can address potential exposure and so help minimize adverse health effects. However, as described in previous AMAP human health assessments (e.g., AMAP, 2009, 2015; and other publications referenced therein), risk communication is not an easy undertaking or a permanent solution to the issue of contaminants in country foods and can only ever be an interim approach to protecting humans from exposure to contaminants. Risk communication in the form of, for example, public health advisories and clinical counselling also needs to be continuously updated based on the most recent scientific information and exposure data. Ultimately, to address contaminants of concern in the Arctic appropriately, levels in the environment must be reduced.

The risk communication chapter in the previous AMAP human health assessment report (Krümmel and Gilman et al., 2015) summarized some of the research on risk communication methodologies and approaches to evaluating risk communication initiatives and gave examples from several Arctic countries. It also considered theoretical approaches to risk communication on how human behavior can be influenced to reduce health risks. Important aspects of risk communication include the need for clear and consistent messaging, trusted sources to deliver the information, and frequent messaging using a range of media appropriate for the region that considers overall context and provides a balanced view. The chapter used examples from several Arctic countries, summarized views from Arctic Indigenous Peoples, and reflected on what makes risk communication effective.

Several gaps in knowledge became apparent from the 2015 human health assessment:

- There have not been enough studies on the effectiveness of risk communication efforts. That is, it is rarely known if risk communication activities have achieved what they were intended to achieve, and if not why not. It is important to note that decreasing levels of contaminants in people are often an effect of other factors and it should not be prematurely concluded that any such decline is due to risk communication activities.
- Few examples of social media use in risk communication were available, although social media sites (such as Facebook) are extremely popular, particularly with Arctic Indigenous Peoples.
- There was a lack of information about how risk communication is practiced in several Arctic countries, particularly in Europe/Scandinavia.

This chapter fills some of the gaps that were identified in the 2015 human health assessment. Risk communication efforts in European Arctic countries have been added where information was previously lacking, and information has been updated for countries and regions as new material has become available. Results from risk communication effectiveness evaluation studies are described for several Arctic countries, including successes and difficulties. Experience of social media use in Alaska is illustrated, and the advantages and challenges of using social media in risk communication are discussed.

6.2 Risk communication in Arctic countries

Dietary guidelines in circumpolar Arctic countries were summarized as part of the work of the Sustainable Development Working Group (SDWG) Arctic Human Health Expert Group (AHHEG) and published by Jeppesen et al. (2011). The Arctic countries/regions considered include Alaska, (northern) Canada, the Faroe Islands, Finland, Greenland, Iceland, Norway and Sweden. Information is also given on food advisories regarding contaminants, although this was not the focus of that work. Notably, there was no information on food advisories for Norway and Sweden. Results indicated that specific dietary advice from the various countries was often difficult to find on the internet.

This chapter does not review general dietary guidelines as these were addressed in Chapter 2 but does summarize food advisories as examples of ongoing risk communication. It also provides updates on experiences with risk communication.

6.2.1 Alaska (USA)

The US Environmental Protection Agency and the US Food and Drug Administration have issued national advice regarding the consumption of fish, which is available on the websites of each agency and includes a link to a downloadable pdf version (USEPA, 2020a; USFDA, 2020). The advice promotes the general eating of fish but also highlights the need to eat fish low in mercury. A chart is included that outlines which fish species are low in mercury and can be eaten more frequently ('Best Choices': two to three servings per week), less frequently ('Good Choices': one serving per week), or fish that should be avoided (which includes shark, swordfish, marlin, and big eye tuna, among others). Links to supporting scientific documents, such as the risk assessment, peer review and other technical information are all available on these websites. The advice also includes a link to State, Territory and Tribe Fish Advisory contacts (USEPA, 2020b) and websites for advisory information on fish caught in local waters by friends and family.

For Alaska, comprehensive guidelines on fish consumption, facts about contaminants in fish, and more information is provided on the website of the Alaska Department of Health and Social Services (State of Alaska, 2020a). This includes the recommendation to eat fish at least twice per week, but also that "women who are or can become pregnant, nursing mothers, and children choose the types of fish they consume wisely". For Alaska women and children, a 'fish consumption point system' is provided, which allocates fish species with a certain number of points (from 0 to 12) and recommends to 'mix and match' fish meals for up to 12 points per week. Fish species with 0 points (which includes several whitefish, dolly varden, Pacific salmon species, Pacific cod, etc.) can be eaten without restriction. For some other fish species in the 3- to 12-point categories, weight and/or length information is included. Everyone outside this risk category (which includes adult men, and adult women who cannot become pregnant) is encouraged to eat as much fish from Alaskan waters as they like. The benefits of fish consumption are also outlined.

While the recommendations and guidelines for eating fish are based on mercury, information on other contaminants – in particular POPs – is also included, stating that all Alaskan fish species tested have either non-detectible or very low concentrations. General fish contaminant data for metals (including arsenic, mercury, lead, selenium) and organic contaminants (polychlorinated biphenyls, PCBs; polybrominated diphenyl ethers, PBDEs; organochlorine pesticides and polyfluoralkyl substances, PFASs) are available as graphs and/or tables on the Alaska Division of Environmental Health State Veterinarian website (State of Alaska, 2020b). This website also has links to a fish monitoring map, and information on Fukushima (radiation) and Alaskan fish, and the results of a survey on the State of Alaska Fish Monitoring Program conducted by the Department of Environmental Conservation.

The Fish Monitoring Program Public Survey was a ten-question survey posted on the webpage, and shared by email, Facebook and newsletter. The first fifty responses are summarized in the posted report (State of Alaska, 2020c). It was found that 86% of respondents were concerned about contaminants in Alaskan fish and shellfish to some degree. Most people were concerned about mercury (80%), which influenced their decision on buying or eating fish. About 54% of people were concerned about other heavy metals, 36% about pesticides, 30% about marine toxins, and 30% and/or less about PCBs, radionuclides, PBDEs, dioxins, and perfluorinated compounds.

Given that fish consumption in Alaska is among the highest reported at 1050 g/week (90th percentile 2653 g/week; the US national rate is 363 g/week), the state's recommendation of unrestricted consumption of certain species of Alaskan fish is supported by human biomonitoring data that help provide reassurance that this recommendation continues to be appropriate for residents. This recommendation was issued by the Alaska Scientific Advisory Committee for Fish Consumption in collaboration with the Alaska Division of Public Health.

The Alaska Division of Public Health has a statewide Hair Mercury Biomonitoring Program and offers free, confidential hair mercury testing for women of childbearing age and children as part of the program (State of Alaska, 2020d). It publishes updates on statewide and regional data and contacts those people with a hair mercury level above 5 ppm for a follow-up evaluation to help identify and mitigate potential sources of mercury exposure (State of Alaska, 2020d). The website includes specific information about a multi-year study (2007–2010) of the US Fish and Wildlife Service and the Alaska Section of Epidemiology on human hair mercury values and fish consumption histories from women in selected rural Alaska communities (Kossover et al., 2016). The study gives recommendations for healthcare providers as well as regionally-specific consumption guidance for northern pike (Kossover et al., 2016). Links to other communication items are provided on the website, such as posters on mercury in northern pike near wildlife refuges from four regions of the state (e.g., the Yukon Delta National Wildlife Refuge, issued in both English and Yup'ik), which give detailed recommendations on how much of this species can be eaten by women and children.

6.2.2 Canada

Dietary advice in Canada is provided within the jurisdiction of the Provinces and Territories, with support from the federal health department if needed (Jeppesen et al., 2011; NCP, 2017). Recognizing the nutritional benefits of eating fish while needing to minimize the risk of exposure to mercury, different levels of government have put in place fish consumption advisories for individuals of different ages and life stages (Government of Canada, 2013). These include recommended consumption limits nationally for commercially available fish and regionally, lake-specific advisories for different species of fish that are locally caught. For example, on the federal (national) level, Health Canada provides consumption advice on fish due to mercury exposure, which is available on the internet (Government of Canada, 2019). The advice explains that while most Canadians do not need to be concerned about mercury exposure from fish, some types of fish can result in high mercury exposure. Fish and shellfish that are high in beneficial fatty acids, vitamin D and nutrients and low in mercury are listed, and include anchovy, capelin, char and herring, among others. The advice lists predatory fish as those that can be high in mercury, including fresh/frozen tuna, shark, swordfish, marlin, orange roughy and escolar. Specific information on escolar (the common name for two species of fish, *Ruvettus pretiosus* and *Lepidocybium flavobrunneum*) owing to gempylotoxin is also provided on a separate fact sheet (Government of Canada, 2008). Canadians are advised to limit their consumption of these types of fish to 150 g/week for the general population, 150 g/month for 'specified women' (those who are or may become pregnant or are breastfeeding), 125 g/month for children aged 5 to 11 years, and 75 g/month for children between 1 and 4 years in age. There is separate consumption advice for canned albacore tuna (often called white tuna) for 'specified women' (300 g/week) and children aged 5 to 11 years (150 g/week) and 1 to 4 years (75 g/week).

While many Canadian Provinces regularly update and publish consumption advisories for fish (mostly based on mercury intake from local fish consumption), this chapter focuses on new information and experiences from Canada's Arctic regions. In Canada, the preference particularly in Indigenous communities is that public health strategies related to contaminant exposure balance the risk and benefits of consuming country foods (Laird et al., 2013; Lemire et al., 2015; Pirkle et al., 2016).

In 2017, the Northern Contaminants Program (NCP) published the fourth Canadian Arctic Contaminants Assessment Report on Human Health (NCP, 2017). The report includes detailed information on regional contaminant communication, which is guided by the NCP management structure. All northern regions (Northwest Territories - including the Inuvialuit Settlement Region, Yukon, Nunavut, Nunatsiavut, and Nunavik) have a Regional Contaminants Committee (RCC), which provides a connection between the NCP, northern researchers, territorial and regional health authorities, and communities (NCP, 2017). The RCCs include a wide range of expertise, such as regional health authorities, along with wildlife, elder and youth experts. This enables them to provide information on overall benefits and risks, as well as a more holistic view of how to communicate and what to communicate to minimize risk and maximize benefit. The health authorities in each region are responsible for dietary recommendations and consumption advisories. Researchers are asked not to provide health advice, particularly not without prior consultation with the appropriate health authorities. There are many positive examples of successful communications, some of which are outlined in Sections 6.2.2.1 and 6.2.2.2. However, these guidelines are not always successfully followed, and one such example is described in Section 6.2.2.3.

6.2.2.1 Nunavik

Examples of where risk communication has been undertaken successfully from a methodological standpoint include the activities of the Communications Working Group of the Nunavik Child Development Study (see Chapter 1, Box 1.2).

The Communications Working Group included members with a wide range of expertise, including hunters, educators, healthcare professionals, researchers, and communicators. It was specifically formed to develop communication recommendations about local country foods and disseminate the results of the Nunavik Child Development Study (Boyd and Furgal, 2022), since risk communication in the past has not always been effective or has even caused confusion and/or fear (AMAP, 2015). To enable the development of appropriate and effective risk communication messages, the process followed a participatory approach and was described in detail by Boyd and Furgal (2022, and references therein). Highlights include:

- The decision-making process was interactive and iterative, with face-to-face and telephone meetings in which risk management and communication decisions were discussed.

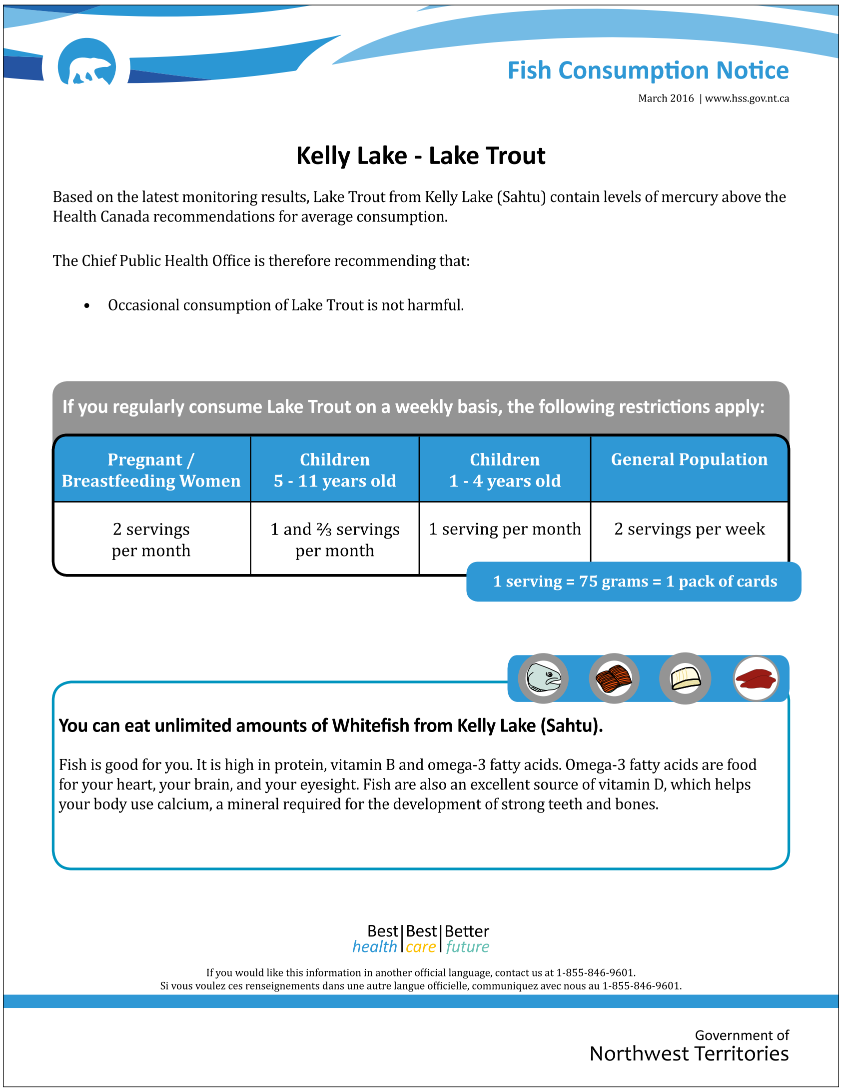
- Decisions were made by consensus, and messages were formulated cooperatively among members. However, the ultimate decision on the health messages was made by the Public Health Director of the Nunavik Regional Board of Health and Social Services.
- The working group learned about the data and gave feedback to the scientists. In some cases, this led to invaluable details on contaminant exposure and nutrient intake, and a revision of the analysis (such as which food item causes the highest mercury exposure and so was likely to need a consumption advisory).
- The working group determined how to provide messages based on what they thought may be effective (such as the source of the message, what the message would be, and which communication channels would be used), and also considered implications and possible indirect impacts. Of high importance was that the message properly reflected the research results, and that the communication material was culturally appropriate.

Overall, the process used by the working group was described as successful by the group members. Several strengths were highlighted: members of the affected population brought an understanding of local perceptions and insight into behaviors that affected exposure to contaminants; the diversity of the group brought a range of valuable expertise and knowledge (including Inuit Knowledge); and good relations between group members, built on mutual respect and trust, enabled the comfort and confidence to ask questions. The only two disadvantages mentioned were that some members lacked formal communication experience and the large amount of time the process took.

The analysis by Boyd and Furgal (2022) resulted in five suggestions from working group members for future risk communications campaigns. (1) A debriefing session should be held after the communication campaign to review communication strategies, examine issues that arose, and determine changes needed for future campaigns. (2) Further strategies should be developed for a series of communication events, aimed at different target groups, rather than a single communication event (some members believed that repeated events or a multi-phase campaign would be more effective). (3) Adequate time should be allowed for the risk management and communication process. (4) Follow-up on policy recommendations is required, such as for discontinuing the sale of lead ammunition (members were unsure if lead ammunition was still being sold after the communications campaign). (5) It is important to evaluate the reception and awareness of the communication to ensure the success of the messages.

It should be noted that an evaluation of the communication campaign in Nunavik took place through structured interviews to determine message recall and reception, and possible changes in food consumption associated with the advisories. The results of the evaluation will be published in due course, and a very short summary of preliminary findings is included in Section 6.3.

Some of the communication materials produced as a result of the Nunavik Child Development Study were described in the previous AMAP human health assessment (Krümmel and Gilman et al., 2015). The overall health messages released in October 2011 included a recommendation to increase intake of country foods, especially those containing omega-3 fatty acids, but that pregnant women and those of childbearing age should decrease their consumption of beluga meat. The need to ban all further use of lead shot ammunition due to adverse effects of prenatal and childhood lead exposure was also emphasized.


Fish Consumption Notice

March 2016 | www.hss.gov.nt.ca

Kelly Lake - Lake Trout

Based on the latest monitoring results, Lake Trout from Kelly Lake (Sahtu) contain levels of mercury above the Health Canada recommendations for average consumption.

The Chief Public Health Office is therefore recommending that:

- Occasional consumption of Lake Trout is not harmful.

If you regularly consume Lake Trout on a weekly basis, the following restrictions apply:

Pregnant / Breastfeeding Women	Children 5 - 11 years old	Children 1 - 4 years old	General Population
2 servings per month	1 and ⅔ servings per month	1 serving per month	2 servings per week

1 serving = 75 grams = 1 pack of cards

You can eat unlimited amounts of Whitefish from Kelly Lake (Sahtu).

Fish is good for you. It is high in protein, vitamin B and omega-3 fatty acids. Omega-3 fatty acids are food for your heart, your brain, and your eyesight. Fish are also an excellent source of vitamin D, which helps your body use calcium, a mineral required for the development of strong teeth and bones.

Best | Best | Better
health | care | future

If you would like this information in another official language, contact us at 1-855-846-9601.
Si vous voulez ces renseignements dans une autre langue officielle, communiquez avec nous au 1-855-846-9601.

Government of Northwest Territories

Figure 6.1 Site-specific Fish Consumption Notice for Kelly Lake, Sahtú Region, NWT, Canada.

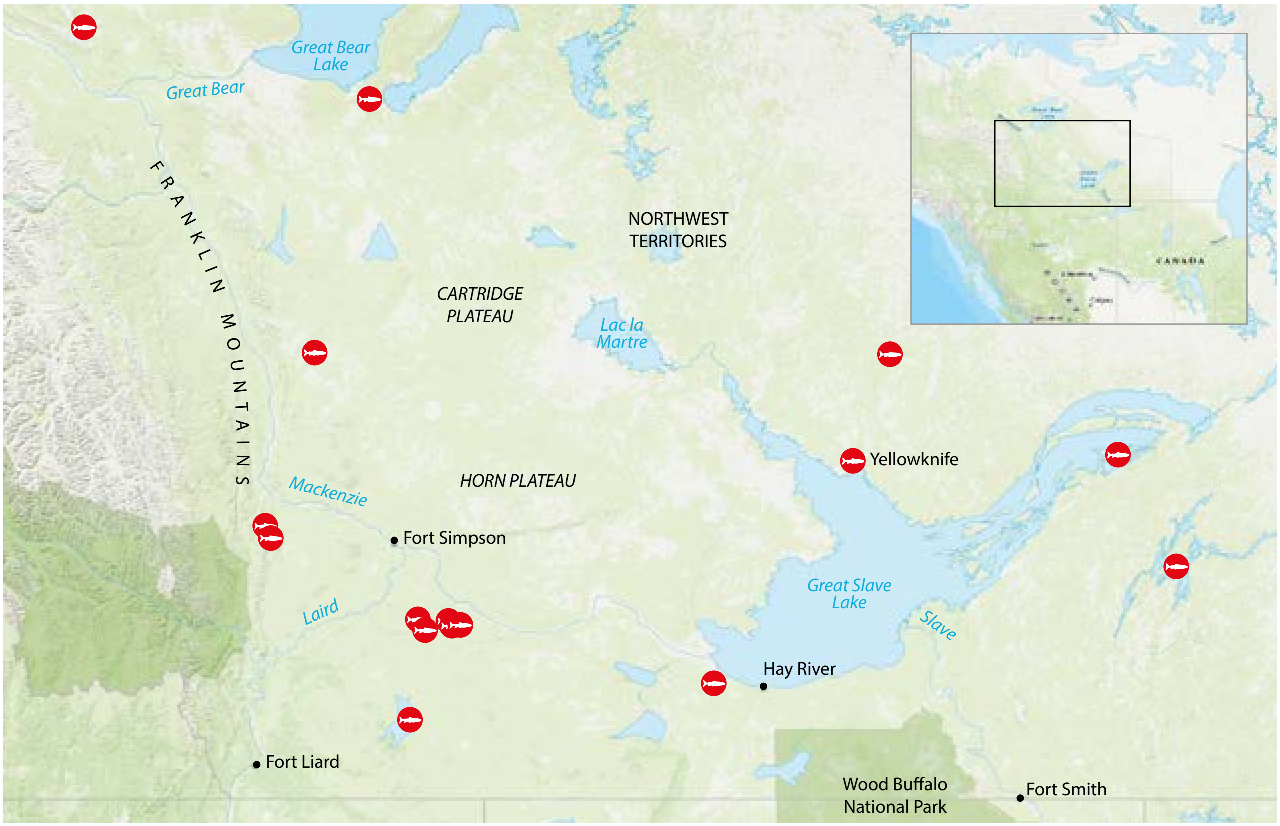


Figure 6.2 Location of fish consumption notices issued by the Government of the Northwest Territories Department of Health and Social Services, December 2019.

Further consultation activities as part of the Nutaratsaliit Qanuingisiarningit Niqituinnanut – Pregnancy wellness with country foods (NQN) project in Nunavik suggested an integrated approach on country food benefits and contaminants (chemicals and pathogens), including Inuit Knowledge, during pregnancy. Personal testing and dietary counseling for pregnant women was also discussed, along with the need to develop targeted training tools (i.e., for physicians, nurses, midwives, pregnant women, elders and hunters), which would include Inuit midwifery knowledge and other issues related to country foods (culture, taste, nutritional benefits, food security, food pathogens) (Lemire et al., in press). Timing of the communication is particularly important due to the seasonality in methylmercury exposure when the beluga hunt and associated beluga meat consumption is taking place, since beluga meat is the local country food most responsible for elevated methylmercury exposure in Nunavik (Pontual et al., 2021).

6.2.2.2 Dehcho and Sahtú regions of the Northwest Territories

Consumption notices in the Northwest Territories (NWT) have been issued with regard to heavy metals, such as arsenic, cadmium (in kidney and liver from moose harvested from the southern Mackenzie Mountains of the Dehcho region; Government of the NWT, 2017), and mercury. Elevated mercury levels in some fish species in certain lakes in the NWT resulted in a series of fish consumption notices that suggested people limit their consumption of particular species (Government of the NWT, 2016). It is worth adding that, as part of the larger biomonitoring project, the Government of the NWT revised their language from 'advisories' to fact sheets and consumption 'notices' to shift the tone from fear to education (Brandow, 2018).

The Government of NWT Department of Health and Social Services creates and publishes all site-specific fish consumption advice and guidance for affected areas in the NWT with the assistance of environmental monitoring research programs. Most consumption notices are created in a one-page PDF format (see the example in Figure 6.1) which can be found on their website (Government of the NWT, 2016). An NWT fish consumption notice map is also available; this shows red circles for regions affected by a consumption notice (see example in Figure 6.2). In certain areas, consumption notices and/or health advisory signs are posted at the affected lake, such as Frame Lake, where an advisory on arsenic levels is in effect (Figure 6.3). Word of mouth is an informal way that risk messaging and consumption notices are communicated between and within northern communities. The effectiveness of these activities is generally not evaluated. However, based on research as part of a larger biomonitoring project in the Dehcho and Sahtú regions, which includes biomonitoring data, dietary surveys, and a Health Messages Survey (Ratelle et al., 2018a,b), the Government of the NWT is considering making changes to fish consumption notices in these regions, where the plan is for some of the notices to be lifted completely and for others to be relaxed (see also Section 6.3). In the NWT, the ultimate decision on health messages rests with the Chief Public Health Officer (Torng pers. comm., 2019).

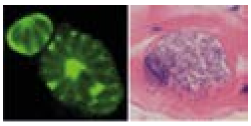
Figure 6.3 Warning of a Public Health Advisory issued for Frame Lake by the Government of the NWT, Yellowknife, NWT, Canada.

Emergence of *Toxoplasma gondii* parasites infecting Beluga whales in the Arctic

In 2009, the cat parasite *Toxoplasma* was first detected infecting heart and diaphragm tissues of Arctic Beluga using molecular PCR techniques. NIH scientists next developed a blood test to detect antibodies against *Toxoplamsa* circulating in Beluga serum, and follow up histological studies have established the presence of infectious forms of the parasite in Arctic Beluga. *Toxoplasma* is known to infect Beluga from the St. Lawrence Seaway, but these parasites have not previously been reported in Arctic Beluga, a hunter-harvested animal of the Inuit.

