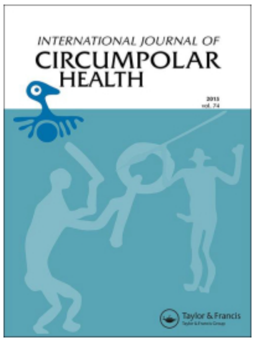

International Journal of Circumpolar Health

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/zich20

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To cite this article: Jordyn A. Stalwick, Mylène Ratelle, Kirsty E. B. Gurney, Mallory Drysdale, Calin Lazarescu, Jérôme Comte, Brian Laird & Kelly Skinner (2023) Sources of exposure to lead in Arctic and subarctic regions: a scoping review, International Journal of Circumpolar Health, 82:1, 2208810, DOI: 10.1080/22423982.2023.2208810

To link to this article: https://doi.org/10.1080/22423982.2023.2208810

INTERNATIONAL JOURNAL OF CIRCUMPOLAR HEALTH
2023, VOL. 82, 2208810
https://doi.org/10.1080/22423982.2023.2208810

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REVIEW ARTICLE (SCOPING AND SYSTEMATIC)

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Sources of exposure to lead in Arctic and subarctic regions: a scoping review

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ABSTRACT
Understanding lead exposure pathways is a priority because of its ubiquitous presence in the environment as well as the potential health risks. We aimed to identify potential lead sources and pathways of lead exposure, including long-range transport, and the magnitude of exposure in Arctic and subarctic communities. A scoping review strategy and screening approach was used to search literature from January 2000 to December 2020. A total of 228 academic and grey literature references were synthesised. The majority of these studies (54%) were from Canada. Indigenous people in Arctic and subarctic communities in Canada had higher levels of lead than the rest of Canada. The majority of studies in all Arctic countries reported at least some individuals above the level of concern. Lead levels were influenced by a number of factors including using lead ammunition to harvest traditional food and living in close proximity to mines. Lead levels in water, soil, and sediment were generally low. Literature showed the possibility of long-range transport via migratory birds. Household lead sources included lead-based paint, dust, or tap water. This literature review will help to inform management strategies for communities, researchers, and governments, with the aim of decreasing lead exposure in northern regions.

ARTICLE HISTORY
Received 17 August 2022
Revised 25 April 2023
Accepted 26 April 2023

KEYWORDS
Lead; metal; Indigenous peoples; north; risk assessment; Dene; First Nations

Introduction

Lead (Pb) is a naturally-occurring metal that has been used in many industries (e.g. gasoline, ammunition, paint, and batteries). Lead contamination can be the result of long-range transport [1–4] or from local sources. High exposure to lead is associated with kidney damage and neurological issues in humans [5,6]. Low levels of lead can cause increases in blood pressure, anaemia, and reproductive issues in adults, and intellectual and behavioural development issues in children [5–7].

Although lead exposure is a global problem, communities in Arctic and subarctic regions appear disproportionately exposed. For example, average blood lead levels (BLLs) in northern Canadian communities are higher than the general Canadian population [8,9]. Many studies attribute this to the ingestion of traditional foods harvested directly from the land using lead ammunition [8,10,11]. However, other local lead sources could be contributing to exposure, including drinking water [12] or household dust [13,14]. Long-range transport may also be a key pathway of lead exposure in northern communities [15,16].

There is a growing need to determine which sources are of the most concern for northern communities. The objective of this paper is to identify potential lead sources and pathways of lead exposure in Arctic and subarctic communities using a scoping review approach. This scoping review focuses on sources and exposure pathways for human populations to help communities determine potential lead sources as well as inform future risk assessments and risk management scenarios for lowering lead exposures.

There are eight Arctic countries with geo-political delimitations north of the Arctic Circle: Canada, Denmark, Finland, Iceland, Norway, Sweden, the Russian Federation, and the United States. Indigenous populations have higher proportional representation in these areas relative to more southern locations. For example, 5% of Canadians self-report as Indigenous while the average value for the three northern territories is 53% [17]. Similarly, the Indigenous People of the Scandinavian Peninsula (e.g. Sami) represent about half of the population of the northern regions of

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/22423982.2023.2208810.

Norway, Sweden and Finland, and Indigenous People represent 9% of the northern Russian population [18]. Indigenous groups are often disproportionately affected by environmental risks [19], commonly facing environmental inequities like inadequate drinking water systems and closer proximity to industrial and mining activities [20]. In addition, Indigenous people in North America have higher tobacco use, poorer housing conditions (e.g. older homes, overcrowding), and frequently consume locally harvested food due to traditional lifestyles, greater cultural connections with the environment, and to protect against food insecurity. Such factors must therefore be considered when evaluating exposure to contaminants for northern communities.

Methods

The scoping review had two aims. The Primary Aim was to identify lead sources, exposure pathways including long-range transport, and the magnitude of lead exposure in northern communities across the globe. The Secondary Aim was to describe the potential role of biological transport of lead (e.g. migrating birds bringing lead from wintering grounds to breeding grounds) for exposures in Arctic and subarctic communities. We followed scoping review guidelines related to searching, selecting, extracting, and synthesising the literature, as outlined by Colquhoun and colleagues [21], and the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist to guide the review process and how to report the methods and findings [22].

The search for the Secondary Aim was completed separately because biological transport is not discussed as often as other forms of long-range transport (e.g. atmospheric, ocean currents) and the extent to which biological transport via migratory birds contributes to human exposures is not typically quantified via human health risk assessment. We therefore attempted to characterise the general potential for the biological transport of lead. Given the greater consumption of wild-harvested birds by people living in northern communities [23] and the long migratory paths of several of these species, it appeared important to explore potential lead exposure pathways for birds both in and beyond the Arctic. Therefore, for this secondary aim, several search strings were included that were not location specific. All searches for the primary and secondary aims were carried out by the first author.

Published literature search

The search of published, peer-reviewed literature was completed from three main academic databases: Scopus®, PubMed®, and Google Scholar. Scopus and PubMed allowed all keywords in one search (see Table S1). For Google Scholar (given its less sophisticated interface), three search strings were used for the Primary Aim while two strings were used for the Secondary Aim. Further, the search string for the Secondary Aim was not used in PubMed (as this database is more focused on health sciences). To screen the results, we used the program Covidence [24]. Covidence allows reviewers to work simultaneously to determine which studies should be included. Results from the Scopus search were downloaded and then uploaded into Covidence. PubMed results were imported to EndNote and then exported in a format that Covidence would accept. The first 100 results for each search string were selected as a review of all results within Google Scholar was unattainable [25] (see Table S2). For each database and search string, only results since 2000 were included. The year 2000 was selected as the earliest inclusion year as it provided at least 20 years of relevant literature since the ban on the general use of leaded gasoline and the partial ban of lead ammunition (1990s and 1999, respectively) [6,26]. Google Scholar results were uploaded into Covidence by adding the first 100 results into "My library" in Google Scholar, uploading those results to EndNote, and then using EndNote to put the results into a Covidence format.

Within Covidence, two sets of blind screening were conducted. To determine which literature should be included, inclusion and exclusion criteria were used (Table 1). After removal of duplicates, results were screened using the title and abstract. For each paper, we had two people vote based on the inclusion/exclusion criteria. The individuals ($n = 4$) involved in the selection process had completed at least a degree in sciences (biology, public health), and at least completed partial graduate studies in environmental health or biology. If they both selected yes, the paper moved to the next step of screening. If they both voted no, the paper was marked as irrelevant. If there was a conflict, a third person made the final decision. For the full text screening, two screeners assessed each paper against the inclusion and exclusion criteria. In the event of a conflict, a third individual gave the deciding vote. The number of included and excluded results are presented in Figure 1.

Table 1. The inclusion and exclusion criteria used for screening.

	Criteria
Inclusion	1. The study was published during or after January 2000. 2. The study was published in English. 3. The study site was located in the Canadian territories, the Inuit Nunangat, the northern parts of the Canadian provinces, or in countries that are a part of the circumpolar north in general UNLESS the study focused on a migratory bird. a. If the bird study was not located in the north, the birds needed to be measured in a way that it was plausible that they could transport lead to a different ecosystem. 4. The study measured lead levels in some way that could affect humans or birds (in the water, air, dust, soil, plants, animals/traditional food, inside homes, in humans).
Exclusion	1. The study was published before January 2000. 2. The study was published in a language other than English. 3. The study site was located outside of the Canadian territories, the Inuit Nunangat, the northern parts of the Canadian provinces, or countries that are a part of the circumpolar north in general UNLESS the study focused on migratory birds. a. Excluded if the birds were found dead outside of the northern regions. 4. The study did not measure lead or measured lead in a way that would not affect humans or birds (e.g. archaeology, geological processes within the crust of the earth or below, experiments in a lab where lead is added). The study was not available in full text.

Grey literature search

The numerical results from the grey literature searches are in Table S3. First, we searched Google using strings in Google Chrome for both the Primary and Secondary Aim. This search was restricted to English only and January 2000 to December 2020. For each search, we screened the first 100 results [25]. All grey literature results were bookmarked and duplicates were identified based on whether the page was already bookmarked [25]. Titles were cross-referenced with the academic papers in Covidence to remove duplicates. Subsequently, a set of Customized Google Searches (e.g. restricted to Government of Canada documents) were completed using the strings from the Primary Aim (See Table S3). Again, the first 100 results were bookmarked, eliminating duplicates for each customised search. In addition, manual searches in specific websites were done to identify reports that may have been missed with the other searches (see Table S3). Finally, the Mackenzie DataStream was used to find projects within the Mackenzie River watershed in northern Canada that included measures of lead. After identifying such projects, we used Google to find project websites and access relevant reports that were publicly available online.

All grey literature results were added to a shared Microsoft Excel file for blind screening. First, we screened based on titles and abstracts. If a result had two yes votes, it was moved on to full text screening, where screeners would visit the webpage. If the result had two no votes, it was marked as irrelevant. If there was a conflict, a third person resolved the conflict. We repeated this voting process for the full text screening.

For both the published and grey literature, references were excluded that: i) only included information from publications that were already included, ii) were duplicates, or iii) ultimately did not fit the inclusion criteria (Table 1).