Beluga, *Delphinapterus leucas*
Photo credit: Neil Fisher and the Vancouver Aquarium

Toxoplasmosis, the illness caused by *Toxoplasma* infection, is generally not serious in healthy people, but the parasite can cause severe disease in the fetuses of pregnant women or those with compromised immune systems. People become infected with *Toxoplasma* via water sources contaminated with infectious forms of the parasite present in cat feces, or by eating undercooked meat. To avoid the possibility of acquiring toxoplasmosis, pregnant women should refrain from eating raw whale meat, and thoroughly wash their hands after handling raw meat. Freezing and cooking kills the infectious forms of this parasite, and the Inuit traditional practice of preparing whale meat in stews or as dried strips should render the meat safe to eat.



Left, *Toxoplasma* parasites that cause acute disease. Right, *Toxoplasma* cysts in Arctic Beluga heart muscle.
Credit: M. Grigg; S. Raverty

Figure 6.4 Press release issued during the 2014 Annual Meeting of the American Association for the Advancement of Science regarding the finding of *Toxoplasma gondii* in beluga samples from the western Arctic.

6.2.2.3 Inuvialuit Settlement Region: *Toxoplasma gondii* in beluga; a negative communication example

On 14 February 2014, during the annual meeting of the American Association for the Advancement of Science (AAAS), scientists reported finding the 'cat parasite' (*Toxoplasma gondii*) in beluga from the western Arctic. Samples had been taken during the annual beluga hunt, which is co-organized by the Department of Fisheries and Oceans and Inuit co-management boards in the Inuvialuit Settlement Region (ISR). The same hunt also supplies samples for contaminant analysis within the Northern Contaminants Program. Certain rules of communication apply, which include that all results are reported back to the community/region before being released to the general public. However, without having reported the results to the community or region beforehand, the scientists published a press release during the conference (Figure 6.4), and gave interviews on their results, which included the finding of *Toxoplasma gondii* in beluga samples. Based on this, the scientists issued a warning against the consumption of raw beluga meat, stating that the parasite can have serious health effects (and can even be fatal to fetuses and immune-deficient individuals). The press release and associated information on the universities' website (UBC, 2014) was picked up by the international media (see Box 6.1 for examples) and published widely on the internet.

This caused great concern in the ISR, since beluga is a very important traditional country food for Inuit in the region. There was also a worry that the long-built trust between researchers, federal government officials and community members involved in the beluga monitoring program could be destroyed by these media releases. Therefore, on 17 February, the ISR held a teleconference that included all parties involved in the program and regional health authorities to discuss what had happened and establish whether or not there was a health concern that would warrant a consumption advisory. On 17 March, a fact sheet was finalized that outlined concerns with regard to toxoplasmosis, and what should be done to prevent individuals getting toxoplasmosis (Figure 6.5).

In addition to the fact sheet, a community tour was organized with regional health authorities and scientists from Fisheries and Oceans Canada, that focused mainly on discussions with Hunters and Trappers Committees and their membership at large in each community. As with all tours, this did not always capture all hunters in the communities. In February 2016, the first Beluga Summit was held in Inuvik, ISR to share knowledge on beluga gathered through the co-management and biomonitoring process of beluga in the ISR (Loseto et al., 2018). A highlight at the summit was a presentation by researchers working on *Toxoplasma gondii* effects on beluga health, demonstrating a low risk for the beluga population (Sharma et al., 2018).

In 2018, a new beluga communication group was developed to address contaminant communication, both in terms of content and messaging (including contaminants and diseases of a zoonotic nature), as well as the methods and media of communication.

Box 6.1 Media reactions to the press release on *Toxoplasma gondii* in beluga

A selection of media reactions in February 2014 to the press release issued by researchers on *Toxoplasma gondii* in beluga at the annual meeting of the American Association for the Advancement of Science (AAAS).

BBC News, UK	"*The cat parasite […], which can cause blindness in people, has been identified in Beluga in the western Arctic. The discovery […] has prompted a health advisory to Inuit people in the region who eat the whale's meat.*" BBC News (2014)
CBC News, Canada	"*Cat parasite found in Western Arctic belugas*", "*Toxoplasma poses danger for pregnant women, people with weak immune systems*", "*vulnerable people […] should be 'extra vigilant' about handling and eating raw whale meat.*" CBC News (2014)
Globe and Mail, Canada	"*University of British Columbia researchers have issued a health advisory to Inuit whalers after discovering an infectious cat parasite in belugas in the Arctic Ocean, a potentially fatal portent of climate change in the North.*" Globe and Mail (2014)

The beluga toxoplasmosis incident received much attention, and was even partially chronicled in a Nature article (Dolgin, 2017). The experience showed the need for strong and constant communication between lead scientists, wildlife/fisheries boards and health authorities. Overall, people involved in the incident reported an enduring negative impact that would not be erased even with best efforts; however, a follow-up study to examine the lasting effect of the experience would be needed to confirm this impression (Loseto pers. comm., 2018). Such a finding would be consistent with research indicating that trust is more difficult to build than destroy (Boyd et al., 2019a), described as the 'asymmetry principle' (Slovic, 1993), where negative, trust-destroying events have a bigger impact than positive, trust-building events, such that once trust is broken it may become challenging or even impossible to rebuild (Slovic, 1993; Wall and Chen, 2018; Boyd et al., 2019a).

Beluga and Toxoplasmosis Fact Sheet

There have been recent media stories regarding the finding of *Toxoplasma* parasite in beluga whales in the Western Arctic. To date, no cases of toxoplasmosis in humans have been linked to belugas that were part of this study. In general, ***beluga and other country food are still safe to eat***.

What is toxoplasmosis?
Toxoplasmosis is caused by the parasite *Toxoplasma*. The parasite infects domesticated animals and wild animals. Toxoplasma is not new to the arctic.

Who is at risk?
Healthy people are generally not at risk, but the parasite can seriously harm an unborn child. Pregnant women, and those with compromised immune systems, are advised to not eat raw whale meat and thoroughly wash their hands after handling raw meat.

What are the symptoms?
Most people with a healthy immune system won't have any signs of the disease.
Short-term effect may include: fever, muscle pain, sore throat, headache, swollen lymph nodes, eye problems and an enlarged spleen. Individuals who think they have toxoplasmosis should talk to their healthcare provider.

How to prevent getting toxoplasmosis?
- At risk individuals, particularly pregnant women and immune-compromised persons should only eat meat that has been thoroughly **cooked**, **frozen** or **dried**.
- Wash hands, cutting boards and utensils after handling raw meat.
- Pregnant women should avoid cleaning litter pans and contact with cats of unknown feeding history.

For questions related to human health concerns around toxoplasmosis, contact the Office of the Chief Public Health Officer at either of the following phone numbers: (867) 920-6204 or (867) 873-2183.

COUNTRY FOODS ARE SAFE TO EAT

FJMC
FISHERIES JOINT MANAGEMENT COMMITTEE

Figure 6.5 Fact sheet prepared with Public Health Agency Canada facts that was contextualized and issued by the Inuvialuit Game Council and the Fisheries Joint Management Committee on *Toxoplasmosis* in beluga.

6.2.3 Greenland

Information on food security is issued by the Greenlandic Board of Food and Environment (e.g., Mulvad, 2018). It outlines the importance of the traditional Greenlandic diet, and that in the interests of health and food security the goal is to promote Greenlandic food items in the general food supply strategy. This includes availability of Greenlandic food items in public institutions, increased knowledge of food hygiene, proper storage and preparation of food, and reduced pollution. The Greenlandic Board of Food and Environment also recommends the consumption of traditional food, especially fish, land mammals and fresh local food products such as berries, seaweed, herbs and vegetables. To reduce exposure to contaminants that already exist in the environment, it recommends replacing those food items that are highly contaminated by food options that are low in contaminants, such as certain fish and terrestrial mammals. Intake of all traditional foods after reproductive age is not considered a health issue. Pregnant and nursing women and young people/children are advised to be cautious about eating polar bear, toothed whales, seabirds and aged seals. Communication to pregnant women is integrated within educational programs for parents and information material for this group. It is recommended that the Greenlandic Board of Food and Environment's ten dietary points are followed (Bjerregaard and Mulvad, 2012). These were recently relaunched by Paarisa, which is the Health Promotion section from the Department of Health and Social Affairs (Government of Greenland, 2020). Paarisa coordinates preventive efforts, promotes common responsibility to contribute to a positive development in society, and works to strengthen cooperation with the municipalities through interdisciplinary initiatives.

In addition, and as already described in Chapter 2 (see Section 2.3.2), to aid in dissemination of knowledge and use of local food in Greenland, 'NERISA - an Arctic food cluster' was established in 2019. NERISA members include over 40 different companies/public institutions.

6.2.4 Iceland

The Icelandic Directorate of Health provides general advice on nutrition on its website (Icelandic Directorate of Health, 2020), promoting consumption of vegetables, fruit, fish and whole grains; a Facebook site is also provided. Detailed information and educational material is available for pregnant women, children/young people, adults and older people. The educational material can be used in schools, and by health institutions, companies and the general public.

As of 2010, health messages have been displayed on milk cartons, including messages to promote regular exercise, good nutrition, mental health, sleep and safe use of the internet.

In terms of nutritional advice, the Nutrition Council (Directorate of Health) recommends eating fish at least twice per week. In 2012, a consumption advisory "due to the presence of harmful substances" was issued for pregnant women, nursing mothers and children below 7 years of age. This advisory was updated in 2015 and 2018. The 2018 pamphlet states (Icelandic Directorate of Health, 2018; translation into English from Icelandic): "Raw fish of any species should be avoided during pregnancy due to bacteria (*Listeria monocytogenes*), which the fish might contain. Also, keep in mind that some marine products may contain contaminants (e.g. heavy metals and persistent organic compounds, such as PCBs) that pregnant and breastfeeding women and women planning pregnancy should avoid. PCBs can build up in liver and fat of some fish species and marine mammals, but these contaminants have been removed from cod liver oil. Mercury is also a contaminant that should be avoided, since it may have negative effects on fetal development and young children. It can be found at high levels in large predatory fish (tuna, big halibut, orange roughy and swordfish), whale meat and eggs of marine birds. For more information, consult the table on foods to avoid during pregnancy."

The table in question gives the following advice on food intake to avoid contaminant exposure: "Avoid during pregnancy: Cured fish, Cold-smoked fish, Sushi containing uncooked fish, Pickled whale, Cod liver, Shark, Swordfish, Large halibut (>1.8 m or 60 kg), Fulmar, Fulmar eggs", "Eat no more than one serving a week: Tuna fish steak, Orange roughy", "Eat no more than two servings a week: Canned tuna, Guillemot eggs, Minke whale meat".

6.2.5 Faroe Islands

The risk communication chapters in the two previous AMAP human health assessment reports (Odland et al., 2009; Krümmel and Gilman et al., 2015) reported on risk communication activities in the Faroe Islands, to avoid duplication that information is not repeated here. It should be noted that particularly due to the wide coverage, as well as continuous and clear messaging from a trusted source (Chief Medical Officer), Faroese risk communication has been viewed as successful. Although mercury concentrations in pilot whales (the main source of contaminants for the Faroese population) have been increasing, mercury levels in the Faroese people have declined significantly (Krümmel and Gilman et al., 2015). However, as pointed out by the Chief Medical Officer, this success came at the cost of loss of cultural identity – a price that not all Faroese are willing to pay, as was evident in the film *The Islands and the Whales*.

Risk communication is unlikely to be successful if undertaken by other (non-trusted) sources that may have different underlying reasons for communicating. In January 2017, a campaign was launched in the Faroe Islands by an Anglo-Faroese not-for-profit organization, Grindahvalur. The organization issued a press release, erected a large billboard advertisement, produced a film and a website, and sent a pamphlet to every Faroese household (Figure 6.6). The material (reviewed by the Chief Medical Officer for accuracy) warned people not to consume pilot whale and recommended eating more fish. However, due to the nature and source of the communication, the Faroese may regard it not as health advice which aims to protect the people, but rather as a means to protect pilot whales from the hunt that is often widely and publicly criticized globally. Since many Faroese people still view the pilot whale hunt as an important part of their culture, which is not understood and is often condemned by outsiders, the messaging by Grindahvalur runs the risk of not being trusted and may even achieve the opposite of what was intended (Weihe pers. comm., 2018).

Figure 6.6 Billboard and pamphlet warning about pilot whale consumption in the Faroe Islands, as produced by the not-for-profit organization, Grindahvalur.

6.2.6 Sweden

6.2.6.1 Dietary advice on fish consumption due to methylmercury or organic pollutants

The Swedish Food Agency provides advice on fish consumption, especially for pregnant and lactating women (due to methylmercury and chlorinated organic pollutants) as well as children and women of childbearing age (due to chlorinated organic pollutants). For other consumers, fish species higher in environmental pollutants are recommended to be limited to once a week at most (Table 6.1).

The Swedish Food Agency advises the general population and particular at-risk groups that fish is beneficial and should be consumed two or three times per week. Yet, the most evident health problem related to fish consumption in Sweden is that only three out of ten people are achieving this (Amcoff et al., 2012) and so a large proportion of the population does not consume enough of the beneficial nutrients present in fish.

The European Commission has established maximum levels for dioxins, dioxin-like PCBs and nondioxin-like PCBs in foodstuffs, regulating what can be placed on the market. Sweden has been granted exemptions from the maximum levels in order to place fish from the Baltic region on the market within Sweden and other member states with similar exemptions (European Commission, 2011). As part of this regulation, the Swedish Food Agency is obliged to monitor levels of dioxins in fish from the Baltic region and to inform consumers of dietary guidelines and potential risks. The communication strategy is determined by the Swedish Food Agency based on what is considered most effective at the time, and is placing an increasing emphasis on digital and social media. Communication efforts are usually increased during times of the year when Baltic fish are consumed in larger amounts, such as the season for eating fermented Baltic herring, or during certain holidays.

The Swedish Food Agency regularly performs surveys to monitor the awareness of the dietary guidelines. They indicate that about 90% of respondents are aware that there are dietary guidelines due to environmental contaminants in fish. Knowledge among parents of young children that the dietary guidelines concern children increased from 19% in 2010 to 60% in 2016 (Orbe and Eriksson Almgren, 2016).

In a study performed in the period 2015–2016 on pregnant women in Arctic countries, all 51 pregnant women from northern Sweden involved in the study were aware of the dietary recommendation on fish consumption (Wennberg et al., 2018).

6.2.6.2 Dietary advice on game meat due to risk of lead contamination

The Swedish Food Agency gives advice to hunters on the handling of game meat shot with lead bullets and restricts consumption of game meat from close to and up to 10 cm from the wound channel if shot with lead ammunition. These parts of the animal are at risk of lead contamination (Bjerselius et al., 2014). The following is a summary of advice provided to hunters and consumers: "The wound channel after the bullet (and affected meat) and in addition another ten cm unaffected meat around the wound should be discarded when the meat is handled. This should not be eaten by humans or animals. Also, for game shot with lead pellets, affected meat needs to be eliminated. By using other ammunition than lead bullets the risk of lead contamination from the meat is avoided". Compliance with this advice on game meat has not been evaluated.

Table 6.1 Dietary advice on fish consumption in Sweden as issued by the Swedish Food Agency.

Pollutant	Fish species restricted to two or three times per year in risk groups and once a week in other consumers	Risk groups
Methylmercury	Perch, pike, pikeperch, burbot, fresh tuna, swordfish, halibut, shark, ray	Pregnant and lactating women, women planning to get pregnant
Chlorinated organic pollutants (dioxins, PCBs)	Salmon, trout, herring from the Baltic Sea, including connecting rivers, Salmon, trout and whitefish from Lake Vänern and Vättern, char from Lake Vättern	Women of fertile age and children

6.2.6.3 Dietary advice on rice consumption due to arsenic

Since 2015, the Swedish Food Agency has given dietary advice on the consumption of rice and rice products due to arsenic content. Rice is not produced in Sweden, so arsenic in rice is not necessarily a national problem for Sweden but is likely to be a global issue. Dietary recommendations on rice consumption due to high levels of arsenic seem not to be issued in the other (Arctic) countries described in this chapter. The advice is summarized as follows: adults should not eat rice or rice products every day and children should not eat rice or rice products more than four times per week (Swedish Food Agency, 2015).

6.2.6.4 Dietary advice to reduce cadmium from food

Cadmium is abundant in many foods. However, some foods contain particularly high amounts of cadmium. Information is available on the webpage of the Swedish Food Agency (Swedish Food Agency, 2020). There it is stated that the following food items should be avoided completely due to high cadmium concentrations: kidney from game meat; brown meat from crab; and the wild mushrooms, prince cap and horse mushroom. In addition, children younger than 13 years in age should avoid kidney and liver from both wild and domestic animals (liver paté is not included in the restriction).

6.2.7 Finland

The website of the Finnish Food Authority (known as 'Evira' before January 2019) contains general information on food safety and dietary recommendations. It advises that fish should be eaten at least twice per week, and that fish species should be varied in the diet. Generally, fish consumption is encouraged for its source of healthy fatty acids (particularly omega-3 fatty acids), vitamins (especially vitamin D), minerals (such as iodine) and protein. The website includes specific recommendations on the safe use of fish (Finnish Food Authority, 2019) and gives a link to a brochure that can be downloaded (Evira, 2007). A fish consumption advisory is given for fish caught in the Baltic Sea, particularly the Gulf of Bothnia and Gulf of Finland (due to possibly higher than normal levels of dioxins and PCBs), as well as predatory fish, particularly pike caught in inland waters and/or in the sea (due to higher than normal levels of methylmercury). Exemptions (consumption restrictions) are as follows: children, young people and persons of fertile age may not eat large herring which uncleaned are longer than 17 cm, or alternatively salmon or trout caught in the Baltic Sea more often than once or twice per month; children, young people and persons of fertile age may not eat pike caught in a lake or in the sea more often than once or twice per month; pregnant women and nursing mothers should not eat pike at all due to the mercury accumulated in pike; and people who eat fish from inland waters on a daily basis are advised to reduce their consumption of other predatory fish that accumulate mercury (these include large perch, pike perch and burbot).

Fish preparation advice is given to reduce contaminants, for example, remove skin before cooking (which reduces dioxins/PCBs by up to a third) or eat smaller fish (uncleaned herring less than 17 cm long) which have bioaccumulated fewer contaminants.

6.3 Risk communication evaluation

As outlined in Section 6.1, the 2015 human health assessment (AMAP, 2015) noted little information on the effectiveness of risk communication. However, information from effectiveness evaluation studies has become accessible in the past few years, especially for the Canadian Arctic, such as a recently accessible report that summarized evaluation exercises on communicating contaminant risk in the four Canadian Inuit regions (Desiré-Tesar et al., 2010). The authors stressed the need for answers to key questions in order to measure the success of a given communication: Did the audience receive the message clearly? What actions did the audience take as a result of receiving the message? What influenced whether the audience received the message? What influenced audience comprehension of the message? The report listed several important areas of impact:

- *Audience segmentation*: Messages need to be developed according to the audiences targeted.
- *Feedback and message revision*: Feedback is needed to evaluate whether the audience has received and understood the message. It was found that directed approaches to soliciting feedback (in focus groups and consultations) were most successful, and that sufficient time is needed to develop and revise a message.
- *Regional institutional capacity*: This was defined as the capacity of the sender group to formulate and carry out communication activities. A formally mandated committee with communications expertise (that can integrate a range of technical and socio-cultural experts) was stated as important, as was having a permanent body within the region. This body would collect and store contaminant and public health information and make it accessible to researchers and health workers. It was also noted that, particularly in the North, this is met by a capacity issue and the difficulty of recruiting and/or retaining regional expertise.
- *Reaching study participants*: In some cases, community meetings were used to reach the audience. In other cases, personal information packages and/or an appointment with a doctor were found to be more successful. It is imperative for the sender of the message to consider which strategy to reach participants will be most effective in a given community setting. Use of the local (Indigenous) language was also found to be very important.
- *Trust*: Three of the four case studies in the Inuit regions emphasized the importance of a trusted messenger in successful communication, as well as placing the messenger in a trusted institutional context. Having Indigenous messengers was found to be very important. However, it was pointed out that if the message to Inuit was to eat less of a certain traditional food item, then most Inuit messengers would not be comfortable with delivering such

a message because it may be construed as being critical of the Inuit lifestyle. The importance of message conformity was also highlighted. If two trusted messengers differed substantially in the content of their message, this can result in confusion (such as the case where the international message was that 'Inuit are being poisoned', while the national/regional messages stated that country foods are safe to eat; AMAP, 2015). Messengers need to be aware of these added difficulties.

- *Persistence of communication*: In at least two of the case studies, there was evidence that the information given out did not persist. A single event may fail to transmit a persistent message, so repeating a message is important. Multiple channels would also increase the likelihood of a message getting through.
- *Counter-argument and inoculation effects*: It is difficult to successfully transmit a message that conflicts with local values and cultural importance. There is significant cultural resistance in northern regions to accepting a message on risk from contaminants in traditional country foods. This may be intensified by weak argumentation that opens room for counter arguing: "Inoculation theory suggests that change agents who do not develop and provide compelling justifications that overcome the potential or prevailing counterarguments, or who fail to demonstrate the validity of those justifications, end up inoculating recipients and increasing their immunity to change" (Ford et al., 2008). This may have happened in three of the four case studies.

In another risk communication evaluation effort, a project was conducted to assess the effectiveness of the communication as part of the Nunavik Child Development Study (see Chapter 1, Box 1.2) and the results are currently being analyzed. Preliminary results show that while most pregnant women (almost 80%) were aware of the benefits of country foods, only 36% had heard the message that pregnant women or women of childbearing age should reduce their consumption of beluga meat, and only 16% of the women knew that hunters should avoid the use of lead-shot ammunition for hunting (Lemire et al., 2021).

Another comprehensive risk perception and message evaluation study was carried out following the Inuit Health Survey contaminants communication in Nunavut (Furgal and Boyd, 2014). The Inuit Health Survey was conducted in Nunavut in 2007–2008, and gathered information on key health issues, including contaminant exposure (Furgal and Boyd, 2014; AMAP, 2015). Results and key health messages were released to the Nunavut public in June 2012. The messages highlighted the benefits of country foods and recommended that they should be eaten. However, they also stated that women of childbearing age should avoid eating ringed seal liver due to its high mercury content and should instead eat ringed seal meat (AMAP, 2015). The Government of Nunavut Department of Health is in the process of reviewing guidance related to ringed seal liver and overall mercury levels in country food (Caughey pers. comm., 2019).

During winter 2013, 545 residents of three communities in Nunavut were asked about their food consumption, their awareness of key messages from the Nunavut Health Survey, and their views on contaminants in the environment and country foods (Furgal and Boyd, 2014). Over 95% of participants reported that they consumed country foods, with more than 60% preferring a mix of country foods and store-bought foods. With regard to messages from the Inuit Health Survey, Furgal and Boyd (2014) reported:

- The majority of participants (around 60%) stated that they had <u>not</u> heard that women of childbearing age should avoid eating ringed seal liver. However, the percentages in the three communities varied between 50%, 60%, and over 80% of respondents who did <u>not</u> hear that message.
- The majority of participants (around 60%) stated that they <u>had heard</u> that ringed seal meat continues to be a healthy option. There were again differences between the three communities: 30% in one community versus over 60% in the other two communities that <u>had heard</u> the message.
- A large majority (around 80%) of respondents <u>had heard</u> about the benefits of country foods with regard to physical health, as well as with regard to cultural and spiritual benefits.
- The majority (around 70%) of respondents did <u>not</u> have any concerns about the quality or safety of their country foods, and had <u>not</u> heard about contaminants in the environment, or in country foods (around 60%, respectively).
- Accordingly, the majority of respondents (around 70%) reported that they had <u>not</u> changed their eating habits since hearing about contamination in country foods.

In terms of information sources, 'friends or family' were among the top three sources in all communities. Other preferred sources included radio, healthcare providers, television, and newspapers, with slight differences within the three communities.

Risk communication evaluation work has been conducted as part of the larger human biomonitoring study in the Dehcho and Sahtú regions of the NWT, Canada (Ratelle 2018a,b). Participants were invited to complete a Health Messages Survey on health and risk communication for contaminants, with a focus on mercury in fish and cadmium in moose (Ratelle et al., 2019). Prior to this study, the level of awareness, perception and understanding of these consumption notices, as well as their impact on behavior, in the NWT was unknown.