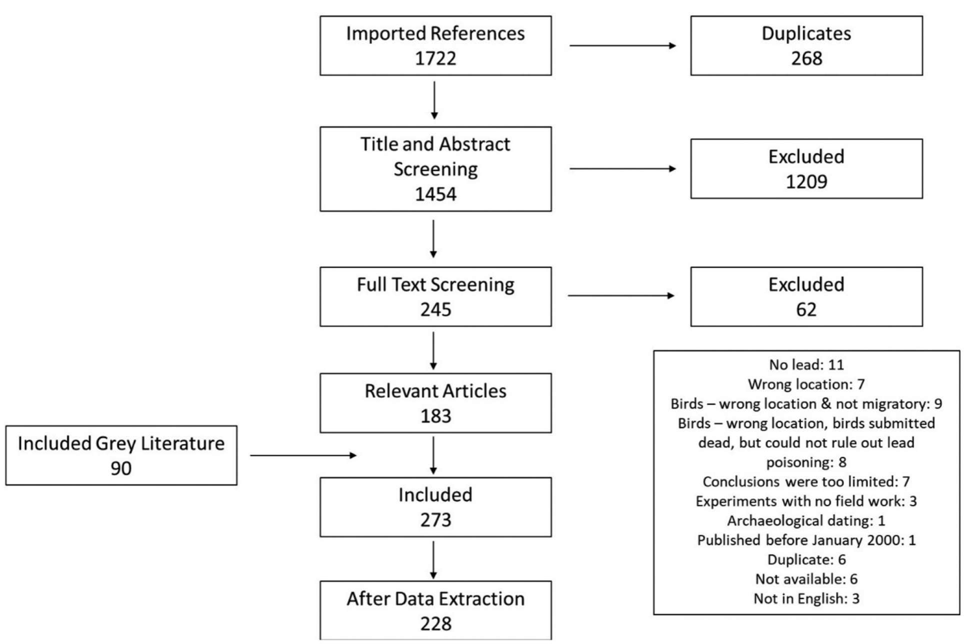

Figure 1. The number of included and excluded published and grey literature from both aims before data extraction with the exclusion reasons for the full text screening of published literature in covidence.

Results

Output of the literature search

After screening, 183 references were obtained from our academic search and 90 from our grey literature search (see PRISMA diagram: Figure 1). During data extraction, the lead author excluded references that on closer inspection were not relevant. There were several references where the information relevant to the aims of this review was referenced from a different publication. In these circumstances, those primary sources were located and used if they were not included already. After data extraction, 228 references remained for review (see Table S4).

The majority of the literature was from studies located in Canada (54.4%), followed by Scandinavia (7.5%; Denmark, Finland, Norway, Sweden), Alaska (7.0%), Greenland (5.3%), and Russia (4.4%). According to the broader geographic scope of the Secondary Aim, some studies were included from other parts of Europe (5.3%), North America (3.5%), and Asia (0.9%). There were also references that focused on multiple countries or did not specify a country (12.3%). Of the 228 references, 88 (39%) included lead in humans, 89 (39%) reported lead in animals or traditional foods in general, 16 (7%) focused on plants, 24 (11%) included water or ice, 9 (4%) included atmospheric lead, 29 (13%) included soil or sediment, 20 (9%) discussed long-range transport (atmospheric or water), 41 (18%) related to the Secondary Aim, and 29 (13%) included household sources or behaviours.

Human health in the north

Current exposure

To better understand the magnitude of exposure, lead levels are commonly compared with health-based guidance values: 5.0 µg/dL in blood for children and women of childbearing age [5,27] and 10 µg/dL for adult men and older women [28]. Less than 6% of studies included in this review reported mean (or median) human BLLs above guidelines (see Tables S5 and S6; [8,9,29–86]). Since 2002, only one study has shown mean BLLs over these guidance values (Inuit women in northern Canada) [30]. However, several authors reported lead levels above the guidelines in multiple participants [9]. Sample maximums greater than the health-based guidance values were in 42–76% of human studies with BLLs. Men generally have higher BLLs than women [8,87,88] (Table S6). Also, due to the long half life of lead in humans (10–20 years) and its accumulation in bone [5], lead concentrations often increase with age [8893189328989,,,] (Tables S5 and S6).

Indigenous peoples in Canada tend to have higher levels of lead than the Canadian national average. The majority of studies in our review report lead levels above the national average from the Canadian Health Measures Survey (CHMS) (see Tables S5 and S6) [90,91]. Of the 68 references that included BLLs (all locations with no separation of sex), 94% had mean BLLs exceeding the closest corresponding year's CHMS survey mean (Table S5). Internationally, people in Arctic communities also have higher BLLs than southern communities [32,33]. In addition, Indigenous people in northern Canadian communities have higher BLLs compared to other ethnicities from the same region [34,35,92].

Studies in Canada, Russia, and Greenland report BLL sample maximums above the threshold of concern or health-based guidance values (see Tables S5 and S6). Gibson et al. [33] reported that Russia and Canada seem to have higher BLLs compared to Norway, Greenland, and Alaska. Russia has the highest BLLs in women of childbearing age in the circumpolar north [93], often exceeding the levels of concern in Russia [94]. However, lead levels are decreasing in the Arctic and subarctic regions [33,95–98]. The decline in BLLs among northern populations (~42% in Table S5) even exceeded the decline in the general population of Canada (~23% from 2009 to 2017) [91].

Health effects associated with lead exposure

Many studies that focus on humans and lead in Arctic communities focus on child health effects (see Table S5). Physically, lead exposure can result in shorter heights, decreased fine motor function, and poorer oral health [36,37,99]. Lead is also associated with iron deficiency anaemia in infants [38]. Regarding cognitive effects, lead exposure can cause slower processing times, poorer memory, and adolescent anxiety (Table S5). IQ decline and low educational performance are also associated with lead exposure [100].

Prenatal and childhood lead exposure can also result in psychological effects later in life [101]. This includes inattention, impulsivity, and irritability [102]. Lead exposure is also correlated with attention-deficit/hyperactivity disorder (ADHD) [39,102]. Lead exposure may have long-term consequences for adults, such as psychiatric, behavioural and personality disorders [100]. In addition, higher risks of adult cardiovascular diseases, pulmonary disease and asthma are associated with childhood exposure [100].

Adult health effects following adult exposure were not reported often. Men with lower haemoglobin have higher lead levels [88]. Also, lead exposure in pregnant women can increase the chances of premature births and lower birth weights [40,102]. Conversely, lead is sometimes negatively associated with body mass index in adults [41,89,103].