The survey took place between January 2016 and March 2018 in six NWT communities, three in the Dehcho and three in the Sahtú, with 87 respondents. It was created using experience with the previously described surveys in Nunavik and Nunavut as part of the Inuit Health Survey. The Health Messages Survey was adapted to the needs of the NWT biomonitoring project such that the questions would be appropriate to the regions of the NWT taking part in the larger study. The survey comprised four sections, covering country food consumption patterns and preferences; awareness of consumption notices and health messages; risk perception of contaminants and changes in food practices based on messaging; and communication preferences. The objective of each section was to gather data on attitude, behavior, and opinion regarding health messages, and consumption notices regarding country foods and contaminants. The survey examined how participants currently

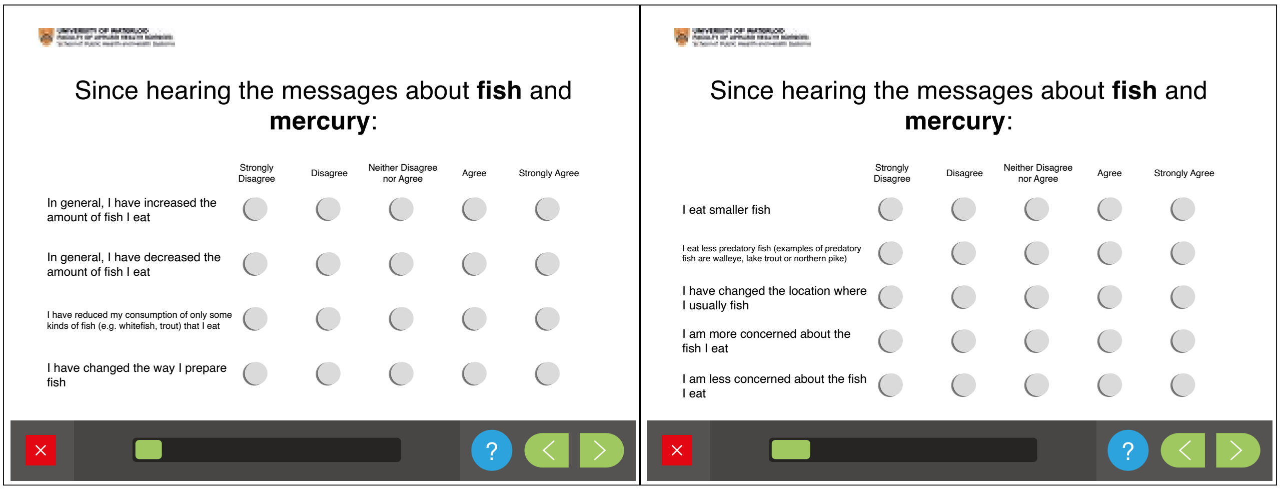


Figure 6.7 Screenshot of Health Messages Survey question.

receive health messages on country foods and contaminants, how people usually hear about consumption notices and other information on health, foods and/or contaminants, and which health message communicators are most trusted. The surveys were completed during the larger human biomonitoring clinics across the Dehcho and Sahtú regions. At the clinics, participants were invited to participate in several project components (hair, urine, and blood sampling, and three surveys); one of the three surveys was the Health Messages Survey (Figure 6.7).

Participants indicated a high consumption of country foods (99%), with 38% who indicated a preference to eat only country foods, rather than store-bought or a mix of both. Ninety percent of respondents indicated that they had heard or seen the message that "country foods can provide a significant variety and amount of nutrients" and 70% of respondents indicated that they had heard or seen messages about fish that had high levels of mercury. When asked, "Since hearing the messages about fish and mercury", respondents reported that they had: decreased the amount of fish they ate (34%), changed the location where they usually fish (20%), and changed the way they prepared fish (15%). Also, since hearing these messages, 42% of respondents reported that they were more concerned about the fish that they eat, and the quality of the country foods they consume. Respondents who said yes to the statement "Since hearing the messages about fish and mercury, I have decreased the amount of fish I eat" had a statistically significant association with lower mercury concentration in hair (mean 1.01 vs 0.49 µg/g; p=0.04) but not in blood (mean 1.24 vs 0.36 µg/g; p=0.15). While this was the only statistically significant association found, probably due to the small sample size and low statistical power, it is more important to note that average hair mercury levels in those who reported changing where they harvested fish were 2.6-fold lower than those that had not made that change. Similarly, those that decreased their overall fish consumption had mercury levels 2.0-fold lower than those that had not.

Mercury was the leading contaminant of concern among participants. Other contaminant concerns for participants included chlorine in drinking water, lead, indoor air quality, antibiotics in meat, asbestos, uranium, radon, PCBs, pesticides, and other heavy metals. When asked, "Which other items do you think may impact the amount of contaminants you are exposed to?", the most reported response was 'water'.

Participants were asked about trust when receiving information about contaminants in the environment and country foods using a five-point scale from "trust a lot" to "do not trust at all". Doctors were trusted the most, with over half of the respondents (51%) trusting them a lot, followed by friends or relatives (45%), elders (44%), university researchers (43%), and other health workers (43%). Federal government and social media were some of the least-trusted information sources with 8% and 9%, respectively, of respondents not trusting these sources at all, and only 16% trusted these sources a lot. In line with these results, most respondents reported normally receiving their health information from friends or relatives (62%), elders (57%), other health workers (nurses, etc.) (56%), and doctors (53%). University researchers were reported as sources of health information by only 25% of respondents, while they were one of the most trusted sources. Although reported to be less well trusted, participants also reported receiving health information via local radio (46%), social media (44%) and from the NWT government (43%).

The results of the Health Messages Survey have been beneficial in providing baseline data on the level of awareness, perception and understanding of consumption notices and contaminants in the NWT. The survey also provided information as to where participants currently get information regarding contaminants and who they trust as their source for this information.

While not solely focused on the Arctic, a literature review on communicating environmental health risks with Indigenous populations summarized findings from 13 articles and extracted factors influencing effective communication with Indigenous populations (Boyd and Furgal, 2019). The importance of having two-way communication between researchers and community members was noted, and that the messages need to be understandable and clear. It was pointed out that there is often no Indigenous term for a common English description or hazard (for example, the Inuit language has no term for chemical contaminants). Studies also stated that messages should be tailored to individual regions or populations, should take into account socio-demographic factors, and should be culturally appropriate. For example, risk reduction strategies may not be followed because they are seen to be threatening to cultural practices or beliefs, and/or would adversely affect traditional lifestyles. Communication strategies were found to be most successful if the target community or population was involved in their design and delivery. The difficulty associated with risk messages reaching specific target groups (such as women of childbearing age) was pointed out in several studies (Boyd and Furgal, 2019).

Some non-Arctic research on risk communication involving pregnant women has reported success with very directed communication efforts. For example, a study in Denmark evaluated the success of dietary advice on seafood consumption for pregnant women (Kirk et al., 2017). A total of 146 women were recruited in connection with prenatal screening and were asked to fill out a questionnaire, including questions about their seafood consumption. Participating women received both oral and written dietary advice, focusing on the benefits of eating fish, and how to prevent mercury exposure (particularly from predatory fish). Hair samples were taken and measured for mercury exposure of the women. A follow-up study took place around four months later and 59% of women sent another hair sample and completed a questionnaire. The authors found that, while reported total seafood consumption did not change according to the completed questionnaires, average mercury concentrations in participating women decreased significantly (by 21%) from enrollment to follow-up (Kirk et al., 2017). They concluded that "focused dietary advice coupled with a hair-mercury analysis can motivate pregnant women to adjust their seafood diets to significantly lower their methylmercury exposure" (Kirk et al., 2017). A similar study of frequent fish consumers (men and women) in the USA also found significant reductions in hair-mercury levels after an initial analysis, followed by information on how to reduce mercury exposure when levels were found to be high, and retesting four years later (Knobeloch et al., 2011). Another randomized controlled trial which focused on promoting fish consumption in pregnant women in Boston, USA found that fish consumption (as reported by participants) increased, while measured mercury levels were unchanged (Oken et al., 2013). However, measured levels of docosahexaenoic acid (DHA), an important polyunsaturated fatty acid that can be obtained from certain fish, did not increase in the plasma of women who reported higher fish consumption. It was not clear if this was related to measurement issues or whether there was a reporting bias due to the women becoming aware of the expectation that they should eat more beneficial fish (Oken et al., 2013).

6.4 Use of social media in risk communication

Several types of social media can be used in risk communication (Table 6.2). Social media has been widely acknowledged as a promising and useful tool in risk communication, although documented experience in this area is scarce (AMAP, 2015; Regan et al., 2016; Wall and Chen, 2018).

Although social media use (particularly Facebook) is popular in many Arctic regions, few examples exist of where and how it has been employed in risk communication there. One example of using YouTube capsules for health messages in Canada was described by AMAP (2015), but the number of views is low in some cases, and the effectiveness of this messaging has not yet been assessed. While several advantages of social media use in risk communication have been reported by researchers, their usefulness and applicability in the Arctic have not been tested and/or reported. Possible advantages include:

Table 6.2 Types of social media used for risk communication (adapted from Wendling et al., 2013).

Type of social media	Example
Social networking	Facebook, Myspace, Friendster
Content sharing	YouTube, Flickr, Vimeo
Collaborative knowledge-sharing social media	Wikis, Forums, Message boards, Podcasts
Blogging and microblogging	Blogger, Worldpress, Tumblr, Twitter

- Behavioral changes are more easily achieved through personalized communication, and social media can be a powerful tool in this area since messages can be easily adapted to different categories of the target population (Wendling et al., 2013).
- Social media can be used to raise community involvement and awareness of risks related to specific geographical areas (Wendling et al., 2013).
- The style of communication can be different, more informal and conversational, which can be positive for audiences that are not receptive to very official informational messages (Wendling et al., 2013).
- Social media can be used to prevent false medical advice from circulating, and to clarify rumors while disseminating good tips (Wendling et al., 2013).
- The more citizens can engage with their government online, the more likely that they will develop trust. Social media may be an effective tool for organizations to reach out to audiences directly and build relationships. This interactive contact may help to create a personal connection with users, facilitate positive attitudes towards the messenger, and could improve transparency and trust in public authorities (Yang and Kang, 2009; Wendling et al., 2013; Kelly, 2014).
- Messages can be disseminated quickly to a large or selective audience using multiple channels, and there is better control of the message that is originally disseminated/posted (Wendling et al., 2013; AMAP, 2015; Regan et al., 2016; Wall and Chen, 2018).
- Use of social media analytics can provide information about the individuals using it (Wall and Chen, 2018).
- Using two-way communication tools makes it possible to know if the message has reached the recipient, as well as allowing the messenger to determine quickly whether the recipient has understood the message (Wendling et al., 2013).

While there is real merit in using social media to facilitate two-way risk communication, it is currently most often used as a one-way communication channel. Several researchers have said that failing to use this valuable feature of social media would be a missed opportunity (Regan et al., 2016; Wall and Chen, 2018).

They also recommend that a social media presence should be established during non-emergency periods and a community of followers needs to be developed early on, such that credibility is already established when a crisis involving heightened consumer anxiety occurs (Wendling et al., 2013; Cool et al., 2015; Wall and Chen, 2018). On the other hand, social media is known to bear certain risks when it comes to controlling the flow of messaging, as it enhances the likelihood of distributing inaccurate, unverified, or biased information. This can cause alarm which can spread rapidly, particularly in unverified and unregulated social media networks (Wendling et al., 2013; Regan et al., 2016). How the challenge of spreading fear and false information on the internet can be effectively managed in a monitored social media setting is described using the following example from Alaska:

The Alaska Native Tribal Health Consortium established the Center for Climate and Health in 2009 to help describe connections between climate change, environmental impacts, and health effects, and in 2012 the 'Local Environmental Observer (LEO)' Network was launched. LEO is web-based technology that is part social network, part observation tool and part publishing platform. It is designed to help residents in rural communities share and document information about the environmental impacts they are experiencing. Many of the posts are about food safety, such as conditions in harvested plants or wild game. LEO Network staff review each post and often connect the observers by email with topic experts who can provide a consultation. Upon review and editorial approval, the completed observation is published to a member-access website (Brubaker et al., 2017).

A post entitled *Bacterial Infection in Broad Whitefish (Coregonus nasus)* illustrates the LEO Network process. The observation from Nuiqsut, Alaska, was shared by a resident who caught 16 sickly whitefish while ice fishing. The geo- and time-coded post, images and description were submitted to the LEO Network platform. The observation was then forwarded to a fish pathologist for feedback. The observer and the consultant were both credited as co-authors and the completed post was published on the LEO Network platform. The post has been added to an online archive that is searchable by the name of the authors, the location by community and other descriptive categories. Every LEO Network member has their own profile page and map, as does every community, which creates an opportunity to generate a timeline of events that can help describe climate change vulnerabilities and contribute to surveillance of emerging regional threats.

Today the LEO Network has a full-time development team, and the system is constantly being updated and improved. But in 2012, it was a small regional project that used Google Maps as a central report platform and Survey Monkey as a mechanism to post local observations. Participants were a small group of tribal environmental managers, agency officials and scientists. LEO Network staff would cut and paste photos and text to create posts in Google Maps and participants could access the system openly. The problem with open projects of this type is that they are searchable and accessible through web browsers. The following experience caused the LEO Network to develop their own independent platform so that security could be enhanced and the rights and use of content could be protected.

In August 2013, an observation was made by a resident of Hydaburg, Alaska. The title was *Growth in Coho Salmon*. The observer reported strange growths in the flesh of silver salmon. "We were fishing for cohos (silver salmon) at the mouth of the Hydaburg River with line and reel. I caught about thirty fish. Most were fine but eight were filled up inside with strange growths that were either white or pink in color." He later identified the growths as henneguya, a relatively common parasite found in Alaska salmon. The observation was shared with the State Fish Pathology Lab and the post was published to the LEO Network (Holter and Meyers, 2013).

At some point following publication, a conspiracy blogger found the LEO post via an internet search, stole images and certain parts of the story and used them to create an alternative story on his blog site. The creation of 'alternative stories' has become common practice in the blogosphere. The blogger attributed the cause of the growths to Fukushima radiation, which was a total fabrication and contrary to anything in the LEO Post. Even though it was on an obscure blog site, the story was searchable and raised concerns and confusion among Alaska fishermen and residents about food safety.

This data misappropriation illustrated the need to protect the platform from open access and search engines. The LEO Network revised the system to member access only and placed all detailed content behind a firewall. This meant that search engines could not find images, text or the names of LEO Network members. The event also spurred LEO to develop strict publishing criteria and member use rules. The LEO Network strives for a safe, respectful and professional space for discussion of the observational content. For an observation to be published on the LEO Network, an observation must meet certain criteria:

- *Specific*: The observation or entry is an event that is time- and location-specific.
- *Witnessed*: The event is witnessed by the observer, or submitted with a witness as a co-author.
- *Significant*: The observation is categorized as either extreme, unusual or significant.
- *Complete*: The observation or entry includes all the basic content needed – title, location, time, description, author and credits.
- *Appropriate*: The content is professional and for the purpose of education, and is not political or to further personal agendas.
- *Respectful*: The content is respectful of personal information, privacy and the general membership.

The issue of data misappropriation has not recurred since these controls were implemented. The LEO Network now has over 1000 observations in the system on a wide range of topics. The platform is available in 15 languages including Yup'ik and Skolt Saami, and membership exceeds 3000 people in over 50 countries. The LEO Network continues to grow and develop, with a focus on the needs of local members and providing an effective tool for sharing knowledge and documenting the impacts of climate and other drivers of environmental change.

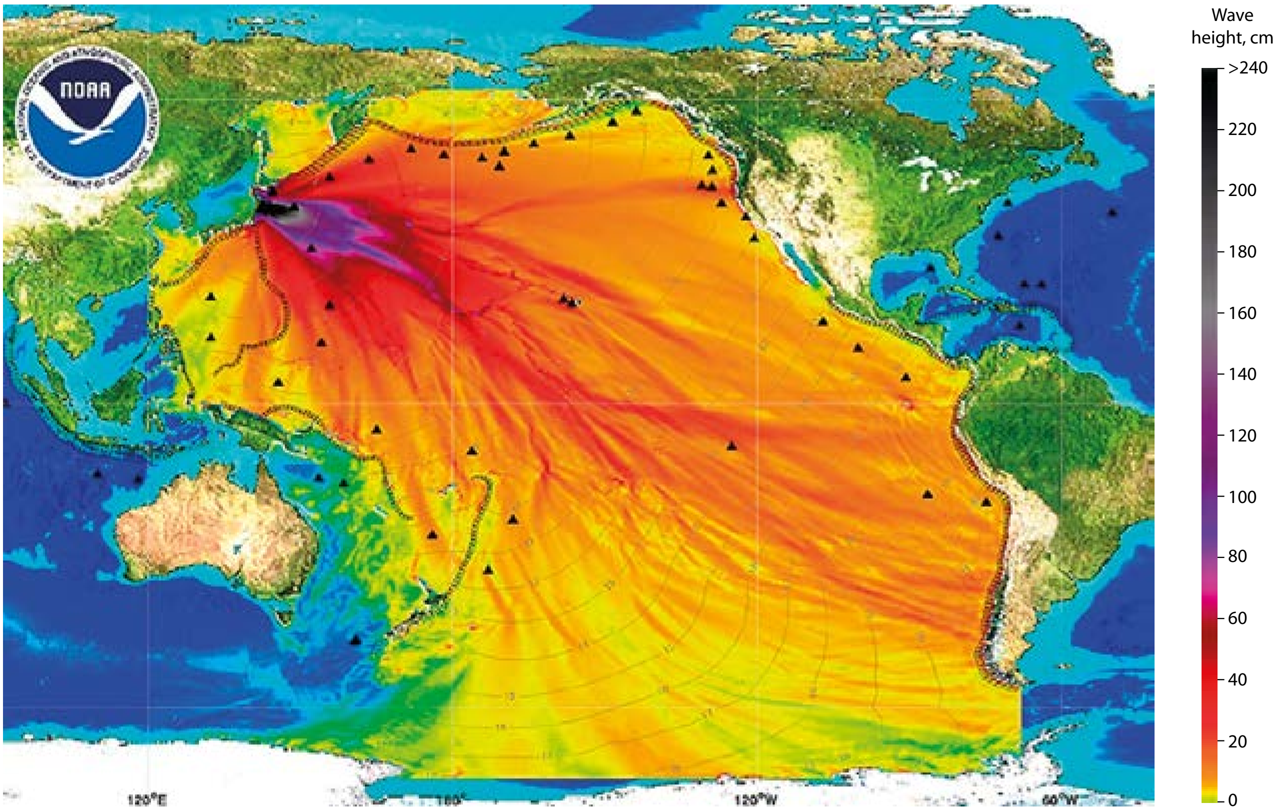


Figure 6.8 Alleged spread of radiation after the Fukushima reactor disaster (Jacobs, 2018). In reality, the map shows wave height distribution of the tsunami that hit Japan after the earthquake in 2011, the cause of the Fukushima nuclear incident. Note the legend which shows the scale of wave heights in cm.

Although risk communication via social media is not without challenges, it is acknowledged that failure to provide information via social media can also be problematic, because "even silence conveys a message and may not be an option anymore" (Wendling et al., 2013). It has also been pointed out that "failure to communicate creates a vacuum for the poison" (Regan et al., 2016) because somebody else will fill the gap, which leaves more room for rumors or 'alternative facts' (Wall and Chen, 2018).

Recommendations are given in the literature to aid the use of social media in risk communication:

- To deal with misinformation online, simply increasing the amount of reliable information is not enough. It is instead suggested to find ways of highlighting trustworthy sites and directing target audiences to those sites (Regan et al., 2016).
- Stick to facts, be as objective as possible, and clearly label information from official channels (Wendling et al., 2013).
- Develop guidelines and a strategy for risk communication, providing precise rules and recommendations on how to engage in social media, and update the strategy on a regular basis because the social media landscape is continually changing (Wendling et al., 2013).
- Open-access social media sites cannot be controlled but respectful correction of inaccurate information can stop the spread of rumors (Wendling et al., 2013).
- Online tools can be used that provide analytics which can help determine the efficacy of social media communication (Kelly, 2014).
- Appropriate resources need to be in place to monitor and direct the flow of online communication to achieve communication objectives (Kelly, 2014).

6.5 From global to regional and local: implications of international communication

Similar to the spread of information on social media, the global nature of the internet presents both opportunities and challenges in disseminating complex and technical material, such as that associated with contaminants (AMAP, 2015; Boyd et al., 2019b). Mass media, including online newspapers, are used as an information source by the public for hazards and risks that are poorly known and/or understood by the general population (Boyd et al., 2019b). This can be problematic when information intended for one audience reaches a different audience for which the information does not apply (AMAP, 2015). As already described in Section 6.4, information may also be taken from a reputable source and misrepresented. Another example involves an online article featuring a Fukushima disaster communication (Jacobs, 2018). Following a major earthquake off Japan, a 15-m tsunami disabled the power supply and cooling of three Fukushima Daiichi reactors, causing a major nuclear incident on 11 March 2011. All three cores largely melted in the first three days. A map generated by the US National Oceanic and Atmospheric Administration (NOAA) to show wave height distribution for the tsunami caused by the earthquake (Figure 6.8) was misused to spread fear of radiation. Jacobs (2018) reported that according to false information on alarmist websites, the NOAA map showed

Box 6.2 Articles from North American media outlets on marine mammal risk from COVID-19

USA Today	*Could COVID-19 spread to wildlife in the Arctic?* 14 October 2020, USA Today (2020)
Fox News, USA	*Whales and other wildlife species could get COVID-19: 'Potential cascading impacts' around the world* 19 October 2020, Fox News (2020)
Toronto Star, Canada	*Narwhals could be at high risk of catching COVID-19: researcher* 29 October 2020, Toronto Star (2020)
Global News, Canada	*Large cruise ship ban in Canadian waters extended until at least February* (see article from 29 October 2020 raising issues on sewage discharges from ships and potential for COVID transmission to marine wildlife) 30 October 2020, Global News (2020)
National Observer, Canada	*Whales and other marine mammals susceptible to COVID-19 through wastewater: study* 9 November 2020, National Observer (2020)

radiation transported throughout the Pacific Ocean, impacting the whole west coast of the American continent. The alarmist and false news about radioactivity hitting the west coast of North America also reached local residents and caused concern about the safety of marine foods in the Inuit populations of western Canada (O'Hara pers. comm., 2019).

The way in which information in original online articles is framed can also significantly affect how a message is received (Boyd et al., 2019b). For example, a positive tone in an article providing direction on how to avoid a hazard is likely to be more effective than one with a negative tone (Boyd et al., 2019b).

The spread of negative, fear-inducing information has been particularly problematic during recent times, when uncertainties associated with the COVID-19 pandemic have caused anxiety around the globe, particularly among Indigenous Peoples in the Arctic (see Chapter 1, Section 1.5). It can be assumed that many studies in the future will analyze the communication associated with the risk of spreading the disease and will contribute to establishing best practices. The following is but one example, which emerged from a live online event on 1 May 2020 (Wilson Centre, 2020), where three scientists were asked about emerging research on human-to-wildlife transmission of COVID-19. This was based on a (pre-peer review) computational study, where the theoretical susceptibility of COVID-19 infection for 410 animal species was modeled using a dataset of specific genetic sequences (this was later published: see Damas et al., 2020).

Examples highlighted during the online event included narwhal in the Arctic and gorillas in Africa, which could be at risk for contracting COVID-19 based on the likelihood of these species having receptors that can potentially bind the virus. One of the scientists involved in the research, who studies narwhal in northern Canada, speculated that one way the virus could reach the whales would be through fecal material in wastewater. While the online event intended to focus on theoretical transmission from humans to wildlife, questions later in the event turned to whether this could affect the subsistence hunt (specifically for narwhal) in the Arctic.

The discussion was picked up by Arctic printed media a week later, which focused on the high risk of narwhal and beluga for a coronavirus infection (Nunatsiaq News, 2020). It reported the researcher as saying that "Inuit subsistence hunters can safely consume the whales they capture", but also raised that "If whales are susceptible to SARS-CoV-2, it could have implications for subsistence hunting – from monitoring whale populations for illness to making sure the virus is not transmitted to hunters and those who consume the whales". Other researchers were quoted, talking about the general occurrence of new viruses in the Arctic, coupled with climate change effects, which could have "profound effects upon the health of animals and the people who depend upon them". The article raised some concern in Canadian Inuit regions and communities already thinly stretched in trying to cope with multiple health and economic implications related to COVID-19. As a result, and based on questions from regional Inuit hunters and trappers organizations with regard to safety of wildlife, Canadian government agencies and Inuit organizations formed a COVID-19 wildlife working group (including a task group on communication) to deal with questions and communication around COVID-19 and wildlife. More focused discussions with Inuit representative organizations will be necessary to provide detailed information around COVID-19 in traditional country foods and how to communicate such information to all affected people in the regions.

Overall, the communication involving the possible susceptibility of narwhal associated with the (at the time) pre-peer reviewed study led to extremely speculative questions around the health of narwhal and the safety of Inuit traditional foods. The online event was to a certain degree able to respond to concerns from the audience through a question and answer period. However, after it was picked up by the printed media, it unnecessarily raised concerns associated with the much-discussed health implications of COVID-19, at a time when anxiety was already high. Similar articles about Arctic marine mammal risk from COVID-19 went on to be published months later in USA Today, Fox News, the Toronto Star, Global News and the National Observer (all large North American media outlets – see Box 6.2), illustrating how wide the messaging can be from a single event/paper. This is another example of how international events far from the Arctic can have an impact at the regional to local level, with potentially negative consequences if concerns cannot be proactively addressed. It demonstrates the need to discuss Arctic health-related research results affecting Indigenous Peoples with regional Indigenous organizations and regional health officials ahead of time, and to answer any concerns that may arise before making results public.