Sources from the environment

Traditional foods

Comparisons of lead levels in traditional foods. Traditional foods are an important part of the diet of Indigenous people and can contribute up to 97% of an adult's dietary lead exposure [10,42]. For instance, consuming moose (*Alces alces*) is one of the top pathways of lead exposure for people living in northern Ontario and northern Sweden [10,43]. However, lead levels in traditional food and other animals and plants are usually lower than subclinical levels associated with adverse health effects for the species or guidelines for human consumption across the circumpolar north (Tables 2–5) [127; 128]. Lead levels in animals have generally decreased across the world [129] (Table 3). However, there are cases where a small proportion of samples from animals have elevated lead concentrations (Tables 2–4). Within these tables, 13% of mammal samples, 16% of avian samples, and 3% of fish and seafood samples had ranges that exceed the elevated lead level thresholds defined within the tables' footnotes.

According to Table 2, caribou (*Rangifer tarandus*) and moose have elevated lead concentrations more often than other mammals when compared to guidelines (>2.8 µg/g ww in liver [156,157], or>0.11 µg/g ww in muscle [158]). While lead is a concern for caribou populations [159], lead contamination is not always observed in caribou populations [160]. Few birds sampled after the late 1990s to early 2000s contained lead pellets or elevated lead levels in blood, liver, and muscles (Table 3). An exception to this is ptarmigan, a bird that is not included in the lead shot ban (Table 3). In addition, common loons (*Gavia immer*) have died from lead poisoning when ingesting lead sinkers from fishing rods [161].

Land mammals and birds have higher levels of lead than freshwater fish and marine animals except for mussels (Tables 2–4) [119,127,162], which are filter feeders [163,164]. Only one study focusing on seafood or fish reported a mean above the Health Canada [165] guideline of 0.5 µg/g ww [152]. In marine mammals, only a few individuals of ringed seals (*Pusa hispida*) in Nunavik, Quebec had elevated levels of lead (range: <0.002–8.53 µg/g dw; Table 2).

Harvesting practices in the north. The use of lead ammunition for hunting is correlated with increased BLLs in humans [30,44,166]. For example, Indigenous people living in western James Bay of northern Ontario had increased levels of lead after the spring hunting season [11]. In addition, Indigenous people in northern Canada had blood lead isotope ratios similar to the isotopes in lead ammunition [11,167,168]. Conversely, in the more southern location of Hamilton, Ontario, the majority of lead isotope ratios in humans were similar to the ratios in lichen (atmospheric exposure) [167]. However, Indigenous women in Alaska had lead isotope ratios that were not similar to lead ammunition [45].

Four of the studies in Tables 2–4 specifically evaluated if the lead within the animal samples was from the use of lead ammunition. Two of those studies presented means that were over the government guidelines for safe consumption (1.9 µg/g ww in ptarmigan meat and organs, *Lagopus spp.*, and 19.5 µg/g ww in caribou muscle). The other two studies reported the number of lead pellets found embedded in the tissues of common eiders (*Somateria mollissima*). They averaged 1.7–2.2 pellets per bird.

After educational outreach regarding the dangers of lead ammunition in Nunavik, Quebec in 1999, prenatal exposure to lead dropped 40% and adult exposure overall dropped 55% [169]. Unless there was another source of lead, lead levels were usually below subclinical levels in hunted birds if lead shot was not used during harvest (Table 3). For example, in the Chukotka region of the Russian Arctic, levels of lead in harvested bird meat did not exceed Russia's maximum permissible concentration unless lead shot was present in the meat [170]. In addition, only nine out of 153 sampled eiders had elevated lead levels in Alaska and Russia and those birds were found in important hunting areas [171].

Exposure of traditional foods to other lead sources. Fillion et al. [30] found that the majority of traditional foods in their study in Nunavut, Canada, had lead isotope ratios that were dissimilar to the ratios in lead ammunition. According to Tables 2–5, eight plant or animal lead levels were the result of mining practices. In addition, a lead-zinc mine in Alaska reported 20 times greater concentrations of lead in animal blood and liver samples near mining roads compared to a reference site [172]. In Sweden, Eurasian eagle owls (*Bubo bubo*) found dead near mines had liver lead isotope ratios similar to an anthropogenic source [149]. Lead levels in vegetation are also usually elevated near mining sites [124–126,172]. In contrast, two studies reported lead levels in mammals (snowshoe hares, *Lepus americanus*, and bearded seals, *Erignathus barbatus*) as being below the detection limit near mines [105,115]. There were also two studies in Table 5 that reported lead levels in plants being the result of background lead (or long-range transport) as opposed to mining [121,123].

As lead is a natural element that can be distributed through long-range transport (both natural and anthropogenic lead), it is normal for biota and environmental

Table 2. Lead levels of mammals in studies located in Arctic and subarctic regions that reported lead concentrations.

Sampled	Sampling Years	Location	n	Tissue	Arithmetic Mean[a]	Range	Lead pellets	Lead Source	Safe	Reference
Arctic Hare	no year	Nanisivick lead-zinc mine, Nunavut, CA	8	liver	NA	<0.5–1.15 µg/g ww	NA	lead-zinc mine		[104]
	no year	Arctic Bay, Nunavut, CA	3	liver	NA	<0.5 µg/g ww	NA	NA		[104]
Snowshoe Hare	2012	Abitibi-Témiscamingue and Northern Quebec, CA	196	meat	0.07 ± 0.45 (SD) µg/g dw	NA	NA	NA	yes	[105]
	2012	Abitibi-Témiscamingue and Northern Quebec, CA	196	liver	0.17 ± 0.70 (SD) µg/g dw	NA	NA	NA	yes	[105]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	3	muscle	0.01 ± 0.003 (SD) µg/g dw	0.01–0.02 µg/g dw	NA	NA		[106]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	6	liver	0.60 ± 0.15 (SD) µg/g dw	0.38–0.77 µg/g dw	NA	NA		[106]
Mountain Goat	2011–2013	south Mackenzie Mountain region of the NWT, CA	9	muscle	0.11 ± 0.27 (SD) µg/g ww	0.003–0.836 µg/g ww[b]	NA	NA		[107]
	2011–2013	south Mackenzie Mountain region of the NWT, CA	13	kidney	0.03 ± 0.02 (SD) µg/g ww	0.005–0.083 µg/g ww	NA	NA		[107]
Caribou/ reindeer	2000	northern Ontario, CA	3	muscle	19.47 ± 21.87 (SD) µg/g ww[b]	1–52.6 µg/g ww[b]	71% of subsamples	ammunition	No	[108]
	2003	Cape Krusenstern to Cape Lisburne, Alaska, US	64	liver	1.09 ± 0.68 (SD) µg/g ww	0.11–2.88 µg/g ww[b]	NA	NA	yes	[109]
	2003	Cape Krusenstern to Cape Lisburne, Alaska, US	64	kidney	2.61 ± 15.7 (SD) µg/g ww	0.03–126.1 µg/g ww[b]	NA	NA	yes	[109]
	2003	Cape Krusenstern to Cape Lisburne, Alaska, US	75	muscle	0.47 ± 0.49 (SD) µg/g ww[b]	0.002–2.91 µg/g ww[b]	NA	NA	yes	[109]
	2003	Cape Krusenstern to Cape Lisburne, Alaska, US	30	rumen	2.39 ± 1.49 (SD) µg/g ww	0.02–5.40 µg/g ww[b]	NA	NA	yes	[109]
	2004–2005	Finmark and Nordland Counties, Norway	29	meat	0.0079 µg/g ww	0.0018–0.0181 µg/g ww	NA	NA	yes	[110]
	2004–2005	Finmark and Nordland Counties, Norway	29	liver	0.272 µg/g ww	0.1445–0.5227 µg/g ww	NA	NA	yes	[110]
	2004–2005	Finmark and Nordland Counties, Norway	15	tallow	0.0286 µg/g ww	0.0113–0.0644 µg/g ww	NA	NA	yes	[110]
	2004–2005	Finmark and Nordland Counties, Norway	9	bone marrow	0.0218 µg/g ww	0.007–0.0363 µg/g ww	NA	NA	yes	[110]
	2005–2009	St. Lawrence Island, Alaska, US	4	liver	0.29 ± 0.08 (SD) µg/g ww	0.22–0.38 µg/g ww	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	2	alumguk	0.35 ± 0.11 (SD) µg/g ww	0.27–0.43 µg/g ww	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	8	meat	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	2	adipose tissue	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	2	heart	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	4	kidney	0.36 µg/g ww[c]	NA	NA	NA	yes	[111]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	3	muscle	0.02 ± 0.004 (SD) µg/g dw	0.016–0.024 µg/g dw	NA	NA		[106]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	6	kidney	0.44 ± 0.19 (SD) µg/g dw	0.27–0.79 µg/g dw	NA	NA		[106]
Moose	2004–2007	southern Mackenzie mountains, NWT, CA	18	kidney	0.004 µg/g ww	0.001–0.021 µg/g ww	NA	NA		[112]
	2004–2007	southern Mackenzie mountains, NWT, CA	18	liver	0.012 µg/g ww	0.001–0.047 µg/g ww	NA	NA		[112]
	2004–2007	Mackenzie/Liard River drainages, NWT, CA	43	kidney	0.051 µg/g ww	0.001–1.660 µg/g ww	NA	NA		[112]
	2004–2007	Mackenzie/Liard River drainages, NWT, CA	43	liver	0.116 µg/g ww	0.001–4.260 µg/g ww[b]	NA	NA		[112]
	2005–2016	Mackenzie River Valley in the Dehcho region of the NWT, CA	81	kidney	0.029 ± 0.185 (SD) µg/g ww	0.0005–1.66 µg/g ww; one outlier: 434[b]	NA	NA		[113]
	2005–2016	Mackenzie River Valley in the Dehcho region of the NWT, CA	60	liver	0.080 ± 0.549 (SD) µg/g ww	0.001–4.26 µg/g ww[b]	NA	NA		[113]
	2005–2016	Mackenzie River Valley in the Dehcho region of the NWT, CA	16	muscle	0.015 ± 0.018 (SD) µg/g ww	0.002–0.053 µg/g ww	NA	NA		[113]
Arctic Fox	1998–2001	Ulukhaqtuuq, NWT, CA	13	liver	<0.02 µg/g ww	NA	NA	NA		[114]
	1998–2001	Arviat, Nunavut, CA	50	liver	0.53 ± 0.10 (SE) µg/g ww	NA	NA	NA		[114]
Wolverine	1998–2001	Kųgluktuk, Nunavut, CA	12	liver	<0.02 µg/g ww	NA	NA	NA		[114]
Polar Bear	2005–2009	St. Lawrence Island, Alaska, US	3	adipose tissue	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	3	meat	0.26 µg/g ww[c]	NA	NA	NA	yes	[111]
Bearded Seal	2003–2005	Kivalina, Alaska, US	9	liver	0.03 µg/g ww	0.03–0.03 µg/g ww	NA	NA		[115]
	2003–2005	Little Diomede and Hooper Bay, Alaska, US	15	liver	0.04 ± 0.02 (SD) µg/g ww	0.03–0.09 µg/g ww	NA	NA		[115]
	2005–2009	St. Lawrence Island, Alaska, US	11	blubber	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	17	meat	<0.15 µg/g ww	NA	NA	NA	yes	[111]

(*Continued*)

Table 2. (Continued).