6.6 Summary and conclusions

This chapter has provided new information on risk communication activities in several Arctic countries. Most of the risk communication information provided concerns fish or other marine biota and is based on mercury levels. Consumption guidelines based on other contaminants are also issued by some countries (such as Finland, Iceland, and Sweden). In most cases, specific dietary guidelines due to contaminants are available as part of general nutritional advice on the internet. It should be noted that, while there are many examples of risk communication with regard to Indigenous Peoples and traditional foods in Canada, there is a lack of information on risk communication specifically for Indigenous Peoples in other Arctic countries (for example, the Saami).

Risk communication experiences provided in this chapter highlight the importance of a trust relationship between all people involved in contaminants work and the communication of possible risks associated with contaminants in the traditional diet. Several authors have emphasized the importance of trust, which is difficult to build but easily damaged or destroyed (e.g., Wall and Chen, 2018; Boyd et al., 2019a).

Some results for measuring the effectiveness of risk communication have been provided. Wall and Chen (2018) pointed out that "the word 'risk' is naturally negative, and risk communication messages often relate to negative information, which may serve to increase consumers' anxiety and concern about food. […] Moving from the main focus being on 'risk communication' to a broader 'food information communication' might afford the opportunity for more positive messages to receive airtime". However, as outlined by Furgal and Boyd (2014), a majority of surveyed respondents in Nunavut were aware of messages on the benefits of traditional foods but only a minority had heard the risk messages. It therefore seems that a certain emphasis on health risks, or targeted communication is required to ensure retention of the message. Studies in other areas (Denmark, USA) found that targeted and personalized messaging was successful in reducing mercury exposure in pregnant women (Knobeloch et al., 2011; Kirk et al., 2017).

Generally, specific data on the evaluation of risk communication effectiveness in the Arctic is still limited to a few regions in Canada and a few other Arctic countries. For national dietary advice, only Sweden includes information about awareness regarding their dietary guidelines. More health communication and risk perception data are important in order to compare results to other regions and countries across the circumpolar Arctic. Data from multiple regions would help to establish whether or not the risk communication has been effective, and to determine best practices for researchers and governments that could be used and adapted based on region and/or community needs. These data also help to provide the information needed to enable more culturally appropriate and relevant contaminant health messages and consumption notices. For instance, risk communication evaluation data in the Northwest Territories in Canada have provided information on two regions where there is considerable trust in doctors, elders, family and friends, university researchers and other healthcare workers. These trusted sources should be used in combination with the preferred media for disseminating health messages. Evaluating the impact of combinations of medium and messenger for various health messages would help understand the optimal communication strategies for different communities. A priority for risk communication should be carefully planned communication strategies, built in partnership with communities, which promote country food consumption while lowering contaminant exposures to maintain and improve health and wellbeing in Arctic communities. It should be highlighted that equitable partnership approaches in research activities are well-suited to address many of the challenges outlined here, especially regarding capacity, resources, and trust (Schott et al., 2020). Holistic projects built on a 'co-production of knowledge approach' are a good example, as these bring together different knowledge systems (such as Indigenous Knowledge and science) while building collaborative and equitable partnerships (Behe and Daniel, 2018).

Similar to previous findings (AMAP, 2015), this chapter highlights issues associated with confusion or fear resulting from the spread of sensationalized or alarmist messages. In some cases, this can arise due to problems when receiving audiences of a single message are both local and global, where a message created for a specific target audience is being read by others. This can create misunderstandings (at a minimum), particularly if the different audiences do not share the same culture (Wendling et al., 2013; AMAP, 2015). It was also stated that a message that may be perceived as contradicting cultural values is unlikely to be accepted, and may be prone to counterarguments and 'inoculation effects', particularly if the message is delivered with weak argumentation and/or from a non-trusted source.

Information spread through the internet without verification and/or local confirmation can result in misinformation (which may lead to overamplification of the risks to public health), can create confusion, and can undermine the confidence of the receivers of the message (Wall and Chen, 2018). This has been illustrated using three examples: *Toxoplasma* in beluga (Section 6.2.2.3), the LEO Network (Section 6.4) and the Fukushima nuclear incident (Section 6.5). In the case of the LEO Network, it was successfully dealt with by adding a security layer to prevent misuse of information.

6.7 Recommendations

Many recommendations for better risk communication and key lessons learned have been provided, both in the published literature (including AMAP, 2015) and in experiences described in this chapter. These include:

- Risk messaging needs to be developed with members of the affected population, and ideally would be created by a diverse group that includes the necessary expertise and knowledge.
- Risk messaging needs to be customized to the intended audience(s) and must be culturally appropriate; there is no one-size-fits-all approach.
- Focused dietary advice coupled with hair-mercury analysis has been found to be successful for targeted vulnerable groups, such as pregnant women.
- Sufficient time should be allowed for the risk management and communication process.
- A trusted relationship between all involved is paramount.
- The information needs to be provided in an open, transparent and timely manner, and must be honest, accurate, consistent and understandable (non-scientific language; when possible and where necessary, Indigenous languages should be used).
- Risk communication strategies need to be developed for a series of communication events (in sustained, continuous communication), customized for different target audiences, and not delivered via a single event.
- Multiple channels should be used to reach the target audience.
- Follow-up on policy recommendations is required, as well as evaluation of the reception and awareness of the communication to ensure the success of the messages.
- Institutional capacity needs to be built to allow for sustained, regional expertise on technical and socio-cultural relevance. Ideally, this expertise would be situated in a permanent body that can store information and can readily provide advice for researchers, health workers and communities.

It should be noted that most of these recommendations are likely to be addressed automatically if the research is developed in a 'co-production of knowledge approach', and in a partnership with affected communities. Ultimately, experience has shown that communication of contaminant risk is a complex undertaking and not a sustainable solution to ensure low levels of contaminants in human populations. It is thus crucial that regulations to lower contaminant levels in the environment are implemented effectively.

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7. The Arctic in a global context

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Key findings

- *For reasons that include dietary change, a warming Arctic may not greatly change contaminant exposure. Current levels of contaminant exposure in Arctic residents and some parts of Europe may have little impact on child development outcome, according the results of the ArcRisk project. Fish consumption is the major source of mercury exposure in the European Arctic. It is difficult to link health outcomes to one specific contaminant because people are exposed to mixtures of a number of different contaminants.*
- *Exposure to legacy contaminants in Arctic residents is decreasing, although this shows regional variation. Long-term data for contaminants of emerging Arctic concern are not available in most regions. Migration from smaller communities to larger towns and cities is a growing trend in the circumpolar North, and is accompanied by changes in diet and a resulting decrease in contaminant exposure.*
- *There is growing awareness of the usefulness of the One Health paradigm as a means to improve the ability of residents, public health agencies, and wildlife resource managers to address existing environmental threats and recognize emerging threats at an early stage.*
- *There is a lack of knowledge about the health impacts of contaminants on wildlife, including a possible immunosuppressive effect, potentially resulting in a rise in active zoonotic infections in exposed wildlife, and increased risk to human consumers. Warming and permafrost thaw may influence both contaminant exposure and the spread of zoonotic infectious diseases. The growing trend in migration from smaller to larger communities and urban centers in the circumpolar North may be accompanied by changes in exposure to contaminants and zoonotic diseases.*
- *Epidemiological zoonotic / human disease models are needed, as well as new approaches to integrate existing and future data. The models should enable estimates of the risk and magnitude of human and wildlife health impacts, and changes in disease and contaminant exposure in response to different climate change scenarios.*
- *Multidisciplinary research is needed on critical issues, including lifetime contaminant accumulation, lifetime exposure to zoonotic pathogens, and health consequences for wildlife and human consumers.*
- *Many components of the One Health model require additional research, including research on contaminants, infectious diseases, drinking water and climate change.*

7.1 Introduction

The Arctic is an important component of the globe and reflects the impacts of climate warming, long-range contaminant transport, increased human activities, and existing and newly emerging infections (such as the COVID-19 pandemic). The Arctic has around seven million inhabitants, and about one million of these are Indigenous (Jungsberg, 2019; Young and Bjerregaard, 2019). Three-quarters of the Arctic population resides in settlements of more than 5000 people, with two-thirds living in permafrost regions (Jungsberg, 2019). This chapter describes the close connections between the Arctic and the rest of the world using two examples: *One Arctic, One Health*, a program developed by the Arctic Council; and *ArcRisk*, an EU-funded research project coordinated by the Arctic Monitoring and Assessment Programme (AMAP) Secretariat.

There are two human health sub-groups under the Arctic Council: the Arctic Human Health Expert Group (AHHEG) under the Arctic Council's Sustainable Development Working Group (SDWG) and the Human Health Assessment Group (HHAG) under AMAP. The HHAG was created almost immediately after AMAP was established because contaminants in the Arctic were clearly a threat to human health. The International Circumpolar Surveillance (ICS) program monitors infectious diseases in countries with Arctic regions and has been integrated into AHHEG in recognition of the key role of climate in the ecology of infectious disease pathogens, including zoonotic pathogens, in the Arctic. The ICS subsequently established the Climate Sensitive Infection Workgroup, which focuses on trends in existing zoonoses and the emergence of newly arriving zoonoses as ocean and air temperatures rise, and range extension carries southern wildlife species further north. The Conservation of Arctic Flora and Fauna (CAFF) Working Group is another of the initial Arctic Council programs and assesses plant and wildlife biodiversity and health in the Arctic.

7.2 'One Health' approach to protecting and improving Arctic health

The One Health concept recognizes that human, animal and ecosystem health are interrelated and interdependent in complex ways. It shows that responses to human mental, physical and social wellbeing demand multidisciplinary and holistic approaches, where human-, domestic animal- and wildlife health practitioners work closely with ecosystem health

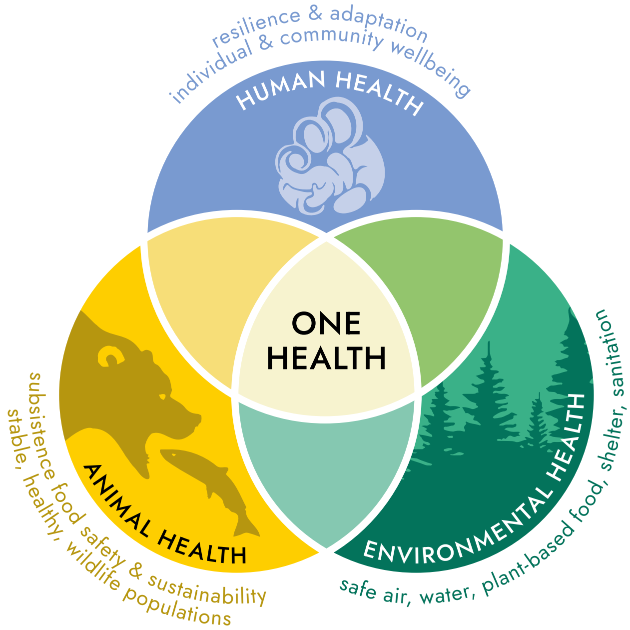

Figure 7.1 One Health – University of Alaska (Fairbanks).

scientists (Figure 7.1). One Health is the intuitive world view of Indigenous People everywhere. It is becoming an increasingly established concept worldwide as populations face the complex challenges associated with global environmental change. These include climate warming and changes in landscape/land-use, including the effects of urbanization; emerging infectious diseases, biological invasive species and biodiversity; global demographic changes; and worldwide circulation of anthropogenic contaminants and existing infectious diseases. The bridging of contact between animals and humans frequently results in the emergence and re-emergence of zoonoses from wildlife reservoirs. Ecosystem change is a major driver of disease emergence (Figure 7.2).

The Arctic Council has recognized the concept of One Health, and that coordination among the various Arctic Council programs and working groups is important for achieving an integrated One Health approach. AMAP, CAFF and SDWG address all elements of One Health, although their scopes of work currently differ owing to the requirements of agencies funding the research, and to a lesser extent by the perceived professional boundaries of the research scientists within the working groups. Nevertheless, there have been significant improvements in collaboration between the working groups. As an example, the ICS group (Parkinson et al., 2008) is a collaboration of members of several Arctic Council Working Groups. ICS studies and evaluates infectious human diseases, and the treatment and prevention of these diseases and now includes those zoonotic diseases linked to Arctic warming. The multidisciplinary cooperation which produced the Arctic Climate Impact Assessment (ACIA, 2004) and more recently the joint report on the COVID-19 pandemic in the Arctic (www.sdwg.org) are all examples of a trend towards a One Health approach to a wide variety of emerging environmental and human/wildlife health issues. The SARS-CoV-2 virus is a 'textbook example' of the development of a novel pathogen in animal species, with movement into the human population and subsequent worldwide infection. Early detection of novel pathogens in biota, and early development of appropriate

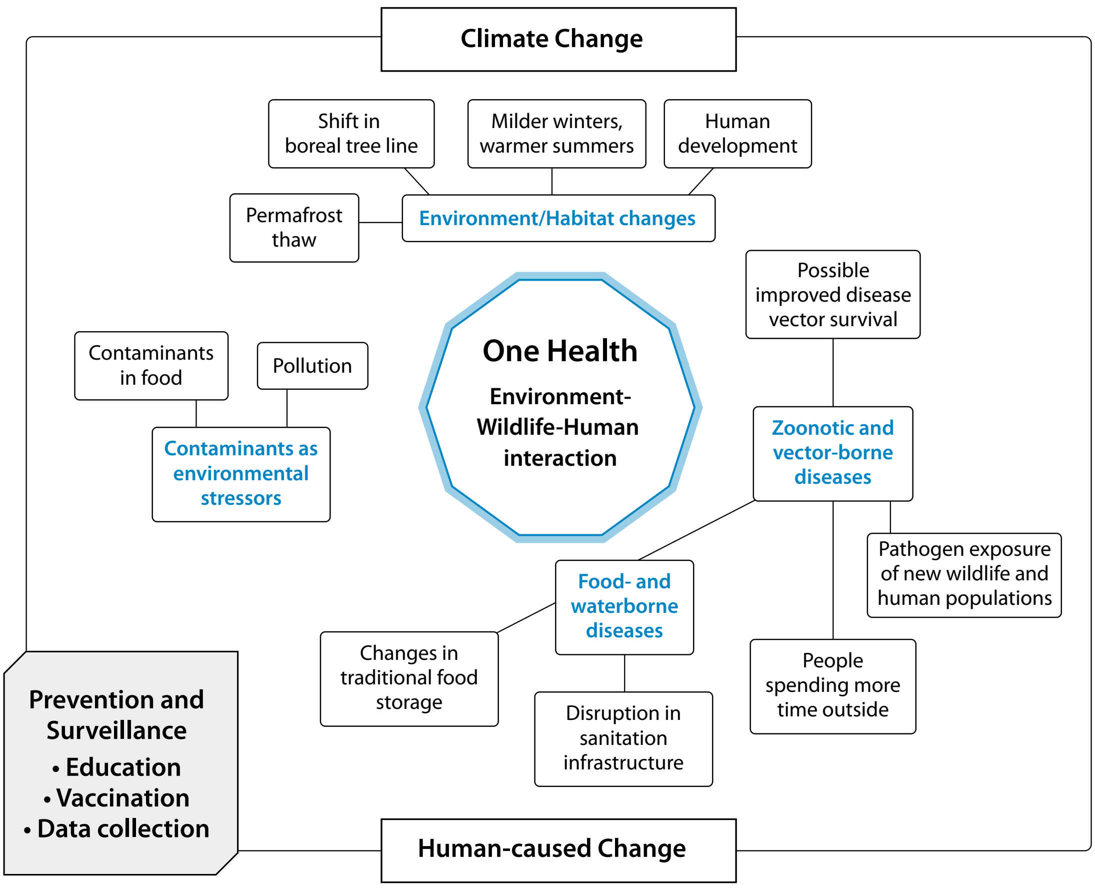

Figure 7.2 Effects of climate and human-caused changes on the Arctic.

monitoring of environmental reservoirs of the pathogen, as well as vulnerable human hosts are both elements of the One Health program (Mushi, 2020).

Operationalizing One Health requires application of the One Health paradigm to the issue to be addressed. It requires the development of metrics to monitor trends in recognized threats and to detect emerging threats, as well as to evaluate results of mitigation and adaptation strategies. The strategy should take advantage of Indigenous and local knowledge, as well as scientific application of technology where appropriate. In the circumpolar North, where many community challenges are climate-sensitive, a One Health approach may help in developing an effective response. Communities benefit from a well-functioning system for systematically monitoring trends in environmental change and diseases or other threats to wildlife, such that local residents and jurisdictional health systems can respond effectively. This may include physical monitoring, for example concerning shoreline erosion or permafrost temperature, as well as biomonitoring to collect evidence of subsistence animal exposure to zoonotic diseases and contaminants. The data from a well-designed community-based, resident-operated program enables communities to develop local adaptation strategies that can be critical to sustaining a traditional diet, protecting vulnerable residents, and protecting village infrastructure (O'Hara et al., 2017).

In applying the principles of One Health to the challenges in Arctic communities, the cooperation and assistance of wildlife- and human health agencies are of equal importance. The holistic view of Indigenous Peoples, and the community's willingness to contribute traditional ecological knowledge, as well as local observations of environmental abnormalities are an essential part of the One Health approach. Local wildlife management agencies and laboratories can help train communities to develop their own environmental monitoring systems. Combining the knowledge of local observers and Western science offers the best opportunity for developing community-based strategies for adaptation and mitigation (Ruscio et al., 2015).

Northern universities have made a significant contribution to the wider application of One Health principles. Contributions to the science of physical environmental monitoring, the application of civil engineering expertise to village environmental health problems, and village-based environmental biomonitoring have all developed through cooperation among community and tribal organizations, wildlife resource agencies, public health agencies and universities (Ruscio et al., 2015). Undergraduate and graduate degree programs are under development in several universities and should eventually result in a steady supply of young scientists trained in applying One Health principles to the growing challenges faced by residents worldwide. For example, the University of Alaska (Fairbanks) has developed a Masters' degree program (www.uaf.edu/onehealth).

During the U.S. Chairmanship (2015–2017) of the Arctic Council, the USA and Canada introduced a One Arctic, One Health project designed to strengthen regional knowledge sharing and coordination regarding a variety of Arctic One Health concerns (see Box 7.1). The main task of the One Health project was to build firm linkages among human-, animal-, and environmental health and local communities, policymakers, researchers and rural residents, to advance Arctic regional resilience and reduce health risks, as mentioned above. One form of operationalizing multi-sectoral collaboration in the case of hypothetical health emergencies (such as forest fires or a transboundary disease outbreak among land/sea animals) is through the One Health Table Top Exercises (TTX) concept (Vesterinen et al., 2019). The scenarios focus on the coordination and information flow needed to rapidly diagnose and respond to the outbreak.

The One Health concept is now an important and useful approach for addressing existing and emerging environmental changes in the circumpolar North. Effective application of the One Health principles requires ongoing collaboration and information exchange between the AMAP and SDWG health expert groups, and other Arctic Council wildlife programs. Development of strategies for actions and programs utilizing One Health to address the consequences of a warming Arctic will depend on these cooperative efforts between scientists with diverse professional backgrounds, together with the contributions of Arctic residents.

Other important agencies, networks and projects for collaboration, such as the University of Alaska (Fairbanks) and the Thematic Network of Health and Wellbeing in the Arctic (under the University of the Arctic), also enhance collaboration and improve the visibility of the education and research of One Health. Collaboration with EU-funded projects is another example, including INTERACT (https://eu-interact.org) in monitoring of possible vectors for zoonotic diseases, and Nunataryuk (https://nunataryuk.org) for modeling and human health risk assessment of anthrax and contaminants from thawing permafrost, as well as the Nordic Centre of Excellence project CLINF (https://clinf.org) for research on climate change effects on zoonotic diseases in the North. The current pandemic arising from the COVID-19 virus represents a classic example of the interdependence of environmental-, wildlife- and human health.

7.3 One Health in the Arctic: current status

7.3.1 Contaminants

Despite phase-out in the production and usage of the persistent organic pollutants (POPs) listed in the annexes to the Stockholm Convention, these contaminants continue to circulate in the environment (Dietz et al., 2019). Environmental factors and the impact of climate change on temperature will affect the volatilization and distribution of POPs and heavy metals (Carlsson et al., 2018; Schuster et al., 2018). For example, despite the general declining trend in polychlorinated biphenyl (PCB) levels in human biological matrices and biota, modeling of atmospheric PCB composition and behavior showed some increase in environmental concentrations under a warmer climate (Carlsson et al., 2018). Environmental contaminants are only one component of a One Health model. For many years, research in all eight circumpolar nations has contributed to evidence of dietary trends and contaminant loads in Arctic populations (see also Chapters 2 and 3).

Box 7.1 One Health

During the U.S. Chairmanship (2015–2017) of the Arctic Council, the USA and Canada introduced the *One Arctic, One Health* project (www.sdwg.org) designed to strengthen regional knowledge sharing and coordination on a range of Arctic One Health concerns, such as infectious and vector-borne diseases, water and food security, environmental contamination, and changes in animal species distribution. The project advanced operational One Health networks in the Arctic by promoting knowledge sharing, international participation in Table Top Exercises (TTX), and collaborative investigations of One Health phenomena. In 2017, Finland joined the project as a co-lead during the Finnish Chairmanship of the Arctic Council (2017–2019), and the project continued under the Icelandic Chairmanship (2019–2021).

The main actions of the first five years began with a circumpolar questionnaire on One Health awareness and practices that had over 200 responders (Ruscio et al., 2015) followed by a study tour in the USA under the International Visiting Leadership Program. The TTXs were held in Anchorage (2017) and Ottawa (2018). The One Arctic, One Health conference was held in Oulu (2019), and a workshop focused on pathogens emerging from thawing permafrost in Hannover (2019, see also Everett, 2020). Additional activities included the establishment of a TremArctic network, a series of published scientific papers (Abass et al., 2018b; Waits et al., 2018; Vesterinen et al., 2019) and joint sessions and presentations at scientific conferences, seminars and workshops. The meetings and collaboration with the other Arctic Council Working Groups, scientific projects and the University of the Arctic have strengthened the network of scientists and communities with an interest in One Health work.

The first One Arctic, One Health conference was held in Oulu, 7–9 February 2019, drawing nearly 100 registered participants from 16 countries, of which 24 were early career researchers and Indigenous participants who received travel grants from the U.S. National Science Foundation. The meeting was an integral part of Finland's Arctic Council Chairmanship program and was open to scientists, students, Indigenous knowledge holders, policymakers, businesses and all other interested stakeholders. Science sections focused on the multidisciplinary themes of the One Health approach (health of environment, wildlife, semi-domestic animals, humans) with social aspects and technological solutions (Abass et al., 2019). One Health requires participatory community-based approaches for identifying and responding to health and wellbeing issues in communities and is best combined with Indigenous and local knowledge.

The Oulu conference identified several key areas for further study in One Health:

- The need for more exchange and educational programs to learn about best practices and how they can be adapted to other Arctic communities.
- The need for better communication, data management and data sharing practices.
- The need for inclusion of non-traditional stakeholders (such as social science and the private sector) in One Health activities, as well as women, youth, and Indigenous communities.
- The need for greater collaboration and coordination between Arctic and subarctic projects and communities, since many One Health phenomena extend beyond the Arctic region.
- Recognition of the importance of addressing new phenomena (such as vectors carrying emerging infectious diseases, marine debris, etc.) and applying new technologies (such as improved diagnostics) to address One Health issues.
- The difficulty and importance of building networks with common language and shared goals across complex and different systems and sectors.
- The importance of demonstrating impact.
- The continuation of One Health conferences to share successes and lessons learned, as well as best practices. The second One Health, One Future conference was online 6–11 April 2021.

The climate in the Arctic is undergoing widespread and rapid change; the change in annual average near surface air temperature in the Arctic is three times that for the global average since 1971 (Box et al., 2021). Global climate models project that annual mean surface air temperature in the Arctic will increase to 3.3–10.0°C above current values under different scenarios by the end of the 21st century (Wang et al., 2021). Higher temperatures in the Arctic cause changes in sea ice, snow cover, permafrost, ocean temperature, and precipitation. Climate change is also occurring together with unprecedented globalization in the Arctic. Greater accessibility to remote locations, increased levels of tourism and industry, and social change all bring new health challenges to the Arctic (Larsen and Fondahl, 2014; Jungsberg et al., 2019), in addition to already complex issues such as the existence of environmental contaminants and rising chronic disease rates in humans (Arctic Council, 2009). The geographic differences in the concentrations and trends in many contaminants reflect the differences in culture, lifestyle and dietary habits evident across the Arctic.

Permafrost thaw caused by climate change has major implications for the global mercury (Hg) cycle. A recent study estimated that over 793 gigagrams (Gg) of Hg are frozen within the permafrost of the Northern Hemisphere (Schuster et al., 2018), which is roughly 10-fold higher than the total global Hg emissions over the past 30 years. The study also revealed that northern permafrost soils represent the largest reservoir of Hg on the planet, storing nearly twice as much Hg as all other soils, the ocean and the atmosphere combined, indicating a need to reevaluate the role of the Arctic regions in the global Hg cycle (see Figure 7.3). It is estimated that the entire Northern Hemisphere permafrost region contains 1656±962 Gg Hg, of

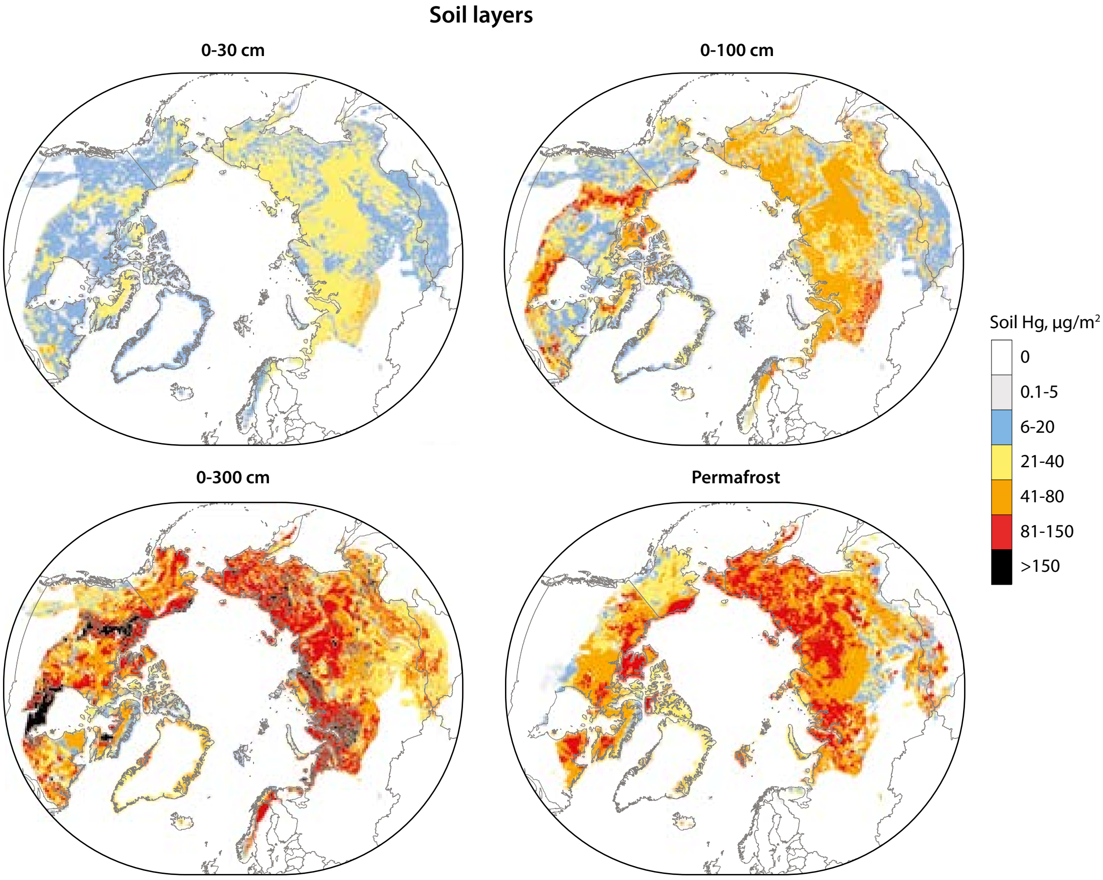

Figure 7.3 Mercury concentrations in Northern Hemisphere permafrost zones for four soil layers: 0–30 cm, 0–100 cm, 0–300 cm, and permafrost derived by multiplying maps of carbon from Hugelius et al. (2014) by the median mercury to carbon ratio (RHgC). The permafrost map represents the Hg bound to frozen organic matter below the active layer depth and above 300 cm depth. Relative uncertainty is 57% for all pixels (Schuster et al., 2018).

which 793±461 Gg Hg is bound to frozen organic matter located below the active layer depth and above 3 m depth. This Hg is vulnerable to release through the permafrost thaw projected for the coming century. Modeling of the atmospheric PCB composition and behavior indicated higher environmental concentrations in a warmer Arctic, but that a general decline in PCB levels is still the most prominent feature (Carlsson et al., 2018). 'Within-Arctic' processing of PCBs will be affected by climate change-related processes such as changes in wet deposition. These in turn will influence biological exposure and uptake of PCBs (Carlsson et al., 2018). Contaminants will also be released from melting sea ice and glaciers.

7.3.2 Infectious diseases in humans and wildlife

Rates of diagnosed infectious diseases in the Arctic are highly variable, depending on country, disease, age, gender of the affected individuals and geographical location (Waits et al., 2018). Overall, improved sanitation, medical treatment, vaccination, and education have decreased infectious disease and health disparities between Indigenous and non-Indigenous populations across the Arctic. However, significant disparities still exist within the Arctic; tularemia cases in the Arkhangelsk region and Khanty-Mansi Autonomous area, for example, are several times higher than averages registered for the Russian Federation as a whole. Current trends in infectious diseases in the Arctic include the re-emergence of tuberculosis, high prevalence of sexually transmitted diseases, introduction of new pathogens such as COVID-19 (see www.sdwg.org; Petrov et al., 2020), changes in the emergence of food- and waterborne diseases, and spread of vector-borne and zoonotic diseases as a result of climate change (Waits et al., 2018; Omazic et al., 2019).

Tuberculosis and sexually transmitted infections are a significant public health concern for the Arctic populations, with higher rates of incidence than for the country's general population and higher incidences in the Indigenous rather than non-Indigenous population. Bourgeois et al. (2018) studied tuberculosis incidence in the Arctic (2006–2016) and found this to vary among Arctic countries and to be higher in males than females. Sexually transmitted infection incidence rates were higher in the Arctic communities than for the country as a whole, and higher in Indigenous than non-Indigenous populations (Gesink et al., 2008).

Globally, parasites constitute a major component of biodiversity (Dobson et al., 2008) and are often identified as wildlife and/or human pathogens. Many animal species inhabit the Arctic, including permanent residents and those that migrate in seasonally. These include over 200 species of bird, 100 species of mammal, 300 species of fish, and thousands of species of invertebrates and microorganisms (CAFF, 2013). Climate change and more human activity threaten the health of the Arctic wildlife. Environmental threats include rising sea and air temperatures, and the associated changes in biota, habitat, foraging grounds, breeding areas, and migration routes. These

Table 7.1 Examples of Arctic changes and associated threats for infectious diseases in wildlife.

Threat	Consequences	Example
More people (and pets) coming into the Arctic	Pets as sources of wildlife exposure to pathogens	Toxoplasmosis (transmitted by domestic cats) found in a spinner dolphin (Daszak et al., 2001)
	Pets become hosts for wildlife pathogens	Domestic dogs carry and spread *Echinococcus multilocularis*, in addition to wild hosts, foxes and lemmings (Bradley et al., 2005)
Climate change	Habitat changes stress wildlife	Higher water temperatures may stress fish, leaving them more susceptible to bacterial and protozoan infectious diseases (Bradley et al., 2005)
	Pathogen range expansion	Northern expansion of fish parasite *Cryptocotyle lingua* (causative agent for 'black spot' disease) resulting from growing areas of warmer water (Tryland et al., 2009)
	More favorable conditions for pathogen development	Higher temperatures and milder winters result in better conditions for pathogen development, survival of larvae, and opportunities to spread to hosts (Davidson et al., 2011)
Increasing industry	Animal husbandry introduces new pathogens	Bison exposed to parainfluenza 3 virus from cattle industry (Bradley et al., 2005)

same environmental changes are also affecting disease-vector populations, ranges, and lifecycles. Simultaneously, the Arctic is the focus of increased human interest and activity, which in turn bring additional challenges that may impact upon infectious diseases among wildlife. For example, increased shipping traffic through the Northwest Passage could introduce rat-borne diseases from ports in northwestern Scandinavia and Russian Federation ports. The rapid influx of people (and their pets) has the potential to introduce new pathogens, establish new hosts, and alter the wildlife environment through industry, construction, and pollution. Change can also stress animals, potentially making them more vulnerable to infectious diseases (Bradley et al., 2005).

Many Arctic pathogens may have environmental hosts that have not been identified; for example, the intracellular bacterium *Coxiella burnetti* (causing human Q fever) has recently been identified in northern fur seals and their placenta, and may well be found in the crabs feeding on these placentas at rookeries in the Bering Sea. *Franciscella tularensis* (a type of aerobic bacterium causing human tularemia) generates an antibody response and is now found in polar bears (Atwood et al., 2017). The environmental reservoirs for new Arctic infections are not known. The ecology of Arctic pathogens is a topic that needs collaborative investigation, involving local knowledge as well as western science.

All such factors contribute to increased infectious disease threats to Arctic wildlife, which include shifts in disease emergence, potential for new pathogens, and increased infection risk for human residents (Table 7.1).

Climate change is predicted to be one of the most influential factors in the emergence of infectious diseases (Omazic et al., 2019) and will have both direct and indirect impacts on human health, especially in relation to infectious diseases (Arctic Council, 2009). Higher sea and land temperatures can increase growth rates of pathogens and animals, including insect vectors (Yasjukevich et al., 2013; Bruce et al., 2016; Noskov et al., 2017). Extreme precipitation events may cause flooding and disrupt water/sanitation infrastructure, raising the risk for waterborne disease outbreaks. Indirectly, climatic factors affect infectious disease transmission by altering human behavior, such as using public bathing waters and enabling more opportunities for the start of a waterborne disease outbreak (Eze et al., 2014) or spending more time outside (e.g., in forests), increasing the likelihood of contracting a tick-borne disease. Changes in climatic factors can expand a disease-vector's geographic range, increase its population size, and allow more vector species and individuals to survive the winter (Burmagina et al., 2014; Mesheryakova et al., 2014; Parham et al., 2015; Bruce et al., 2016; Yastrebov et al., 2016; Chashchin et al., 2017). However, increased public and health personnel education, vaccination programs, and hygiene can help combat the spread of disease, potentially reducing infections despite more opportunities for infection as a consequence of climate change.

7.3.3 Drinking water

Clean, safe, fresh water is one of the most important natural resources and the focus of one of the United Nations Sustainable Development Goals under Agenda 2030. Safe drinking water and adequate sanitation are key factors for human life and health. Arctic climate conditions affect water security and sanitation services in the Arctic countries. Some challenges, such as loss of permafrost, affect regional water and sanitation services in similar ways, while others are more limited in distribution (Table 7.2). There are still people in Arctic regions that lack centralized drinking water and sanitation systems, and alternative drinking water sources and transport options continue to be needed. The state of water services in the Arctic was reviewed for the One Arctic, One Health project (Miettinen, 2019).

7.4 ArcRisk project

Interest in the Arctic has resulted in research programs and projects in countries outside the Arctic, including the European Union. For example, the European Polar Research Program is one part of Horizon Europe (2021–2027) which is funded by the European Research Council. Over the past decade there have been several EU-funded research projects that address issues concerning the linkage between climate change, environmental contaminants and risks for human health. Two of the many projects funded through the Seventh Framework Programme included Arctic populations: ArcRisk

Table 7.2 Water services in Arctic nations (based on Abass et al., 2019; Miettinen, 2019).

Country	Water system, drinking water	Special concerns	Source
Alaska (USA)	Public water systems often use surface water for drinking water production	Permafrost restricts use of groundwater (effects on piping, sewage leaks, etc.); lack of running piped water or sanitation in many Indigenous communities	Hennessy et al., 2008; ADEC, 2018
Canada	Drinking water usually good quality	Permafrost restricts use in some regions; unsafe drinking water in some Indigenous communities, creates need for boiled water advisory and trucks	Daley et al., 2014; NCCEH, 2014; Black and McBean, 2017
Greenland	Surface waters (lakes, rivers) used for drinking water Centralized drinking water covers entire population	Permafrost prevents use of groundwater	Government of Greenland, 2018
Iceland	Drinking water usually good quality, 95% from groundwater	Small, rural water supplies; 6 outbreaks of waterborne infections in 5 years	Gunnarsdottir et al., 2016
Norway	Drinking water usually good quality	Small waterworks, use of untreated surface water and deterioration of pipelines; 41 outbreaks of waterborne infections in 12 years	Nordheim et al., 2016; Mattilsynet, 2018
Sweden	Drinking water usually good quality One million inhabitants use a private well	Chemical contamination and overexploitation threaten groundwater sources; 59 outbreaks of waterborne infections in 15 years	Guzman Herrador et al., 2016; Gunnarsdottir et al., 2017; Swedish Water, 2018
Finland	Drinking water usually good quality 500,000 inhabitants in rural areas use private wells	Aquifers shallow, unconfined and vulnerable to microbial pollution; 95 outbreaks of waterborne infections in 20 years	Klöve et al., 2017
Russian Federation (Arctic parts)	Quality of drinking water poor	Limited access to running water; lack of water pretreatment; old systems; serious issues in general water hygiene	Dudarev et al., 2013a,b, Dudarev, 2018

(Arctic Health Risks: Impacts on health in the Arctic and Europe owing to climate-induced changes in contaminant cycling, 2009–2014) coordinated by the AMAP Secretariat, and CLEAR (Climate change, Environmental contaminants and Reproductive health, 2009–2013) coordinated by Aarhus University Hospital (Denmark). Both projects collaborated and both included Arctic population parent-child cohorts (from Greenland in CLEAR; AMAP cohorts in ArcRisk).

The CLEAR project focused on how climate change may influence human exposure to contaminants and how contaminants may disturb reproduction. The conclusions of the CLEAR project were that "the climate change might not directly cause major changes in environmental exposure levels of POPs for the Arctic populations, and adult exposure might not have marked influence on male and female fertility or child growth and development" (Toft et al., 2014). The study focused more on male reproductive health than female, and child development and long-term effects of fetal exposure on reproductive health were not studied. However, researchers did identify an ongoing dietary shift away from traditional food items to imported food items in many Arctic communities.

The ArcRisk project comprised a consortium of 21 partners and its main aim was to investigate the potential influence of climate change on the exposure of humans to contaminants in the Arctic, and for comparison several areas of Europe. Policy recommendations and projections of the future changes and adaptation actions needed were a key aim. This section summarizes the main health results of the ArcRisk project, based on the published articles and reports funded by the project. The main research tasks of the health component of the project were to estimate: contaminant levels and health outcomes in relation to contaminant exposure in the Arctic and selected European cohorts; possible effects of climate/global change on future dietary exposure; and human placental transfer of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). The project included case studies on Hg and PCBs, which were contaminants chosen for inclusion for research in all 'work packages' of the ArcRisk project (modeling global transport; bioaccumulation; process studies; health). The results of this synthesis work and integration of research results are available in two review articles (Sundseth et al., 2015; Carlsson et al., 2018) and one policy outcome (Pacyna et al., 2015). Health researchers taking part in ArcRisk have published around 50 scientific papers in total based on project work.

More information about the ArcRisk project, including a list of all the published papers prepared during and after the project, is available via the AMAP website (www.amap.no/projects?archived=yes).

7.4.1 Mercury

The main findings for heavy metals and essential elements in the ArcRisk publications are shown in Table 7.3. Mercury levels in the ArcRisk cohorts showed large inter-individual variation in most of the studies (Figure 7.4) with the highest levels found in the Greek PHIME and Norwegian NFG cohorts. The Greek participants of the PHIME cohort were from the islands of the eastern Aegean Sea where the population mostly consumes locally caught fish, which contain higher Hg levels than fish from markets (mostly aquacultured fish). Similar values are reported for the Spanish islands, where mainly local fish are consumed. Mercury deposits are the reason for the locally higher Hg levels in soil and water, forming a belt in the Mediterranean region. Living inland or in coastal areas in Norway also affected blood Hg levels in humans, with higher levels in coastal populations due to higher fish consumption. In the Russian study groups, Hg levels in adult males and females were within the same range but somewhat higher than in the

Table 7.3 Main findings on heavy metals and essential elements in the ArcRisk publications.

Geographical region/ Cohorts/ Projects	Main findings	Source
Mercury		
Mediterranean cohorts Slovenia, Italy, Croatia, Greece / PHIME	Large inter-individual variation between blood levels in all cohorts; highest Hg levels in Greece (eating locally caught fish)	Miklavčič et al., 2013
North-West Russia / Nelmin-Nos, Izhma and Usinks / n=209; 72 females	Blood Hg levels increased with age. Parity did not affect levels	Rylander et al., 2011a
Northern Norway / MISA / n=211	Ten toxic and essential elements were measured during and after pregnancy. Fish consumption was a positive predictor for Hg and Se levels. Multivitamin intake associated for Se, and inverse association between parity and Hg levels of mothers	Hansen et al., 2011
Slovenia (PHIME, ArcRisk, national funders)	Total Hg levels in cord blood and hair and MeHg levels in cord blood are suitable biomarkers of low-level Hg exposure through fish consumption	Miklavčič et al., 2011
Norway / NFG (n= 184)	Fish consumption and coastal region are the main determinants of total Hg in blood; results based on food frequency questionnaires (FFQs), total Hg in blood and urine	Jenssen et al., 2012
Norway / NFG (n=111, subgroup of high consumption of seafood and game, reference group n=77)	Six elements (I, Hg, Se, As, Cd, Pb) measured in blood/urine and food items, and FFQs. Iodine, Se and Hg reflected seafood intake	Birgisdottir et al., 2013
Menorca / INMA (n=302 4-yr old children)	FFQs and Hg levels in hair. 20% of total Hg above WHO recommended values. Higher levels in girls than boys. Fish and seafood consumption related to Hg values (especially oily fish, shellfish, squid). No association between Hg levels and motor and cognitive abilities at age 4 years	Garí et al., 2013
Northern Finland / NFBC 1966 (n=249, subgroup from eastern and western part of Finnish Lapland)	Males had higher total Hg levels in blood (whole) than females. This was connected to consumption of fish, reindeer, moose, wild fowl and alcohol. 8.4% of the study group had higher levels than cut-off points	Abass et al., 2017
BeWo choriocarcinoma and MCF-7 cells	An experiment with $HgCl_2$ was not possible to perform since it was too toxic to cells	Kummu et al., 2012
Review (n=87 papers; statistical significance of the relationship between maternal Hg exposure and child development)	Literature review found no consistent evidence of a relationship. Authors reported analyzed health outcome variables based on their *p*-value rather than on the stated primary research question	Nieminen et al., 2015
Toxicokinetic modeling based on total Hg blood levels (NFG)	Toxicokinetic modeling gave higher daily intake values of Hg than FFQ. This may reflect non-dietary exposure, such as dental amalgam	Abass et al., 2018a
Cost-benefit analysis in DEMOCOPHES project (17 European countries, hair Hg concentration; LIFE+, COPHES, PHIME, ArcRisk)	Reduced MeHg exposure has economic benefits, especially in southern Europe where Hg levels are higher. There is need for extended biomonitoring of human MeHg exposure	Bellanger et al., 2013
Arsenic		
Norway / NFG (n=111, subgroup of high consumption of seafood and game, reference group n=77)	Arsenic levels reflected seafood intake	Birgisdottir et al., 2013
Northern Norway / MISA	Fish consumption a positive predictor for As	Hansen et al., 2011
NFBC 1966 (n=249, subgroup from eastern and western part of Finnish Lapland)	29 males and 21 females had As levels above 1.0 mg/L (ATSDR)	Abass et al., 2017
Cadmium		
NFG (n=111, subgroup of high consumption of seafood and game, reference group n=77)	Cd in urine associated with crab consumption in non-smokers. 24% had high consumption and 8% of reference group had levels above tolerable total weekly intake	Birgisdottir et al., 2013
North-West Russia / Nelmin-Nos, Izhma and Usinks (n=209; 72 females)	Blood levels of Cd increased with age	Rylander et al., 2011a
NFBC 1966 (n=249, subgroup from eastern and western part of Finnish Lapland)	Average blood level of Cd in males (n=126) was higher than for females. Cd levels elevated in smokers and those with lower education level	Abass et al., 2017
BeWo choriocarcinoma cells and MCF-7 cells	$CdCl_2$ inhibits *ABCG2* function in both cells, may increase fetal exposure to compound via this transporter	Kummu et al., 2012

Table 7.3 Continued

Geographical region/ Cohorts/ Projects	Main findings	Source
Lead		
NFG (n=111, subgroup of high consumption of seafood and game, reference group n=77)	Pb level associated with game consumption and wine consumption	Birgisdottir et al., 2013
North-West Russia / Nelmin-Nos, Izhma and Usinks (n=209; 72 females)	Males had higher blood Pb levels than females	Rylander et al., 2011a
NFBC 1966 (n=249, subgroup from eastern and western part of Finnish Lapland)	Males had higher blood Pb levels than females. Higher Pb levels were related to sugar-sweetened soft drinks, smoking, alcohol use and lower educational level. Two people had a blood Pb above 100 mg/L	Abass et al., 2017
BeWo choriocarcinoma cells and MCF-7 cells	No effect on *ABCG2* transporter function	Kummu et al., 2012
Copper		
NFBC 1966 (n=206, 116 males / 90 females; subgroup from eastern and western part of Finnish Lapland)	No difference between males and females in Cu levels. Association of Cu level with the inflammatory load in body; no association to biomarkers for chronic vascular diseases	Palaniswamy et al., 2019

COPHES: Consortium to perform human biomonitoring on a European scale; DEMOCOPHES: Demonstration of a study to coordinate and perform human biomonitoring on a European scale; INMA: Environment and Childhood study; MISA: Northern Norway Mother-and-Child Contaminant Cohort Study; NFBC 1966: Northern Finland Birth Cohort 1966; NFG: Norwegian Fish and Game Study; PHIME: Public Health Impact of Long-term Low-level Mixed Element Exposure in Susceptible Population Strata.

NFG high fish consumers. However, Hg levels in pregnant women in Russia were lower, and within the same range as maternal blood from Italy, Croatia and Arctic Norway, and lower than in maternal blood from Greece.

In the PHIME cohorts, exposure to Hg was low and levels did not significantly affect neurodevelopment in children by the age of 18 months (Miklavčič et al., 2011, 2013). In the INMA-Menorca cohort follow-up there was no association between total Hg and motor and cognitive abilities at the age of 4 years (Garí et al., 2013). Exposure of the fetus to higher Hg levels during gestation did not cause lower performance in cognitive, language or motor neurodevelopmental test results of the child. However, other correlated variables (such as socio-economic indicators and maternal IQ) were correlated with developmental performance outcomes. Higher fish consumption in pregnancy was associated with higher cognitive and language (but not motor) neurodevelopmental performance of the child at 18 months of age in the PHIME cohorts. Distribution of hair-Hg concentrations in women of reproductive age (n=1875 from eight countries, DEMOCOPHES project) and from the literature (n=6820 subjects from eight countries) were used to estimate neurotoxicity effects on estimated economic loss, using estimated economic benefit of a higher IQ, based on lifetime income, adjusted for purchasing power parity (Bellanger et al., 2013). The cost-benefit analysis showed that reducing methylmercury (MeHg) exposure also has economic benefits, especially in southern Europe, and highlighted the need for extended biomonitoring of human MeHg exposure.

In a systematic literature review (n=87 papers, 1995–2013) of associations between the number of reported outcome

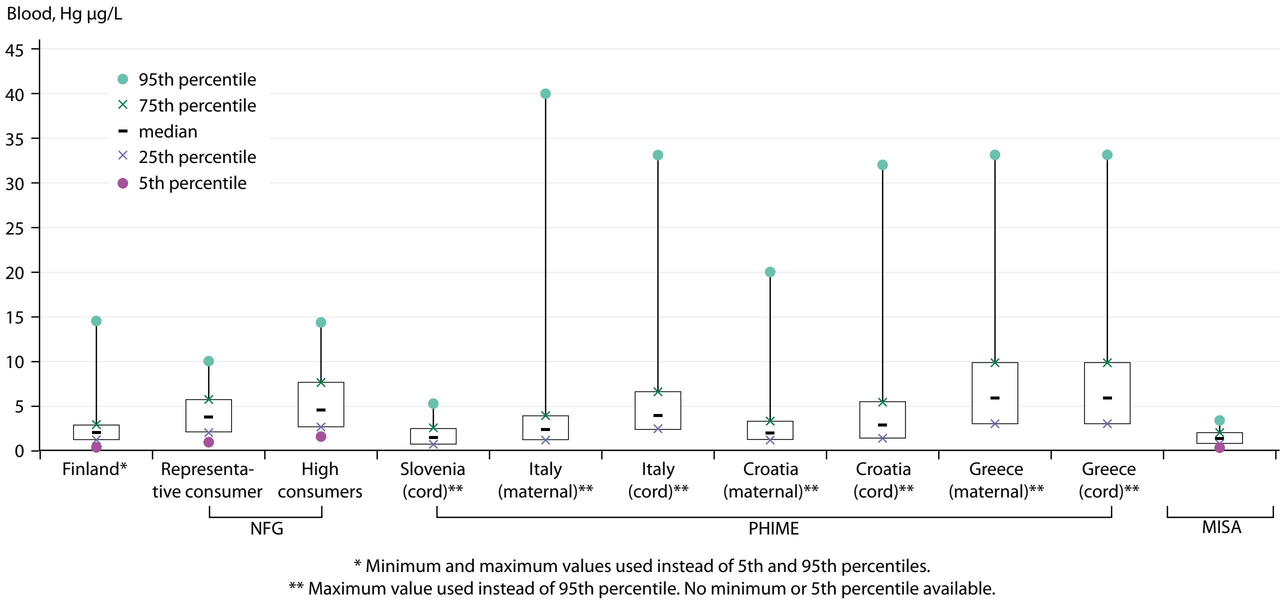

Figure 7.4 Overview of mercury concentrations in blood in the ArcRisk study groups (Sundseth et al., 2015).