Sampled	Sampling Years	Location	n	Tissue	Arithmetic Mean[a]	Range	Lead pellets	Lead Source	Safe	Reference
	2005–2009	St. Lawrence Island, Alaska, US	2	rendered oil	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	2	liver	<0.15 µg/g ww	NA	NA	NA	yes	[111]
Ringed Seal	1998	northern Baffin Bay, CA	9	muscle	0.01 ± 0.01 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	9	liver	0.01 ± 0.01 (SD) µg/g ww	NA	NA	NA		[116]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	14	muscle	0.65 ± 2.19 (SD) µg/g dw	<0.002–8.53 µg/g dw[b]	NA	NA		[106]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	14	liver	0.13 ± 0.35 (SD) µg/g dw	0.02–1.34 µg/g dw	NA	NA		[106]
	2017–2018	Frobisher Bay, Nunavut, CA	18	muscle	0.059–0.11 µg/g ww[c]	0.025–0.53 µg/g ww	NA	NA		[117]
	2017–2018	Frobisher Bay, Nunavut, CA	17	liver	0.031–0.086 µg/g ww[c]	0.011–0.68 µg/g ww	NA	NA		[117]
Spotted Seal	2005–2009	St. Lawrence Island, Alaska, US	3	blubber	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	4	meat	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	2	rendered oil	<0.15 µg/g ww	NA	NA	NA	yes	[111]
Walrus	2005–2009	St. Lawrence Island, Alaska, US	24	blubber	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	7	oil	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	30	meat	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	14	liver	0.33 µg/g ww[c]	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	5	heart	<0.15 µg/g ww	NA	NA	NA	yes	[111]
Beluga Whale	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	50	liver	0.02 ± 0.01 (SD) µg/g ww	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	45	kidney	0.01 ± 0.03 (SD) µg/g ww	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	11	muscle	not detected	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	11	blubber	not detected	NA	NA	NA		[118]
Bowhead Whale	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	55	liver	0.03 ± 0.02 (SD) µg/g ww	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	48	kidney	0.02 ± 0.02 (SD) µg/g ww	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	36	muscle	0.02 ± 0.02 (SD) µg/g ww	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	34	blubber	0.02 ± 0.01 (SD) µg/g ww	NA	NA	NA		[118]
	1983–1997	Barrow, Kaktovik, Wainwright, Pt Lay, Point Hope, Alaska, US; Inuvik, Northwest Territories, CA	8	epidermis	not detected	NA	NA	NA		[118]
	2005–2009	St. Lawrence Island, Alaska, US	2	rendered oil	<0.15 µg/g ww	NA	NA	NA	yes	[111]
	2005–2009	St. Lawrence Island, Alaska, US	4	meat	<0.15 µg/g ww	NA	NA	NA	yes	[111]

n is the sample size, SD is standard deviation, SE is standard error, dw is dry weight, and ww is wet weight. The lead source column states confirmed lead sources. If the study stated if lead levels were safe for human consumption, it was recorded here as yes or no.

[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.

[b]A mammal was considered to have elevated lead levels if the liver levels were above 2.8 µg/g ww or the kidney levels were above 5.25 µg/g ww (acute lead poisoning [157]; converted using moisture levels of caribou livers and moose kidneys from Health Canada 2018) or if the muscle or meat levels were above 0.11 µg/g ww [158–] based on safe levels of lead in cattle for human consumption). Other tissue types were compared to the liver levels. Moose liver lead levels were considered elevated if above 3.05 µg/g ww and marine mammal liver levels were considered elevated if above 2.85 µg/g ww, which was based on ringed seals [157]Health Canada 2018).

[c]These averages did not include the values that were below the detection limit, therefore the actual average should be lower.

Table 3. Avian lead levels in studies located in Arctic and subarctic regions that reported lead concentrations.

Sampled	Sampling Years	Location	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Range	Lead pellets[a]	Lead Source	Safe?	Reference
Common Eider	1995	Table Bay, Newfoundland and Labrador, CA	55	whole	NA	NA	NA	2	ammunition		[130]
	1997–1998	Southampton Island, Nunavut, CA	252	whole	NA	NA	NA	1.7	ammunition		[130]
	1997–1998	Cape Dorset, Baffin Island, CA	152	whole	NA	NA	NA	1.7	ammunition		[130]
	1997–1998	Baltic Sea by Finland	245	blood	0.09 µg/g ww	NA	0.02–1.56 µg/g ww[b]	NA	NA		[131]
	1988–2002	Above 50° N in Canada	149	liver	NA	1.7 ± 3.1 (SD) µg/g dw	NA	NA	NA		[132]
	2000–2001	Belcher Islands and Neta Islands, Nunavut, CA and Greenland	48	radius	NA	0.76 µg/g dw	0.14–2.54 µg/g dw	NA	NA		[133]
	2000–2001	Belcher Islands and Neta Islands, Nunavut, CA and Greenland	48	humerus	NA	0.72 µg/g dw	0.13–2.44 µg/g dw	NA	NA		[133]
	2000–2001	Belcher Islands and Neta Islands, Nunavut, CA and Greenland	48	ulna	NA	0.66 µg/g dw	0.10–2.36 µg/g dw	NA	NA		[133]
	2000–2001	Belcher Islands and Neta Islands, Nunavut, CA and Greenland	48	femur	NA	1.02 µg/g dw	0.14–3.50 µg/g dw	NA	NA		[133]
	2000–2001	Belcher Islands and Neta Islands, Nunavut, CA and Greenland	48	tibia	NA	1.09 µg/g dw	0.15–3.83 µg/g dw	NA	NA		[133]
	2000–2002	Nuuk, Greenland	219	whole	NA	NA	NA	1.7–2.2	ammunition		[134]
	2004	Amchitka and Kiska Islands, Alaska, US	54	egg	NA	0.2 µg/g ww	NA	NA	NA		[135]
	2007	Amchitka and Kiska Islands, Alaska, US	30	feather	0.456 µg/g dw	0.53 ± 0.0665 (SE) µg/g dw	NA	NA	NA	yes	[136]
	2007	Amchitka and Kiska Islands, Alaska, US	30	eggs	0.0809 µg/g dw	0.306 ± 0.0995 (SE) µg/g dw	NA	NA	NA	yes	[136]
	2008	Tern Island, Nunavut, CA	10	liver	NA	0.181 µg/g dw	0.060–0.586 µg/g dw	NA	NA		[137]
	2008	East Bay, Nunavut, CA	10	liver	NA	0.089 µg/g dw	0.060–0.263 µg/g dw	NA	NA		[137]
	2008	Table Bay, Newfoundland and Labrador, CA	10	liver	NA	0.088 µg/g dw	0.060–0.737 µg/g dw	NA	NA		[137]
	2000–2014	Prudhoe Bay, Alaska, US	17	kidney	0.07–0.09 µg/g dw	0.07–0.10 µg/g dw	0.03–0.15 µg/g dw	NA	NA		[138]
	2000–2014	Prudhoe Bay, Alaska, US	40	liver	0.04–0.33 µg/g dw	0.04–5.39 µg/g dw	0.02–8.14 µg/g dw[b]	NA	NA		[138]
	2013 & 2014	Mittivik Island in Northern Hudson Bay, CA	193	blood	0.008 (0.001 SD) µg/g ww	0.009 ± 0.006 (SD) µg/g ww	0.005–0.043 µg/g ww	NA	NA	yes	[139]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	5	muscle	NA	2.07 ± 4.18 (SD) µg/g dw[b]	0.05–9.53 µg/g dw[b]	NA	NA		[106]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	5	liver	NA	3.75 ± 8.30 (SD) µg/g dw	<0.002–18.6 µg/g dw[b]	NA	NA		[106]
	2014–2015	Cape Dorset, Nunavut and Ivujivik, Quebec, CA	21 lakes	fecal matter	NA	1.05 ± 0.07 (SD) µg/g dw	NA	NA	NA		[140]

(*Continued*)

Table 3. (Continued).

Sampled	Sampling Years	Location	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Range	Lead pellets[a]	Lead Source	Safe?	Reference
King Eider	1996	northern Alaska, US	15	blood	NA	0.10–0.13 µg/g ww[c]	NA	NA	NA		[141]
	2001	Karrak Lake and Adventure Lake, Nunavut, CA	63	blood	0.011 µg/g ww (95% CI: 0.009, 0.013)	NA	NA	NA	NA	yes	[142]
	2002	Karrak Lake and Adventure Lake, Nunavut, CA	69	blood	0.021 µg/g ww (95% CI: 0.019, 0.024)	NA	NA	NA	NA	yes	[142]
	2003	Karrak Lake and Adventure Lake, Nunavut, CA	74	blood	0.021 µg/g ww (95% CI: 0.019, 0.023)	NA	NA	NA	NA	yes	[142]
	2000–2014	Prudhoe Bay, Alaska, US	17	kidney	0.10–0.12 µg/g dw	0.10–0.15 µg/g dw	0.03–0.37 µg/g dw	NA	NA		[138]
	2000–2014	Prudhoe Bay, Alaska, US	19	liver	0.04–0.10 µg/g dw	0.05–0.18 µg/g dw	0.02–0.40 µg/g dw	NA	NA		[138]
Spectacled Eider	1996	northern Alaska, US	45	blood	NA	0.12–0.64 µg/g ww[b,c]	NA	NA	NA		[141]
	2000–2014	Prudhoe Bay, Alaska, US	19	kidney	0.04–0.18 µg/g dw	0.06–0.29 µg/g dw	0.02–1.20 µg/g dw	NA	NA		[138]
	2000–2014	Prudhoe Bay, Alaska, US	19	liver	0.04–0.10 µg/g dw	0.04–0.19 µg/g dw	0.02–0.89 µg/g dw	NA	NA		[138]
Steller's Eider	2000–2014	Prudhoe Bay, Alaska, US	13	kidney	0.26–0.44 µg/g dw[b]	0.26–16.38 µg/g dw[b]	0.03–81.40 µg/g dw[b]	NA	NA		[138]
	2000–2014	Prudhoe Bay, Alaska, US	25	liver	0.18–0.22 µg/g dw	0.25–0.72 µg/g dw	0.04–4.73 µg/g dw	NA	NA		[138]
Lesser Scaup	2001	Yukon Flats National Wildlife Region, Alaska, US	14	blood	NA	0.29 µg/g ww[b,c]	NA	NA	NA		[143]
Long-tailed duck	2000–2014	Prudhoe Bay, Alaska, US	18	kidney	0.04–0.08 µg/g dw	0.04–0.27 µg/g dw	0.02–0.98 µg/g dw	NA	NA		[138]
	2000–2014	Prudhoe Bay, Alaska, US	46	liver	0.16–0.28 µg/g dw	0.58–2.35 µg/g dw	0.01–41.0 µg/g dw[b]	NA	NA		[138]
Snow Goose	2005–2009	St. Lawrence Island, Alaska, US	2	meat	NA	<0.15 µg/g ww	NA	NA	NA	yes	[111]
Tundra Swan	2007–2008	Alaska, US	653	blood	NA	<0.2 µg/g ww	NA	NA	NA	yes	[144]
Arctic Loon	2005–2009	St. Lawrence Island, Alaska, US	3	meat	NA	<0.15 µg/g ww	NA	NA	NA	yes	[111]
Black guillemot	1998	northern Baffin Bay, CA	10	muscle	NA	0.04 ± 0.02 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	10	liver	NA	0.03 ± 0.02 (SD) µg/g ww	NA	NA	NA		[116]
Dovekie	1998	northern Baffin Bay, CA	9	liver	NA	0.27 ± 0.61 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	10	muscle	NA	0.09 ± 0.22 (SD) µg/g ww	NA	NA	NA		[116]
Little Auk	no year	Ariekammen slope, Hornsund, Svalbard	74	body feather	NA	1.23 ± 1.66 (SD) µg/g dw, excluded one outlier	<0.32–10.98 µg/g dw[b,d]	NA	NA		[145]
	no year	Ariekammen slope, Hornsund, Svalbard	74	throat feather	NA	1.53 ± 2.43 (SD) µg/g dw, excluded two outliers	<0.32–20.22 µg/g dw[b,d]	NA	NA		[145]
	no year	Ariekammen slope, Hornsund, Svalbard	18	body feather	NA	66% were<0.32 µg/g dw[d]	NA	NA	NA		[145]
	no year	Ariekammen slope, Hornsund, Svalbard	16	throat feather	NA	0.32 ± 0.42 (SD) µg/g dw	<0.32–1.24 µg/g dw[d]	NA	NA		[145]