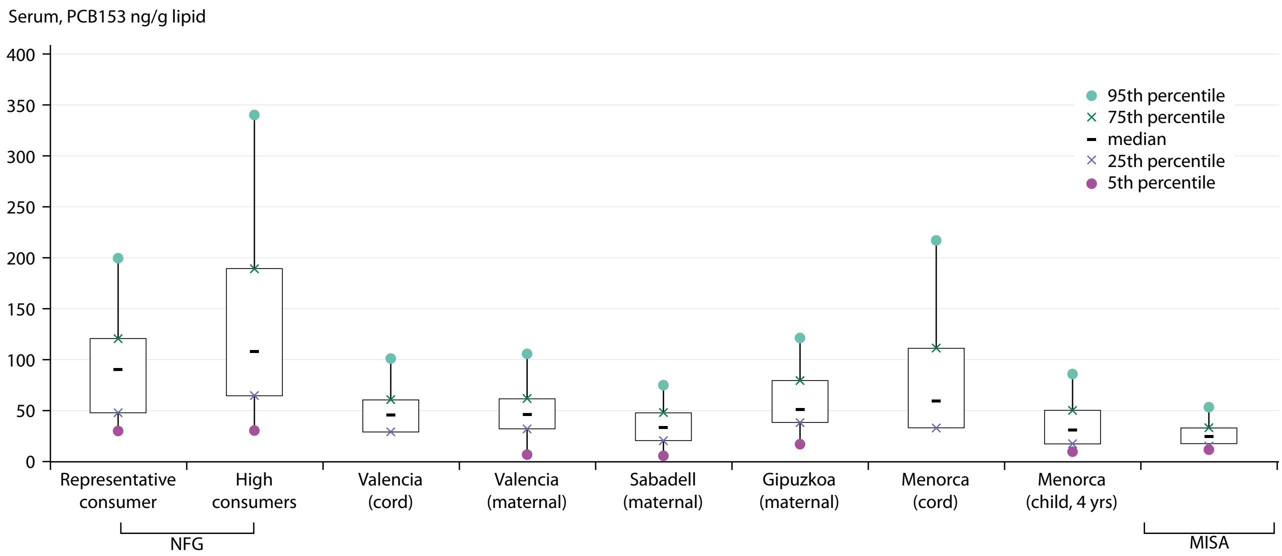

Figure 7.5 Overview of serum PCB153 concentrations in the ArcRisk study groups (Carlsson et al., 2018).

variables and statistical significance of the relationship between environmental Hg exposure and child development (Nieminen et al., 2015), there was no evidence of a relationship between maternal Hg level and child development. In many cases, the motivation of authors to report outcomes is associated with the size of their *p*-value rather than their intrinsic scientific value. Better education of researchers, reporting of all studies, and their systematic inclusion in meta-analyses is important to help combat the bias this introduces (see also Amrhein et al., 2019).

Two papers focused on modeling (Jenssen et al., 2012; Abass et al., 2018a; see also Chapter 5). The aim of Jenssen et al. (2012) was to measure total Hg levels in blood and estimate dietary exposure, tolerable intake values, and the relationship between dietary Hg and Hg in blood. Results showed seafood consumption and demographic variables explained up to 65% of observed variation in the blood Hg concentrations of participants. It is important to eat fish, even if fish eaters have higher blood Hg levels. Abass et al. (2018a, see also Chapter 5) developed a toxicokinetic modeling system based on blood levels of total Hg, and included three linear models for describing the fate of MeHg, inorganic Hg, and metallic Hg in the human body in order to estimate daily Hg intake. The toxicokinetic modeling gave higher daily intake values of Hg compared to those from food frequency questionnaires (FFQ). The properties of the toxicokinetic model or limitations in the dietary exposure assessment could be reasons for the differences between the respective methods (see also Chapter 5, Section 5.3.3.2). One non-dietary reason could be the influence of other sources of exposure, such as amalgam fillings in dentistry.

The results of the ArcRisk study groups showed that Hg levels were in the same range, with high inter-individual variation. The review by Sundseth et al. (2015) noted a declining trend in Hg levels in the Arctic, and concluded that reduced Hg emission from anthropogenic sources occurs worldwide. It was not possible to predict whether climate change would increase or decrease risk of exposure to Hg in the Arctic; for example, the recent results of high Hg levels found in the permafrost may increase risk of exposure (Schuster et al., 2018). Fish consumption is a major source of Hg exposure for humans in Europe and the European Arctic and the origin of the fish and fish species was one determinant of Hg levels. There may also be other sources of Hg exposure, such as elemental Hg in food in highly contaminated areas or Hg vapor from amalgam fillings, but their contribution is minor (Abass et al., 2018a). The highest MeHg exposures occur in coastal and island populations. Mercury levels vary greatly by species and origin, and wild-caught fish have higher concentrations than aquacultured fish. In the ArcRisk studies, exposure to Hg was low and did not significantly affect neurodevelopment of children at age 18 months or 4 years in the PHIME cohorts, and higher fish consumption in pregnancy was associated with higher cognitive and language (but not motor) neurodevelopmental performance at 18 months of age (Karagas et al., 2012; Valent et al., 2013). Neurodevelopment was associated with child intake of fresh fish and maternal IQ, but the expected beneficial effect of maternal fish intake (from maternal polyunsaturated fatty acids) was not found. A multicenter population study (with joint design) could be helpful to ensure more weight of evidence in meta-analyses of effects of Hg exposure on health outcomes in children (Nieminen et al., 2015).

Research results for other heavy metals (see Table 7.3) show that arsenic (As) levels reflect seafood and fish consumption, and that cadmium (Cd) was associated with crab consumption in Norway (Hansen et al., 2011; Birgisdottir et al., 2013). *In vitro* placental studies suggested that Cd may increase systemic and fetal exposure to other harmful compounds transported by ABCG2 (one of the main efflux transporters in human placenta) by inhibiting its activity (Kummu et al., 2012, see also Chapter 4). Lead levels are associated with game and wine consumption, sugar-sweetened soft drinks, smoking, alcohol use and lower educational level, and males have higher levels than females (Rylander et al., 2011a; Birgisdottir et al., 2013; Abass et al., 2017).

7.4.2 PCBs and other POPs

Median levels of PCB153 in serum were roughly the same in all ArcRisk cohorts (Figure 7.5). The highest levels occurred in participants in the Norwegian Fish and Game Study and the lowest in the Spanish INMA study groups and Norwegian

Table 7.4 Main findings on PCBs in the ArcRisk publications.

Geographical region/ Cohorts/ Projects	Main findings	Source
North-West Russia / Nelmin-Nos, Izhma and Usinks (n=209; 72 females)	PCB153 was the highest concentration level of 18 PCB congeners. Males and older people have highest levels of PCBs	Rylander et al., 2011a
North-West Russia / 70 food items in different regions	Estimated daily intake of PCBs is equal range compared to Sweden and Denmark	Polder et al., 2010
Menorca / INMA Menorca cohort (n=285, 4-year olds)	Girls had higher PCB levels than boys. Levels in breastfed children higher than formula-fed children. Breastfeeding the major exposure route	Grimalt et al., 2010
Valencia / INMA (n=499 mothers from Latin American or European background)	PCB levels higher in cord blood of mothers of European descent than Latin American descent	Vizcaino et al., 2010
Valencia / INMA (n = 174) and Menorca (n=91)	Distribution of PCB congeners differs. Highest PCB levels in people living in Menorca	Vizcaino et al., 2011a
Northern Norway / MISA (subgroup of 50 for organochlorines and lipids measured during and after pregnancy)	Optimum sampling window is from last weeks of third trimester to early postpartum days	Hansen et al., 2010
Northern Norway / MISA (subgroup of MISA, meconium samples, n=40; comparison to maternal serum biomarkers, 8 organochlorines)	Lipid-adjusted organochlorine concentration in meconium is a sensitive and informative fetal exposure index	Veyhe et al., 2013
Norway / NFG cohort (n=195) and Lake Mjosa Study (n=66)	Development of predictive models for blood levels of PCBs and dioxins using dietary intake	Kvalem et al., 2012
European cohorts (n=7990 mothers from 15 cohorts) / OBELIX, ENRICO, ArcRisk	Low-level PCB exposure impairs fetal growth, and the effect on birth weight was a decline of 150 g for every 1 µg/L increase in PCBs	Govarts et el., 2012
Norway / MoBa cohort (n=83,524 pregnant women)	Dietary exposure of PCBs and dioxins in pregnancy and breastfeeding positively associated with maternal age, education; with gain in pregnancy, being a student, and alcohol consumption in pregnancy, Dietary exposure negatively associated with pre-pregnancy BMI and smoking	Caspersen et al., 2013
Northern Norway / Tromsø study (n=53 males, samplings since 1979, five time points, last 2007)	Decline in serum levels of POPs (n=41), except chlordanes. Estimates from the CoZMoMAN emission-based model support findings	Nøst et al., 2013
Toxicokinetic modeling / Estimation of health risk, PCB153, using blood levels	Health risk assessment of PCB153 characterized by toxicokinetic modeling	Abass et al., 2013
Czech Republic / Breast Milk Monitoring study (15 years, 9 regions, n=4753 mothers)	PCB levels declined during monitoring period. Connection between parity and PCB153 levels seen only for PCB153	Mikeš et al., 2012
Systematic review (influence of parental PCB exposure on sex ratio, n=15 articles)	No strong or moderate indication that parental exposure to PCBs alters sex ratio of children	Nieminen et al., 2013a
Meta-analysis and research synthesis (relationship between PCBs and birth weight of newborns, n=24 articles)	Standardized regression coefficient as effect size index was developed. Birth weight decline related to increase in PCB level.	Nieminen et al., 2013b
Northern Norway / MISA (n=391; 19 POPs, 10 thyroid parameters, multipollutant assessment, PCA)	PCB levels inversely associated with parameters of thyroid function (T_3, T_4 and FT_4). POPs exposure can alter maternal thyroid homeostasis	Berg et al., 2017a

PCA: principal component analysis.
ENRICO: ENvironmental Health RIsks in European Birth Cohorts; INMA: Environment and Childhood study; MISA: Northern Norway Mother-and-Child Contaminant Cohort Study; MoBa: Norwegian Mother and Child Cohort Study; NFG: Norwegian Fish and Game Study; OBELIX: OBesorgenic Endocrine disrupting chemicals: Linking prenatal eXposure to the development of obesity later in life.

MISA study. The Norwegian Fish and Game Study participants were the oldest participants, which might explain the higher levels of PCB153 compared to the other cohorts (median: 55 years, range: 21 to 80 years).

The organohalogen concentrations observed in European people from the Mediterranean cohorts are similar to previously reported levels for general populations in developed countries (Vizcaino et al., 2010; Table 7.4). The main risk factors for higher organohalogen levels are a local source, sex, breastfed, maternal weight gain, and mother of European descent. However, in comparison to other European studies, the Mediterranean populations exhibit higher median blood levels of hexachlorobenzene (HCB), β-hexachlorocyclohexane (β-HCH), and DDT and its metabolites (Table 7.5). The results of the INMA cohort showed associations between higher HCH levels in cord blood and higher thyroid-stimulating hormone (TSH) levels in newborns (Lopez-Espinosa et al., 2010). The Northern Norway MISA cohort showed inverse associations between thyroid homeostasis (T_3, T_4 and FT_4) and levels of HCB and nonachlors (Berg et al., 2017a).

In the European context, PCB levels in residents of Slovakia and the Czech Republic are much higher than in Mediterranean populations (Mikeš et al., 2012). These specific cases have been attributed to a PCB factory in the Michalovce district in Slovakia and to the intensive industrial activity, especially the chemical sector, in the former Czechoslovakia. In Menorca Island INMA cohort members, girls had higher levels of PCBs, DDE, DDT, and HCB than boys at age four years and levels were higher in breastfed children (Grimalt et al., 2010).

Table 7.5 Main findings on POPs other than PCBs in the ArcRisk publications.

Geographical area/ Cohorts/ Projects	Main findings	Source
DDT and DDE		
North-West Russia / Nelmin-Nos, Izhma and Usinks (n=209; 72 females)	Clear decrease in *p,p'*-DDE levels in 10 years for both sexes. Only 2% had detectable DDT concentrations	Rylander et al., 2011a
North-West Russia / 70 food items / different regions	Recent contamination of DDT, high levels found in butter, pork and fish samples. Importance of control	Polder et al., 2010
Menorca / INMA Menorca cohort (n=285, four year-old children)	DDE and DDT levels higher in breastfed children than those fed by formula. Girls had higher levels than boys	Grimalt et al., 2010
Valencia / INMA Valencia (n=499 mothers from Latin American or European background)	Latin American descent infants had higher levels of DDE and DDT than European ones. Increase of 4,4′-DDT in newborns from mothers with higher education and high BMI	Vizcaino et al., 2010
Mozambique / Manhica	DDT and DDE levels in breastmilk samples increased from 2002 (n=45) to 2006 (n=50)	Manaca et al., 2011
Mozambique / Manhica	Measurements of DDT and metabolites in indoor air and wall materials estimate the exposure levels for humans	Manaca et al., 2012
Mozambique / Manhica (n=214; collected 2002–2006)	Levels of DDT and metabolites in cord blood are same as in western countries. Lower levels were associated with mothers of multiple pregnancies and higher education	Manaca et al., 2013
European cohorts (n=7990 mothers from 15 cohorts) / OBELIX, ENRICO, ArcRisk	Exposure to DDE was not associated with birth weight adjusted for gestational age	Govarts et al., 2012
Czech Republic / Breastmilk monitoring study (15 years, 9 regions, n=4753 mothers)	The rapid decrease in levels of DDT (7–9 % of levels in 1994 were found in 2002). Levels of DDE are about 72% of those in 1994	Mikeš et al., 2012
HCHs		
North-West Russia / different regions / 70 food items	Meat and poultry are main sources for HCH intake	Polder et al., 2010
Czech Republic / Breastmilk monitoring study (15 years, 9 regions, n=4753 mothers)	Rapid decrease in levels of gamma-HCH and HCB (7–9% of levels in 1994 were found in 2002)	Mikeš et al., 2012
β-HCH		
Valencia / INMA Valencia (n=453 newborns)	Higher levels of β-HCH associated with higher levels of thyroid-stimulating hormone at birth	Lopez-Espinosa et al., 2010
HCB		
Menorca / INMA Menorca cohort (n=285, four years' old children)	Levels of HCB higher in breastfed children than those fed by formula. Girls had higher levels than boys	Grimalt et al., 2010
Valencia / INMA Valencia cohort (n=499 mothers of Latin American or European descent)	Levels of HCB higher in cord blood from mothers of European descent than Latin American ones	Vizcaino et al., 2010
Valencia and Menorca/INMA cohorts (n=174) and Menorca (n=91)	Higher values of HCB in Menorca	Vizcaino et al., 2011a
North-West Russia / Nelmin-Nos, Izhma and Usinks (n=209; 72 females)	Decrease in HCB levels, especially in males, over 10 years	Rylander et al., 2011a
Northern Norway / MISA (n=391; 19 POPs, 10 thyroid parameters, multipollutant assessment, PCA)	HCB inversely associated with levels of T_3, T_4 and FT_4. Exposure to POPs can alter maternal thyroid homeostasis	Berg et al., 2017a
Nonachlors		
Northern Norway / MISA (n=391; 19 POPs, 10 thyroid parameters, multipollutant assessment, PCA)	Nonachlors inversely associated with levels of T_3, T_4 and FT_4. Exposure to POPs can alter maternal thyroid homeostasis	Berg et al., 2017a

PCA: principal component analysis.
ENRICO: ENvironmental Health RIsks in European Birth Cohorts; INMA: Environment and Childhood study; MISA: Northern Norway Mother-and-Child Contaminant Cohort Study; OBELIX: OBesorgenic Endocrine disrupting chemicals: Linking prenatal eXposure to the development of obesity later in life.

Literature reviews/meta-analyses have been prepared using the results of these studies on PCBs and DDTs in relation to several health outcomes. The critical reviews/meta-analyses (Govarts et al., 2012; Nieminen et al., 2013a,b) showed a negative correlation between birth weight of newborns and maternal exposure to PCBs, as well as no correlation between the sex ratio of newborns and parental exposure, or between birth weight and exposure to DDTs. A standardized regression coefficient was developed as an effect size index by Nieminen et al. (2013b), since research findings could not be combined by using effect size statistics (Nieminen et al., 2013b). Variability across studies with regard to the selection of variables and reporting practices made it difficult to combine and compare the results of the original studies, and there were problems with methodology, presentation of findings and reporting results in the form of descriptive statistics. It is important to provide detailed information on study protocols, analysis and reporting practices so that other researchers can use the results in their summaries and meta-analyses of the magnitude of effects (Nieminen et al., 2013a,b).

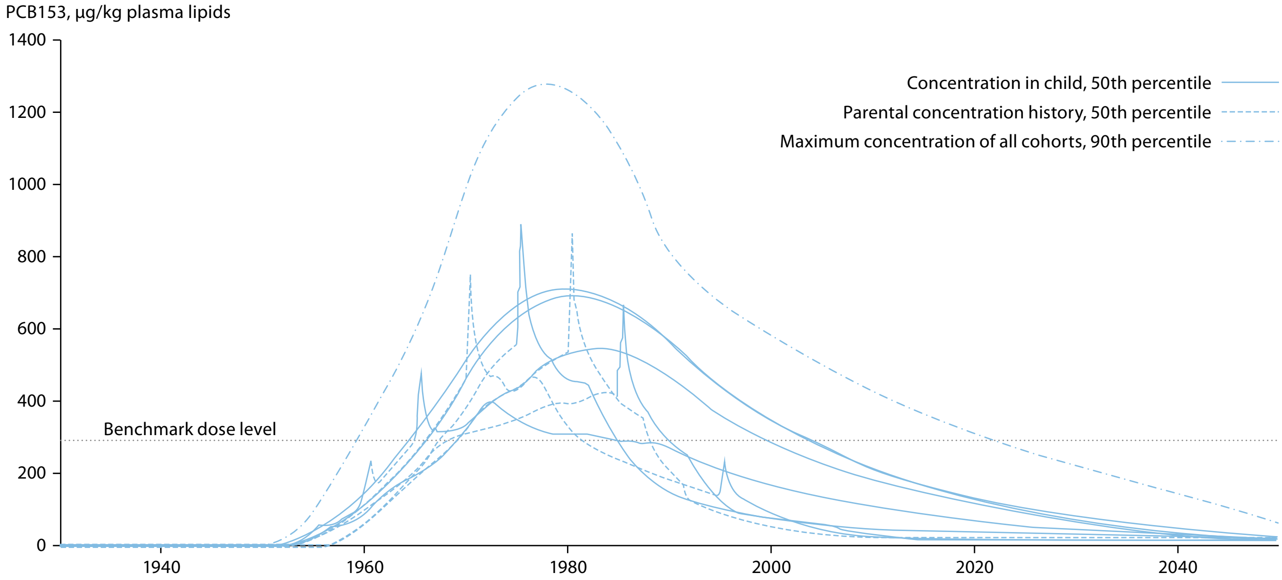

Figure 7.6 Extrapolated concentrations of PCB153 in pooled plasma lipids among pregnant Inuit women living in Nunavik (Quebec, Canada), Disko Bay (Greenland), and Nuuk (Greenland). Curves represent the birth cohorts of 1940, 1950, 1960, 1970, 1980, and 1990 (Abass et al. 2013).

Overall, the levels of PCBs and other POPs have generally declined over the 20 to 30 years of follow-up for the ArcRisk populations studied, the size of the decrease depending on compound, region, and population characteristics (see also Chapter 3). A decline in serum levels for all POPs (n=41) except chlordanes was found in males of the Tromsø study in the 30-year follow-up. The long-term data indicate an ongoing decline in concentrations of POPs in breastmilk in populations of central Europe. However, concentrations of some POPs are still high, and levels of some (e.g., PCB153) are stable in certain Arctic populations of Europe and Russia. Mean concentrations of PCBs in Indigenous children and adults in Indigenous populations are unchanged in the Russian Arctic (see also Chapter 3).

One of the new approaches in the ArcRisk project was to develop new methodologies, such as modeling. The toxicokinetic modeling for Inuit women living in Disko Bay (Greenland), Nuuk (Greenland), and Nunavik (Quebec, Canada) used PCB153 concentrations from the AMAP monitoring program. Inuit born in the 1960s and 1970s have a greater lifetime exposure than Inuit born earlier or later (Figure 7.6).

The known disposition of the chemical in the body together with population toxicokinetic modeling makes extrapolation possible with acceptable accuracy. Exposure of babies during breastfeeding was highest between the 1980s and 2000s, but more rapid elimination at a younger age lowers the body burden quickly such that the lifetime exposure is lower than for older cohorts. Another modeling approach for human health risk assessment was used in connection with long-term monitoring of POPs in breastmilk in the Czech Republic (Mikeš et al., 2012).

7.4.3 Brominated and perfluorinated compounds

The Mediterranean population studied showed higher concentrations of polybrominated diphenyl ethers (PBDEs; especially PBDE209) than populations in other parts of Europe (Figure 7.7, Table 7.6). Young children (0 to 6 years in age) had the highest concentrations, probably related to high exposure during growth. Attention deficit hyperactivity disorder (ADHD) and poor social behavior were associated with PBDE levels measured in children at age four years in the INMA cohort (Cascon et al., 2011).

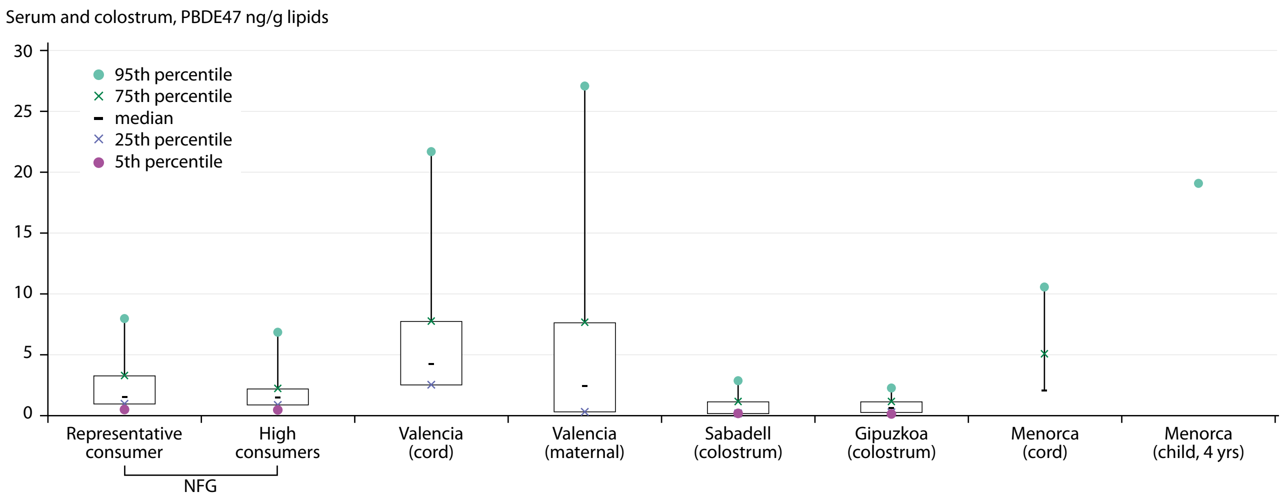

Figure 7.7 Overview of serum and colostrum PBDE47 concentrations in ArcRisk study groups (AMAP, 2014).

Table 7.6. Main findings on brominated chemicals, fluorinated chemicals and others in the ArcRisk publications.

Compound	Geographical area / Cohorts / Projects	Main findings	Source
BFRs	Norway / HUMIS (subgroup n=239 women, 6 PBDEs, part of samples HBCD and PBDE209)	No association between TSH of newborn and exposure to HBCD and PBDEs. PBDE levels in human milk in Norway same as found in Europe and Asia	Eggesbø et al., 2011
PBDEs	Spain / Catalonia (n=731, general population).	Inverse age-dependent levels of PBDE209 and other PBDEs. Highest levels in Europe, Asia, New Zealand and Australia; lower than in North America	Garí and Grimalt, 2013
PBDEs	Spain / Valencia (n=174 pregnant women, cord blood and serum samples from mothers)	Most abundant PBDEs were PBDE47, PBDE99 and PBDE153. In cord blood levels of PBDEs were 45% of maternal serum	Vizcaino et al., 2011b
PBDEs	Spain / INMA Menorca cohort (n=482, children at 4 years)	ADHD and poor social behavior were associated with levels of PBDEs in children at 4 years	Cascon et al., 2011
PFOS, PFOA	Finland / Human placental *ex vivo* perfusion system	Organic anion transporter 4 may decrease fetal exposure to PFASs and protect fetus from maternal exposure to PFASs. PFOS and PFOA across human placenta	Kummu et al., 2015
PFASs	Norway / MoBa study (n=487; associations of 4 PFASs, socio-economic status, FFQ)	Previous pregnancies and duration of breastfeeding the most important determinants of PFASs	Bransæter et al., 2013
PFASs	Northern Norway / Tromsø study (n=53 males, samplings since 1979, five time points, last one 2007)	Temporal trend data of levels of 10 PFASs followed trend in historic production and use over 30 years	Nøst et al., 2014
PFASs	Northern Norway / MISA (n=391; 19 POPs, 10 thyroid parameters, multipollutant assessment, PCA)	Among 26 PFASs, PFOS was positively associated with TSH; PFDA and PFUnDA inversely with T_3 and FT_3. Exposure to POPs can alter maternal thyroid homeostasis	Berg et al., 2017a
Xenoestrogens (bisphenol A and para-nonylphenol)	Experimental study / human first trimester / term placental villous explant culture	Environmental xenoestrogens decrease placental ABCG2 transporter protein expression in human term placental explant cultures. (ABCG2 is protecting fetus against foreign chemicals)	Sieppi et al., 2016
Pyrethroids	Mozambique / Manhica region (n=22 breastmilk samples)	Insecticides found in breastmilk samples, and in dwellings	Feo et al., 2012
Benfuracarb	*In vitro* metabolism	Human CYP3A4 is the major enzyme in carbofuran formation and main source for human inter-individual variations	Abass et al., 2014a
Benfuracarb	Species-specific metabolism	Metabolism differs between species (e.g., rat, mouse, humans) and this should be taken into account when estimating chemical risk assessment based on experimental studies	Abass et al., 2014b
Cyclic volatile methylsiloxanes (cVMS)	Norway / NOWAC and MISA cohorts (sub-groups of n=94 and n=17, respectively)	No significant correlation between levels of cVMS and reported body cream use	Hanssen et al., 2013

PCA: principal component analysis.
HUMIS: Norwegian Human Milk Study; INMA: Environment and Childhood study; MISA: Northern Norway Mother-and-Child Contaminant Cohort Study; MoBa: Norwegian Mother and Child Cohort Study; NOWAC: Norwegian Women and Cancer Study.

The perfluorinated compounds, perfluorooctane sulfonic acid (PFOS) and PFOA, have been shown to cross the human placenta in an *ex vivo* perfusion system (Kummu et al., 2015). Findings also suggest that these environmental contaminants interact with placental transporter proteins, which may affect fetal exposure to xenobiotic compounds. The data imply that transporter protein function may cause person-to-person variation in fetal exposure to environmental contaminants, which may affect individual risk for adverse events after exposure to harmful compounds. PFOS was associated with thyroid hormone homeostasis in newborns and POPs may alter maternal thyroid status in the MISA cohort (Berg et al., 2017b). Temporal trend data for per- and polyfluoroalkyl substance (PFASs) levels follow the production, use and restriction of compounds over the 30-year period for participants of the Tromsø study (Nøst et al., 2014) (see also AMAP, 2015; Gibson et al., 2015).

7.4.4 Other research in the ArcRisk project

The ArcRisk project also included research focused on new chemicals (e.g., bisphenol A), exposure through skin or air, the establishment of new cohorts or registers, research reports on climate change and new methods for risk estimation (see Table 7.7). One important topic was diet and contaminants in foodstuffs.

The dietary shift from traditional food items (especially marine mammals) to imported foods from other regions will affect exposure to POPs in the rural Arctic (see also Chapter 2). Models suggest that such transitions can result in reductions in POPs exposure in excess of an order of magnitude over a period of decades (Pacyna et al., 2015). This dietary transition may therefore swamp other potential effects of global climate change on human exposure to organic contaminants in the North, especially if it involves a major reduction in the

Table 7.7 Main findings from remaining papers arising from the ArcRisk project.

Topic	Geographical area / Cohorts / Projects	Main findings	Source
Diet + apolipoproteins	Russia / Arkhangelsk County / Cross-sectional study (n=249, rural Nenets region and Arkhangelsk City)	Rural region had healthier dietary sources, less atherogenic lipid profile in blood compared to those in urban regions. Fish consumption had no effect on apolipoprotein profile	Petrenya et al., 2012
PCA analyses and dietary intake	Northern Norway / MISA (n=266-498)	Use of PCA is helpful for calculating interrelationships within contaminant groups (toxic metals, essential elements, POPs) and dietary items	Veyhe et al., 2015
Cohort description	Northern Norway / MISA	Description of MISA cohort	Veyhe et al., 2012
Climate change and environmental impacts	Review / Climate and environmental changes on maternal and newborn health	Climate change increases the impacts on human health, efforts should be made to reduce risks on next generations (e.g. global politics and research)	Rylander et al., 2011b
Iodine status	Northern Norway / MISA study (n=197; association of iodine status and thyroid homeostasis)	Iodine deficiency is found among MISA participants, and it affects maternal thyroid homeostasis and is risk for fetal development	Berg et al., 2017b
Birth register	Russia and Norway (Murmansk County, Northern Norway; n=17302 births)	Perinatal mortality was higher in Murmansk than northern Norway	Anda et al., 2011
Lifestyle, living condition and fish supplies	Russia / Nenets Autonomous area and Arkhangelsk city (n=134, n=166 adults, respectively)	Locally caught whitefish is major part of food in rural region, cod and cod-family fish were used in urban region	Petrenya et al., 2011
Human biomonitoring	Mini-review	In the sparsely populated areas there are special challenges, such as importance of ethics and communication strategies, especially among Indigenous Peoples	Odland and Nieboer, 2012
Urban air particles	Risk assessment of inhalation scenarios	New approach for human health risk assessment using inhalation scenarios has been developed	Čupr et al., 2013

PCA: principal component analysis.
MISA: Northern Norway Mother-and-Child Contaminant Cohort Study.

consumption of marine mammals. The influence of climate and environmental change on future exposure to POPs in food will largely depend on the amount and type (wild or farmed) of fish and other seafood consumed (see also AMAP, 2015, 2019). It is not possible to draw any final conclusions about exposure trends and effects on population health.

7.5 Conclusions and recommendations

In many of the EU-funded projects the focus has been on developing networks for informing policymakers about environmental contaminants and their risks for human health in Europe, the Arctic and other countries. These projects, as well as ArcRisk, suggest the need for more collaboration, harmonized human biomonitoring programs and study designs, and joint databases for national cohorts to provide more evidence about the causal relationship between contaminant levels and human health.

Although the environmental levels of POPs are generally declining, there are regions and populations where concentrations are stable, variable, or even rising, such as for PBDEs. The trend in levels of contaminants may vary in different geographical areas in the Arctic and Europe, for example, new ‘hot spots’ may develop. The warming Arctic and permafrost thaw may influence future exposure patterns in the Arctic. Natural catastrophic events due to global climate change, such as tsunamis and floods, which can spread contaminants to other areas may affect contaminant levels in food.

There is a need for new methodology for risk assessment and better use of existing data. Improved models are required to better characterize exposures, such as concentrations of contaminants in human tissues (e.g., breastmilk, urine, hair, blood). For each population there may also be other possibly more significant sources of exposure that are not generally considered in a conventional risk assessment (such as dermal exposure, air pollution). In the Arctic, migration from rural areas to bigger communities and urban settlements is a growing pattern, and must be accounted for in future estimates of contaminant exposure. It is difficult to link health outcomes to one specific contaminant when people are exposed to mixtures.

Harmonized study protocols are required to improve estimates of links between health effects and exposure. Avoiding adverse effects on human health from exposure to contaminants requires an overall strategy that integrates policies and measures to reduce the use and release of contaminants, monitoring of environmental levels and human exposure, education and risk communication, and where necessary food consumption advice to critical groups (see also Chapter 6).

Future work in One Health must include continued promotion of a One Health approach, creating opportunities for knowledge sharing, simulation exercises, collaboration with other networks, and joint research and educational programs as tools for continued capacity building. Inclusion of traditional and local knowledge is a key aspect of One Health for regional resilience.

There is a growing body of research on the impact of metal contamination in terrestrial water bodies, and the development of antimicrobial resistance in resident bacteria without prior exposure to antibiotics (Bischofberger et al., 2020). This has added an important dimension to the ongoing research on contaminant impacts on human and wildlife health.

The link between infection and cancer in the circumpolar North and globally has been recognized for decades (Oh and Weiderpass, 2014). The association between metals and organohalogen contaminants has also been well described (see Chapter 3). The possible role of contaminant exposure, in the presence of infectious agents associated with cancer such as the Epstein-Barr virus or the bacterium *Helicobacter pylori*, both known often to be asymptomatic infections has been less frequently considered. The interaction of two potentially carcinogenic stressors could be statistically examined using blood sample data from the AMAP databases, together with longitudinal health records. Demonstrating an association of increased risk of cancer in a population with both risk factors would add urgency to efforts to decrease human exposure to microorganisms associated with cancer, in a setting with known anthropogenic contaminant exposure.

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8. Key findings, research priorities and recommendations

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This chapter comprises three sections: key findings from the chapters of this assessment, knowledge gaps and priorities for future research, and recommendations. The relationship between these conclusions and those from previous AMAP assessments is described. While some of the findings reported in this assessment have helped to refine areas of uncertainty reported previously, there remain many areas in which further work is needed.

8.1 Key findings

8.1.1 Dietary transition

- Most Arctic populations have experienced a transition towards more imported foods.
- The dietary transition has had adverse impacts on health in some populations, such as an increase in obesity or impaired dental status.
- Intakes of vitamin D and iodine have decreased due to lower fish and/or milk consumption. These nutrients should be monitored in Arctic populations.
- Positive health impacts of the dietary transition include significantly reduced levels of contaminants in the blood of pregnant women.
- Whether dietary transition is negative or positive for health depends on the composition of the new diet, as well as the extent to which the traditional diet is maintained.
- Communication about dietary risks and benefits is vital.
- Food insecurity is a growing concern in some Arctic populations and collaboration between countries should be established to address this.
- There are gaps in the research field of dietary studies within Arctic Indigenous populations. More studies are needed, especially within the many Arctic populations in Russia.

8.1.2 Human biomonitoring and exposure

- The highest levels of mercury and persistent organic pollutants (POPs) are in Greenland, the Faroe Islands, and Nunavik (Canada), plus coastal Chukotka (Russia) for POPs only.
- Perfluorooctane sulfonic acid (PFOS) is the predominant per- and polyfluoroalkyl substance (PFAS) measured in most populations across the Arctic, and concentrations for pregnant women and children measured in the past decade are generally highest in Greenland. Perfluorooctanoic acid (PFOA) is the second most predominant PFAS, although there are a few exceptions: higher levels of perfluorononanoic acid (PFNA) than PFOA on St. Lawrence Island, Alaska (USA) and in the Canadian Arctic (especially in Nunavik) and in pregnant women from Greenland; higher levels of perfluorohexane sulfonic acid (PFHxS) than PFOA in children from Sweden; and higher levels of PFOA than PFOS in children from Finland.
- Concentrations of most POPs and metals are declining in Arctic regions where time trend data exist, although the declines are neither uniform nor consistent across all regions. The exception is PFASs, with concentrations of some long-chain PFASs such as PFNA increasing in Nunavik, Greenland and Sweden.
- Several contaminants previously identified by AMAP as chemicals of emerging Arctic concern have been detected in the Arctic. Baseline levels have been measured in parts of the Canadian Arctic and Greenland; only in Sweden are there sufficient data to establish time trends.
- A comparative study of mercury levels in pregnant women across seven Arctic countries found the highest mean mercury levels to occur in Greenland and Nunavik. A comparison of POPs in pooled samples from five of the original regions found the highest levels of POPs in pregnant women in Nunavik, while levels in Norway, Sweden and Finland were similar and relatively low. Levels of most PFASs in pregnant women were similar between regions, although PFOS, PFNA and perfluoroundecanoate (PFUnDA) levels were higher in Nunavik and PFOA and PFHxS levels were higher in Finland. Levels of many dioxins and furans were below the limits of detection; detected levels were highest in Iceland and Finland.
- Levels of mercury, PCB153 and DDE in some Arctic regions are comparable to those in some non-Arctic regions, but for those Arctic regions with the highest levels of these contaminants, concentrations are generally higher than for most non-Arctic regions. Levels of polybrominated diphenyl ethers (PBDEs) are relatively low in the Arctic (except for Alaska), while PFAS concentrations are comparable to those in many non-Arctic regions.

8.1.3 Health effects associated with measured contaminants in the Arctic

- Contaminants found in the Arctic, such as mercury, lead, PCBs, and PFASs, have known or suspected adverse health impacts on humans – especially on developing fetuses and children. Lifestyle, diet and nutrition, and genetics can influence the risk of these impacts.
- Dietary exposure to some POPs, PFASs, and metals such as mercury can have negative impacts on the brain and immune system, increase the risk of childhood obesity, increase the risk of Type 2 diabetes later in life, and negatively affect fetal growth and development.
- Foods with high levels of mercury can diminish the cardiovascular benefits of omega-3 fatty acids. Mercury toxicity has also been associated with adverse neurological outcomes, which may be underestimated in studies that fail to account for the beneficial effects of omega-3 fatty acids.
- Genetic makeup, lifestyle, nutrition status, and contaminants interact to influence the risk of adverse effects such as cancer, reproductive effects, impacts on fetal and child

growth, metabolic disease, and nervous system disorders. Exposure to contaminants, including some POPs, PFASs, and phthalates, plays a role in the increased incidence of cancer in Arctic regions.

8.1.4 Human health risks associated with contaminants in the Arctic

- Different jurisdictions set different guidance values for POPs and metals designed to protect health. The guidance values can differ based on, among others, estimated dietary intakes, approaches to uncertainty, population to be protected, purpose of the guidance, and the mandate of the organization issuing the guidance.
- Guidance values can vary in complexity, from a maximum level in a food item, to a recommended maximum dietary intake, to a level measured in human matrices below which effects are unlikely to be observed. These guidance values can be based on epidemiological, experimental and/or modeling studies.
- Since the 1990s, there has been a trend of decreasing mercury and lead exposure, resulting in fewer exceedances of guidelines. The regions where mercury and lead guidelines were exceeded are Nunavik and Greenland.
- Indigenous Arctic populations were identified as a population in need of improved contaminant exposure estimation tools.
- Future studies are necessary in order to reduce uncertainties in the estimates of health risks from exposure to environmental contaminants by better identifying the sources of contaminants; deriving and/or updating reference values for key contaminants; exploring risk assessment methods to address risks associated with mixtures; and improving the overall process of health risk assessment, including harmonizing reference values where possible.

8.1.5 Contaminant risk communication update

- Current risk communication activities in most Arctic countries emphasize the importance of a nutritious diet. Contaminant-related restrictions are mostly based on mercury; a limited amount of dietary advice is also based on other contaminants.
- Specific data on effectiveness evaluation is limited to a few regions in Canada and a few other countries. Only Sweden has provided information on the effectiveness of their national dietary advice. More health communication and risk perception data are important in order to compare results to other regions and countries across the circumpolar Arctic.
- There is a lack of information on risk communication specifically for Indigenous Peoples in Arctic countries other than Canada (such as Saami in Europe).
- Risk communication with Arctic Indigenous Peoples should be developed in full partnership with the affected people (regions and/or communities) and needs to involve regional health authorities and local clinicians (nurses, physicians, Indigenous midwives).
- In risk communication activities, trusted relationships between all involved parties (particularly between communicators and recipients of the messages) are crucial for the success of the communication. This trust is difficult to build and very easily damaged or destroyed.
- Very targeted, regular, clear communication, and timely and personalized messaging, is required to ensure retention of messages and to enable reduced contaminant exposure.
- Risk communication needs to be well-balanced, and should take into account cultural aspects and benefits of country, local and traditional foods.
- Sensationalized and alarmist messages that contradict cultural values of local audiences can result in confusion, fear, or 'inoculation effects', and thus can threaten the success of future communication.
- Social media, when properly managed, may be a useful tool in risk communication. It enables two-way communication, may help to better reach target audiences, and may help build relationships. Information on its use in risk communication (especially in the Arctic) is still very limited.
- Communication of contaminant risk is a very complex undertaking. Risk communication is a tool available to protect populations under current conditions; however, it is not a sustainable solution to ensure low levels of contaminant exposures in human populations. It is therefore crucial that regulatory actions to decrease contaminants in the environment are implemented effectively.

8.1.6 The Arctic in global context

- For reasons that include dietary change, a warming Arctic may not greatly change contaminant exposure. Current levels of contaminant exposure in Arctic residents and some parts of Europe may have little impact on child development outcome, according to the results of the ArcRisk project. Fish consumption is the major source of mercury exposure in the European Arctic. It is difficult to link health outcomes to one specific contaminant because people are exposed to mixtures of a number of different contaminants.
- Exposure to legacy contaminants in Arctic residents is decreasing, although this shows regional variation. Long-term data for contaminants of emerging Arctic concern are not available in most regions. Migration from smaller communities to larger towns and cities is a growing trend in the circumpolar North, and is accompanied by changes in diet and a resulting decrease in contaminant exposure.
- There is growing awareness of the usefulness of the One Health paradigm as a means to improve the ability of residents, public health agencies, and wildlife resource managers to address existing environmental threats and recognize emerging threats at an early stage.
- There is a lack of knowledge about the health impacts of contaminants on wildlife, including a possible immunosuppressive effect, potentially resulting in a rise in active zoonotic infections in exposed wildlife, and increased risk to human consumers. Warming and permafrost thaw may influence both contaminant

exposure and the spread of zoonotic infectious diseases. The growing trend in migration from smaller to larger communities and urban centers in the circumpolar North may be accompanied by changes in exposure to contaminants and zoonotic diseases.

- Epidemiological zoonotic / human disease models are needed, as well as new approaches to integrate existing and future data. The models should enable estimates of the risk and magnitude of human and wildlife health impacts, and changes in disease and contaminant exposure in response to different climate change scenarios.
- Multidisciplinary research is needed on critical issues, including lifetime contaminant accumulation, lifetime exposure to zoonotic pathogens, and health consequences for wildlife and human consumers.
- Many components of the One Health model require additional research, including research on contaminants, infectious diseases, drinking water and climate change.

8.2 Research priorities

8.2.1 Harmonized approaches

Use of harmonized approaches is required to ensure high quality data and comparability of results.

The need to develop uniform methods to allow for comparisons of studies across the Arctic was established in 1998 (AMAP, 1998) and supported in subsequent assessments (AMAP, 2003, 2009, 2015). Reporting of health outcomes using uniform indicators and similar reporting structures helps to understand trends and make meaningful comparisons (AMAP, 2009). In 2015, AMAP recommended that guidance on harmonized study designs, statistical methodologies and results reporting would make it possible to carry out strong meta-analyses and enhance the ability to compare results across all regions (AMAP, 2015).

Previous assessments have provided significant amounts of information on the general health of Arctic residents (e.g., AMAP, 2003, 2009). In 2009, AMAP recommended that its assessments include the systematic collection, analysis and reporting of health status, especially for Indigenous Peoples (AMAP, 2009).

One mechanism for achieving harmonized results is through the use of biobanks. It was reported in the early AMAP assessments (AMAP, 1998, 2003) that the creation and management of biobanks was important. The establishment and maintenance of a biobank of human specimens is a huge undertaking; and yet, there are well-established biobanks in many regions. Results from the MercuNorth project reported in this assessment (see Chapter 3) provide evidence for the value of biobanks. Samples from pregnant women recruited from across the circumpolar Arctic and included in different studies were analyzed by several laboratories to provide comparable baseline levels of mercury prior to the ratification of the Minamata Convention. Biobanks are also an important resource for screening contaminants of interest in the future.

Many cohort studies have been initiated (see Chapter 1, Table 1.1); however, there is still more work to be done to develop and introduce harmonized study designs and methods. For example, the importance of guidance on appropriate matrices to ensure that sampling protocols accurately reflect exposures was highlighted in a study of Norwegian adults, in which perfluorohexanoic acid (PFHxA) was detected in whole blood but not in serum or plasma. Similarly, the importance of guidance on the timing of sample collection is demonstrated by the seasonal differences in contaminant levels that have been linked to differences in dietary patterns that reflect increased country, local and traditional food consumption in summer and autumn.

Participation by analytical laboratories in external quality assurance and quality control (QA/QC) schemes provides confidence that comparisons between laboratories are valid and data are of high quality. The participation of laboratories in different QA/QC programs for data submitted to this assessment is outlined in Chapter 3, Table 3.1. As contaminants of emerging Arctic concern are identified and included in monitoring programs, the importance of QA/QC programs is even greater to ensure that emerging methodologies and new data are comparable.

Despite some harmonization, there are still gaps in comparable approaches.

Priorities for future work include:

- Participation in QA/QC programs as a requirement for all laboratories submitting data for inclusion in AMAP assessments.
- Guidance on harmonized study designs, statistical methodologies and results reporting, including harmonized methods for assessing dietary intake, food security, health outcomes, and northern food environments, to enable comparisons that are more accurate across populations and over time and that consider season, and gender- and age-based differences in consumption.
- The creation and maintenance of biobanks for as many projects as possible.
- A systematic update on the general health status of Arctic inhabitants.

8.2.2 Interactions between nutrients and contaminants

Studies of the interactions between nutrients and contaminants will help to provide balanced advice on reducing risks from contaminants in food while maintaining the nutritional benefits of country, local and traditional foods and imported foods.

In its second human health assessment, AMAP recommended that studies on the nutrient content of country, local and traditional food items should be promoted (AMAP, 2003). Promoting improved access to country, local and traditional foods that have lower levels of contaminants and higher levels of nutrients was subsequently recommended in its third human health assessment (AMAP, 2009), as was the importance of studying the interactions between contaminants and nutrients (AMAP, 2009, 2015). It was also noted that more research was needed on determinants of food choice and availability, including age and gender differences, to inform dietary advice. Studies that included both biomonitoring and total diet components were also needed to better characterize exposure estimates and provide dietary advice (AMAP, 2009).

This assessment describes dietary transitions across the circumpolar Arctic (see Chapter 2). The dietary transition is well documented in some areas through the use of regular surveys (e.g., Faroe Islands, Greenland, Iceland, Norway, Sweden). In other areas up-to-date information is lacking (e.g., Finland, Russia). In general, there has been a shift towards imported or store-bought foods. However, country, local and traditional food consumption has been consistent over the past 25 years in some areas (e.g., fish and terrestrial foods consumption in the Northwest Territories, Canada; fish consumption in Finland; fish consumption in Chukotka, Russia). Similarly, there has been no change in some food preparation methods (e.g., use of the *hjallur* in the Faroe Islands).

Whether dietary transitions have positive or negative effects on health depends on which food components are adopted from a new diet and to what extent components of the local diet are changed and/or continue to be consumed. Positive outcomes of the observed dietary transition include a decline in contaminant levels, such as mercury in the Faroe Islands and Greenland; increases in dietary fiber in Greenland and Norway; and, decreases in trans-fatty acid intake in Iceland. In some cases, it is the availability of imported foods, rather than messaging about contaminants, that is suspected to have resulted in the positive effects observed (such as declining mercury levels in individuals in the Faroe Islands). Adverse consequences of the observed dietary transitions include documented declines in nutrient levels linked to declines in country, local and traditional food consumption, such as declines in Vitamin D in Alaska and Canada; omega-3 fatty acids in Greenland; and iodine in young Icelandic and Norwegian women. The declines in Vitamin D and iodine differ substantially by country. Other negative impacts include increasing obesity, metabolic disorders, and dental problems related to the consumption of high-sugar and processed foods.

Country, local and traditional foods have been found to be a large contributor for important nutrients. This is supported by the finding that vitamin D levels were higher in Russian ethnic groups with a more traditional lifestyle than in those leading a less traditional lifestyle. Initiatives to increase awareness of the benefits of country, local and traditional foods, the best types of country, local and traditional food to consume (low in contaminants, high in nutrients), the development of programs to increase access to country, local and traditional foods, and education around food handling and preparation have been undertaken in Canada and Greenland. In other countries, efforts to improve vitamin D levels have occurred through supplementation of dairy products and margarine and use of cod liver oil. Finland has also addressed iodine levels through fortification of cow fodder and table salt. These efforts are important as nutrient deficiencies have been associated with adverse outcomes (see also Chapters 2 and 4).

Increased rates of obesity and/or diabetes have been noted in Indigenous populations in Alaska, Greenland, Canada, the Saami in Norway and Sweden, and in the populations of Iceland and Sweden. Decreases in cardiovascular disease have been observed in Sweden, with a change to more unsaturated fats as a contributing factor. In Chapter 4 of this assessment, evidence is presented for increased risk of overweight/obesity and Type 2 diabetes as a result of prenatal exposure to POPs. However, no significant associations were observed between PCBs, organochlorine pesticides and blood pressure among Greenlanders. Most remarkable is a recent prospective study of Inuit in Greenland showing no association between blood mercury and the risk of developing cardiovascular diseases.

The findings of this assessment validate previous recommendations for studies on the nutrient content of country, local and traditional foods and interactions between contaminants and nutrients that affect health outcomes. Proposed work under the SAMINOR study (Norway), the HALDI study (Sweden) and the Inuit Health Survey (Canada) will provide important information for Indigenous Peoples in the Arctic. The goal should be getting the best out of both the traditional and imported components of the diet.

Priorities for future work include:

- Understanding modern dietary changes and reasons behind dietary choices. Dietary intakes should be continuously monitored in Arctic populations, especially in Russia, where there is a lack of dietary studies.
- Risk-benefit analyses to compare country, local and traditional foods with store-bought foods while considering health, economics, local contexts, cultural resilience, and sustainability.
- The effects of low nutrient levels on human health status.
- The influence of sex, age, socio-economic status and geographical location on dietary intakes and dietary transition patterns.
- Promotion of knowledge of the most healthy country, local and traditional foods.
- The interactions between contaminants and nutrients and the benefits and risks associated with country, local and traditional foods.
- Monitoring of Vitamin D and iodine levels in Arctic populations, and consideration of the need for dietary enrichment.
- Partnerships among academics and Arctic Indigenous communities and organizations conducting dietary research using an approach based on co-production of knowledge.

8.2.3 Risk communication messaging

Risk communication messaging should promote the nutritional value of foods while providing information on the risk of contaminants.

Risk communication has always been acknowledged as a necessary but challenging endeavor. Early recommendations were to enhance the development of local information and advice for Indigenous Peoples (AMAP, 1998, 2003). These recommendations were followed up by further advice that regional health authorities should collaborate with communities to develop effective, culturally appropriate strategies and to enhance messaging about the benefits of country, local and traditional foods, in addition to promoting the benefits of breastfeeding and providing balanced advice that includes the benefits of country, local and traditional foods and the risks concerning contaminants (AMAP, 2009, 2015). Similarly, since the first human health assessments, AMAP has noted the need for relevant and up-to-date tolerable intake values (AMAP, 1998, 2003), because these would help to interpret and communicate risk-benefits. In 2009, AMAP recommended that communication efforts should be evaluated with respect to their impact on the intended audience (AMAP, 2009).

This assessment includes several examples that provide evidence of work being done in these areas to improve risk communication messaging (see Chapter 6). Several countries have published consumption guidance for certain food items. In the Faroe Islands, a campaign against eating pilot whale included information about the nutritional qualities of fish that are low in contaminants. Similar advice has been issued in Greenland. In addition to examples of messaging that is co-developed with communities, there are also examples of evaluation studies that can help to inform future messaging. These types of studies provide important information on the successes and challenges of communication efforts and help to formulate best practices. Some recent research findings support the benefits of fish consumption in relation to cardiovascular effects (see Chapter 4). These types of findings should be incorporated into risk-benefit messages.

There have been many examples of good messaging over the past twenty years; however, there continue to be situations that challenge the importance of balanced messaging and the effects of widespread messaging reaching an unintended local audience (such as unfounded concerns regarding a beluga with toxoplasmosis – see Chapter 6). Trusted relationships between all involved parties (particularly between communicators and recipients of the messages) are crucial for the success of risk communication activities.

As reported in this assessment, the source of the messaging is very important, as is the medium through which it is delivered, since alarmism can spread rapidly in unverified and unregulated social media networks. Groups have worked to make meaningful data accessible to the appropriate audience, while attempting to minimize misuse of information (such as the LEO network). More can be done to use social media as a two-way communication tool.

Risk communication can be supported by research studies to reduce uncertainties in the estimates of health risk from exposure to environmental contaminants by better identifying the sources of contamination, and by improving the overall process of health risk assessment (see Chapter 5).

It is clear that risk communication is key to educating and empowering communities to make the best food choices. However, experience has shown that communication of contaminant risk is a complex undertaking and is not a sustainable solution to ensure low levels of contaminants in human populations. It is therefore crucial that regulations to decrease contaminant levels in the environment are implemented effectively.

Priorities for future work include:

- Balanced messaging that appropriately presents the risks and benefits of country, local and traditional foods.
- Promoting increased consumption of species low in contaminants to increase dietary consumption of nutrients.
- Evaluation studies, including follow-up on policy recommendations to evaluate reception and awareness of the communication to ensure the success of the messages, and studies of the effectiveness of social media in risk communication. In addition, evaluation of the combinations of medium and messenger for a variety of health messages to improve understanding of optimal communication strategies for different communities.
- Data on health communication and risk perception are needed to compare results with those from other regions and across Arctic countries to help identify best practices, including cultural appropriateness, that could be used and adapted to specific regional and community needs.
- Collaborative communication projects undertaken with affected communities that take into consideration social, economic, and cultural factors to ensure that the projects are culturally appropriate.
- The development of tools (e.g., guidance values) and models to help reduce uncertainties in the estimates of health risks from exposure to contaminants.

8.2.4 Cohort studies and biomonitoring programs

Cohort studies and biomonitoring programs are needed to support time trends, follow populations with elevated levels, study health effects and identify contaminants of emerging Arctic concern.

AMAP identified the importance of establishing temporal trends in contaminant levels as early as 1998 (AMAP, 1998) and reiterated this finding in each subsequent human health assessment (AMAP, 2003, 2009, 2015). Even as declines were observed in the levels of many POPs, high exposure levels in some regions warranted continued monitoring in Arctic populations (AMAP, 2009, 2015). Other contaminants were identified, including short-chain chlorinated paraffins, pentachlorophenol, siloxanes, and parabens, and it was also recommended that future work should look at sources of contaminants because country, local and traditional foods are not associated with all contaminants of emerging Arctic concern in the same way that some POPs are (AMAP, 2009).

AMAP acknowledged the importance of health studies, especially cohort studies, in its first assessment (AMAP, 1998) and emphasized the importance of ongoing studies in the Arctic to better understand health effects and risk associated with current levels of exposure in the Arctic in all subsequent assessments (AMAP, 2003, 2009, 2015).

These recommendations remain valid. The time trends established through ongoing national and international efforts provide evidence for international chemicals management, which is the most viable solution for reducing exposure to contaminants in Arctic populations. Monitoring programs are important for documenting declining trends in POPs and for establishing trends for contaminants of emerging Arctic concern, such as PFASs. The value of this work can be seen in the ways in which these data have been used as evidence for the need to establish, and subsequently adopt, global conventions (e.g., Stockholm Convention, Minamata Convention) and to determine the limits now in place on more than thirty POPs under the Stockholm Convention.

Biomonitoring studies have documented exposure to POPs and metals, as well as other contaminants, some of which were identified in AMAP's report on chemicals of emerging Arctic concern (AMAP, 2017) (see Chapter 3). While there is a rich database for some contaminants, more data are needed for others in order to establish regional and temporal trends. For example, this assessment report presents more data on PFASs than AMAP's previous human health assessments, but there are still limited PFAS data over time and for several regions, as well as for some population groups.

Cohort studies not only provide a means to study contaminant-related effects on sensitive endpoints, but can also be used to study the effects of changing conditions on these associations (e.g., climate change, dietary transitions). Arctic cohorts were described in detail in AMAP's previous human health assessment (AMAP, 2015) and briefly summarized again here (see Chapter 1, Table 1.1). These studies are expensive, resource intensive and invaluable to the study of contaminants in the Arctic (see Chapter 4).

Priorities for future work include:

- Regular biomonitoring studies (e.g., every five years) to obtain data to support time trends, including inclusion of contaminants of emerging Arctic concern, particularly new PFASs.
- Support for, and expansion of, the use of cohort studies, which are important for making links between exposures and health outcomes in Arctic populations.
- Studies to identify the mechanisms through which exposure can lead to health impacts, to support the findings of epidemiological studies.
- A continued focus on exposure and health effects studies of pregnant women and women of child-bearing age whose diets involve significant consumption of marine mammals. This should include identification of prenatal and postnatal windows of vulnerability – the periods during which the fetus and infant are most vulnerable to impacts from exposure.
- Research on mixtures of POPs and their effects on reproductive health, cardiovascular outcomes and the immune system.

8.2.5 Multidisciplinary efforts and cooperation

Multidisciplinary efforts and cooperation between researchers and organizations with different mandates are required to address the complexities of contaminant research and to study contaminants within a holistic perspective.

In 1998, AMAP recommended multidisciplinary cooperation to combine expertise from multiple disciplines such as biomarker research, epidemiology and monitoring programs (AMAP, 1998). It was subsequently suggested that specific studies could support understanding of susceptibility and genetics, the toxicology of chemicals of emerging Arctic concern (e.g., polybrominated and perfluorinated substances), and the relationship between mercury and cardiovascular disease in Arctic populations (AMAP, 2009).

In its second human health assessment, AMAP recommended to pursue a more holistic health impact assessment of the influences of environmental pollution on the health of Arctic peoples and the associated risk factors affecting them, coordinated with related public health work initiated through the Sustainable Development Working Group (AMAP, 2003). In its third assessment, AMAP identified the need for research on climate change impacts on contaminants, including predictive models (AMAP, 2009). This was followed by a Climate Change and POPs assessment which included input from the Human Health Assessment Group (UNEP/AMAP, 2011). The need for climate-contaminant work was reiterated by AMAP in its fourth human health assessment (AMAP, 2015), along with the need to identify any change in contaminants in wildlife and availability/access to country, local and traditional foods as a result of climate change. Similar to other disciplines, harmonized approaches are important, as are region-specific adaptation strategies (AMAP, 2015).

As recommended in previous AMAP human health assessments, results reported in this assessment (see Chapter 4) have included studies of genetics and cardiovascular disease. Furthermore, health effects research has also included studies on the central nervous system, immune system, and reproductive system, as well as on endocrine disruption, diabetes, and cancer incidence.

Initial findings of the ArcRisk study (Arctic Health Risks: Impacts on health in the Arctic and Europe owing to climate-induced changes in contaminant cycling) were reported in the previous human health assessment (AMAP, 2015). Additional information on the outcomes of this project are presented in this assessment (see Chapters 4 and 7); this assessment also addresses other areas of a holistic assessment, including dietary transitions (Chapter 2), risk assessment methodologies (Chapter 5) and the One Health approach (Chapter 7).

Priorities for multidisciplinary work include:

- Collaborations with experts on zoonoses and climate change using a holistic approach, such as the One Health model.
- Acknowledgement of the importance of Indigenous knowledge and equitable engagement of Indigenous Peoples.
- Improved understanding of the health impacts of contaminants on wildlife, including possible immunosuppressive effects that could lead to an increase in active zoonotic infections in exposed wildlife and increased risk to human consumers.
- Research on critical questions related to lifetime contaminant accumulation, lifetime exposure to zoonotic pathogens, and the associated health consequences for wildlife and human consumers.

- Collaborative studies to investigate lifestyle implications (e.g., smoking), and interactions with influences outside the field of contaminants (e.g., climate change).
- Work to integrate research with other disciplines through support for other AMAP expert groups.

8.2.6 International cooperation on chemicals management

It is crucial that international efforts to regulate chemicals in the environment continue and that these regulations are implemented effectively.

International cooperation on chemicals management is the most important step in reducing chemical exposures for vulnerable populations in the Arctic. This can include measures to reduce and control regional industrial emissions (AMAP, 1998, 2015), strengthened efforts to control product uses and emissions (AMAP, 2003), support for international conventions (AMAP, 1998, 2003, 2009, 2015) and encouragement of global assessments of health and the environment (AMAP, 2003). In 2009, AMAP recommended that perfluorinated compounds be added to the Stockholm Convention and included in future routine monitoring, and that a global agreement on mercury be established (AMAP, 2009). In 2015, AMAP recommended that a precautionary approach to chemicals management be used for the introduction of contaminants of emerging Arctic concern (AMAP, 2015). AMAP has supported international chemicals management and has agreed to increase its presence both virtually and in person (AMAP, 2009). AMAP has already agreed that risk communication is not the solution and that continued efforts at the international level are required to reduce levels of contaminants in the Arctic (AMAP, 2015).

Since 2009, new POPs have been added to the Stockholm Convention. These include some perfluorinated compounds such as PFOS and PFOA. Other chemicals (PFHxS, its salts and PFHxS-related compounds, dechlorane plus, methoxyclor and UV-328) are currently at different stages of review and/or recommendation. Data from Arctic countries have supported these nominations. The Minamata Convention on Mercury was adopted in 2013 and entered into force in 2017. Through national programs and the MercuNorth project (see Chapter 3), AMAP has reported baseline levels of mercury in the Arctic that can be used to evaluate the effectiveness of the Minamata Convention in future years.

Priorities include:

- Advocating for reducing or eliminating contaminants at the source.
- Supporting the Stockholm Convention and Minamata Convention.
- Contributing to the identification of contaminants of concern to human health in the Arctic.

8.3 Recommendations

Based on the findings of the *AMAP Assessment 2021: Human Health in the Arctic,* and building on earlier AMAP assessments of human health impacts in the Arctic, AMAP recommends the following (AMAP, 2021):

Reduce or eliminate contaminants at the source

- Arctic States and all parties to the Stockholm and Minamata Conventions should strengthen and accelerate measures to eliminate POPs and human-made mercury emissions globally.
- Arctic States should take steps to reduce or eliminate chemicals of emerging Arctic concern such as PFASs through national policies and international agreements.

Promote healthy food choices

- To get the best out of country, local and traditional foods and store-bought Western foods, governments can, for example, promote consumption of foods low in contaminants. Effective communication can increase the use of healthy country, local and traditional foods (e.g., fish and terrestrial animals such as reindeer/caribou, musk ox, and sheep) and reduce intake of foods that are likely to have high levels of contaminants or that are otherwise unhealthy.
- Vitamin D and iodine levels should be monitored in Arctic populations and the need for supplements and fortification should be evaluated.

Monitor and address food insecurity in Arctic communities

- Food insecurity is a growing problem in some Arctic Indigenous populations as diets transition toward expensive store-bought food and environmental factors such as climate change affect the availability of country, local and traditional foods. Governments and non-governmental organizations should take an active role in monitoring food insecurity in Arctic communities and collaboratively develop proactive approaches to address it, building on and learning from existing best practices and models.

Expand efforts to collect data on exposure, dietary transitions, and health impacts

- Arctic States and research funding bodies should work to fill information gaps, such as the need for more data on lifelong human health impacts in the Arctic related to exposure to contaminants, dietary transitions, and nutrition. There are also geographical gaps in Arctic data on contaminant levels and trends in humans: the need to expand monitoring and research is especially evident in Russia, where only a few dietary studies have evaluated Arctic Indigenous populations.
- Research should continue to focus on the effects of contaminants on pregnant women and women of childbearing age whose diets involve significant consumption of marine mammals. New, collaborative studies are required to study levels of chemicals of emerging Arctic concern, routes of exposure, health effects, lifestyle implications, and interactions with influences outside the field of contaminants for these specific groups. There should be more focus on mixtures of POPs to which people are exposed and their effects on reproductive health and the immune system.

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Acronyms and Abbreviations

β-HCH	β-hexachlorocyclohexane
2-OH-MIBP	Mono-2-hydroxy-isobutyl phthalate
ACCEPT	Adaptation to Climate Change, Environmental Pollution, and dietary Transition
ADHD	Attention-deficit hyperactivity disorder
ADI	Acceptable daily intake
Ag	Silver
AhR	Aryl hydrocarbon receptor
Al	Aluminum
ALT	Alanine aminotransferase
AMAP	Arctic Monitoring and Assessment Programme
As	Arsenic
ATSDR	Agency for Toxic Substances and Disease Registry
ATSDR-MRL	Minimal risk level established by the ATSDR
BMD	Benchmark dose
BMI	Body mass index
BPA	Bisphenol A
BPE	Bisphenol E
BPF	Bisphenol F
BPS	Bisphenol S
BPZ	Bisphenol Z
Br	Bromine
bw	Body weight
CAC	Codex Alimentarius Commission
CACAR	Canadian Arctic Contaminant Assessment Report
CAFF	Conservation of Arctic Flora and Fauna
Cd	Cadmium
CHDA	Cyclohexane-1,2-dicarboxylic acid
CHMS	Canadian Health Measures Survey
CI	Confidence interval
CLEAR	Climate Change, Environmental Contaminants and Reproductive health
Cr	Chromium
CTQ	Centre de Toxicologie du Québec
Cu	Copper
DBP	Dibutyl phosphate
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DEHP	Diethylhexyl phthalate
DHA	Docosahexaenoic acid
DINCH	Di(isononyl)cyclohexane-1,2-dicarboxylate
DINP	Diisononyl phthalate
DPP	Diphenyl phosphate
E%	Percentage of energy consumed
EDI	Estimated daily intake
EFSA	European Food Safety Authority
EPA	Eicosapentaenoic acid
ER	Estrogen receptor
FAO	UN Food and Agriculture Organization
Fe	Iron
FFQ	Food frequency questionnaire
FNBI	First Nations Biomonitoring Initiative
FT3	Free triiodothyronine
FT4	Free thyroxine
Gg	Gigagram
HBGV	Health based guidance value
HBM	Human biomonitoring
HBV	Hepatitis B virus
HCB	Hexachlorobenzene
HCH	Hexachlorocyclohexane
Hg	Mercury
HpCDD	Heptachlorinated dibenzo-p-dioxin
HpCDF	Heptachlorinated dibenzofuran
HQ	Hazard quotient
HTMV	2,2,4-Trimethyl-3-hydroxy valeric acid
HxCDD	Hexachlorinated dibenzo-p-dioxin
HxCDF	Hexachlorinated dibenzofuran
IARC	International Agency for Research on Cancer
IPCS	International Programme on Chemical Safety
IPY	International Polar Year
IQR	Interquartile range
ISR	Inuvialuit Settlement Region
JECFA	Joint FAO/WHO Expert Committee on Food Additives
LEO	Local Environmental Observer
LOD	Limit of detection
LOQ	Limit of quantification
MAL	Maximum allowable level
MBzP	Mono-benzyl phthalate
MCHP	Mono-cyclohexyl phthalate
MCHpP	Mono-(7-carboxy-n-heptyl) phthalate
MCiNP	Mono(carboxy-isononyl) phthalate
MCiOP	Mono-(carboxy-isooctyl) phthalate
MCMHP	Mono-(2-carboxy-methylhexyl) phthalate
MCPP	Mono-3-carboxypropyl phthalate
MECPP	Mono-(2-ethyl-5-carboxypentyl) phthalate
MeHg	Methylmercury
MEHHP	Mono-(2-ethyl-5-hydroxyhexyl) phthalate
MEHP	Monoethylhexyl phthalate
MEHTM	Mono(2-ethylhexyl)trimellitate
MEOHP	Mono-(2-ethyl-5-oxohexyl) phthalate
MEP	Mono-ethyl phthalate
MHBP	Mono-(3-hydroxy-n-butyl) phthalate
MHiDP	Mono(hydroxy-isodecyl) phthalate
MHiNP	Mono(hydroxyl-isononyl) phthalate
MiBP	Monoisononyl phthalate
MiDP	Monoisodecyl phthalate

MINCH	Cyclohexane-1,2-dicarboxylic monoisononyl ester
MiNP	Mono-isononyl phthalate
MISA	Northern Norway Mother-and-Child contaminant Cohort
MMP	Monomethyl phthalate
MnBP	Mono-n-butyl phthalate
MnOP	Mono-n-octyl phthalate
MOiDP	Monooxoisodecyl phthalate
MOiNP	Monooxoisononyl phthalate
MONICA	Monitoring of Trends and Determinants in Cardiovascular Disease
MPC	Maximum permissible concentration
MRL	Maximum residue level
n	Sample size
NCDS	Nunavik Child Development Study
NCP	Northern Contaminants Program
NFBC	Northern Finland Birth Cohort program
NHANES	National Health and Nutrition Examination Survey
Ni	Nickel
NOAEL	No observed adverse effect level
NWT	Northwest Territories
OAT	Organic anion transporter
OCDD	Octachlorodibenzo-p-dioxin
OCDF	1,2,3,4,6,7,8,9-octachlorodibenzofuran
OCP	Organochlorine pesticide
OR	Odds ratio
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PBA	3-Phenoxybenzoic acid
PBDE	Polybrominated diphenyl ether
PBPK	Physiologically-based pharmacokinetic
PCB	Polychlorinated biphenyl
PCDF	Polychlorinated dibenzofuran
PCP	Pentachlorophenol
PCDD	Polychlorinated dibenzo-p-dioxin
PeCB	Pentachlorobenzene
PeCDD	Pentachlorodibenzo-p-dioxin
PeCDF	Pentachlorodibenzofuran
PFAA	Perfluoroalkyl acid
PFAS	Per- and polyfluoroalkyl substance
PFBA	Pentafluorobutanoic acid
PFBS	Perfluorobutane sulfonic acid
PFCAs	Perfluoroalkyl carboxylic acids
PFDA	Perfluorodecanoic acid
PFDoDA	Perfluorododecanoic acid
PFDS	Perfluorodecane sulfonic acid
PFHpA	Perfluoroheptanoic acid
PFHpS	Perfluoroheptane sulfonic acid
PFHxA	Perfluorohexanoic acid
PFHxPA	Perfluorohexylphosphonate
PFHxS	Perfluorohexane sulfonic acid
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PFOSA	Perfluorooctane sulfonamide
PFPeA	Perfluoropentanoic acid
PFSA	Perfluoroalkane sulfonic acids
PFTeA	Perfluorotetradecanoic acid
PFTrA	Perfluorotridecanoic acid
PFTrDA	Perfluorotridecanoate
PFUnDA	Perfluoroundecanoate
PHIME	Public Health Impact of Long-term Low-level Mixed Element Exposure in Susceptible Population Strata
POD	Point of departure
POP	Persistent organic pollutant
PUFA	Polyunsaturated fatty acid
QA/QC	Quality assurance / quality control
RDA	Recommended dietary allowance
RfD	Reference dose
RFDIL	Recommended food daily intake limit
RMI	Recommended maximum intake
RV95	95th percentile of the measured pollutant concentration level in a reference population
SD	Standard deviation
Se	Selenium
SNP	Single nucleotide polymorphism
T3	Triiodothyronine
T4	Thyroxine
TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
TCDF	2,3,7,8-tetrachlorodibenzofuran
TCR	Target cancer risk
TDI	Tolerable daily intake
TEQ	Toxic equivalent
TH	Thyroid hormone
THI	Total hazard index
THQ	Target hazard quotient
TMI	Tolerable monthly intake
TMPD	2,2,4-Trimethyl-1,3-pentanediol
TOTM	Trioctyl trimellitate
TSH	Thyroid-stimulating hormone
TTCR	Total target cancer risk
TWI	Tolerable weekly intake
TXIB	2,2,4-Trimethyl-1,3-pentanediol diisobutyrate
US EPA	United States Environmental Protection Agency
VIP	Västerbotten Intervention Programme
WCBA	Women of childbearing age
WHO	UN World Health Organization
ww	Wet weight
XAR	xeno-androgenic receptor
XER	xeno-estrogenic receptor
Zn	Zinc

Arctic Monitoring and Assessment Programme

The Arctic Monitoring and Assessment Programme (AMAP) was established in June 1991 by the eight Arctic countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the United States) to implement parts of the Arctic Environmental Protection Strategy (AEPS). AMAP is now one of six working groups of the Arctic Council, members of which include the eight Arctic countries, the six Arctic Council Permanent Participants (Indigenous Peoples' organizations), together with observing countries and organizations.

AMAP's objective is to provide 'reliable and sufficient information on the status of, and threats to, the Arctic environment, and to provide scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions to reduce adverse effects of contaminants and climate change'.

AMAP produces, at regular intervals, assessment reports that address a range of Arctic pollution and climate change issues, including effects on health of Arctic human populations. These are presented to Arctic Council Ministers in 'State of the Arctic Environment' reports that form a basis for necessary steps to be taken to protect the Arctic and its inhabitants.

This report has been subject to a formal and comprehensive peer review process. The results and any views expressed in this series are the responsibility of those scientists and experts engaged in the preparation of the reports.

The AMAP Secretariat is located in Tromsø, Norway. For further information regarding AMAP or ordering of reports, please contact the AMAP Secretariat (The Fram Centre, P.O. Box 6606 Stakkevollan, N-9296 Tromsø, Norway) or visit the AMAP website at www.amap.no.

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