(*Continued*)

Table 3. (Continued).

Sampled	Sampling Years	Location	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Range	Lead pellets[a]	Lead Source	Safe?	Reference
Thick-billed murre	1975 & 1993	Lancaster Sound, Nunavut, CA	20	liver	NA	not detected	NA	NA	NA		[146]
	1998	northern Baffin Bay, CA	10	muscle	NA	0.06 ± 0.05 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	10	liver	NA	0.05 ± 0.02 (SD) µg/g ww	NA	NA	NA		[116]
Northern fulmar	1975 & 1993	Lancaster Sound, Nunavut, CA	20	liver	NA	not detected	NA	NA	NA		[146]
	1998	northern Baffin Bay, CA	10	muscle	NA	0.01 ± 0.01 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	10	liver	NA	0.02 ± 0.02 (SD) µg/g ww	NA	NA	NA		[116]
Black-legged kittiwake	1993	Lancaster Sound, Nunavut, CA	10	liver	NA	not detected	NA	NA	NA		[146]
	1998	northern Baffin Bay, CA	10	muscle	NA	0.02 ± 0.01 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	10	liver	NA	0.02 ± 0.01 (SD) µg/g ww	NA	NA	NA		[116]
Glaucous gull	1998	northern Baffin Bay, CA	10	muscle	NA	0.04 ± 0.05 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	9	liver	NA	0.02 ± 0.03 (SD) µg/g ww	NA	NA	NA		[116]
	2004	Amchitka and Kiska Islands, Alaska, US	13	egg	NA	0.01 µg/g ww	NA	NA	NA		[135]
Ivory gull	1998	northern Baffin Bay, CA	5	muscle	NA	0.12 ± 0.20 (SD) µg/g ww	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	2	liver	NA	0.01 ± 0.01 (SD) µg/g ww	NA	NA	NA		[116]
Thayer's gull	1998	northern Baffin Bay, CA	1	muscle	NA	not detected	NA	NA	NA		[116]
	1998	northern Baffin Bay, CA	1	liver	NA	0.07 µg/g ww	NA	NA	NA		[116]
Sandhill Crane	2005–2009	St. Lawrence Island, Alaska, US	2	meat	NA	<0.15 µg/g ww	NA	NA	NA	yes	[111]
Ptarmigan	NA	Nunavik, Quebec, CA	36	meat, liver, heart, gizzard	1.9 µg/g ww[b]	NA	NA	NA	ammunition	No	[147]
Willow Ptarmigan	2014	Kuujjuaraapik, Nunavik, Quebec, CA	3	muscle	NA	1.90 ± 3.23 (SD) µg/g dw	0.01–5.63 µg/g dw[b]	NA	NA		[106]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	6	liver	NA	0.49 ± 0.77 (SD) µg/g dw	0.07–2.05 µg/g dw	NA	NA		[106]
Gyrfalcon	2004–2007	Yukon Delta National Wildlife Refuge, Alaska, US	4	3 eggs, 1 juvenile	NA	not detected	NA	NA	NA		[148]
Eurasian Eagle Owl	1978–2013	Sweden	122	liver	NA	0.179 µg/g dw	0.015–1.55 µg/g dw – outlier: 40.7[b]	NA	mostly background, few were mine related		[149]

n is the sample size, SD is standard deviation, SE is standard error, CI is confidence intervals, dw is dry weight, and ww is wet weight. The lead pellets were embedded in tissue. The lead source column states confirmed lead sources. If the study stated if lead levels were safe for human consumption, it was recorded here as yes or no.

[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.

[b]A bird was considered to have subclinical levels of lead when the wet weight was 0.2 µg/g for blood, 2 µg/g ww for liver and kidney [273], and 0.5 µg/g for muscle [274] or the dry weight was 6 µg/g for liver, 8.6 µg/g for kidney, 10 µg/g for bone [275], and 2 µg/g for muscle [274]. These levels are based on concentrations found in Anseriformes and Falconiformes.

[c]These averages did not include the values that were below the detection limit, therefore the actual average should be lower.

[d]A detection limit was not given for lead so we indicated that any measurements below the detection level were below the smallest measurement given.

Table 4. Fish and seafood lead levels in studies located in Arctic and subarctic regions that reported lead concentrations.

Sampled	Sampling Years	Location	n	Tissue	Arithmetic Mean[a]	Range	Lead Source	Safe?	Reference
Crab	2005–2009	St. Lawrence Island, Alaska, US	7	eggs	<0.15 µg/g ww	NA	NA	yes	[111]
Blue Mussel	2014	Kuujjuaraapik, Nunavik, Quebec, CA	5	whole	0.61 ± 0.17 (SD) µg/g dw	0.36–0.83 µg/g dw	NA		[106]
Sea Urchin	2014	Kuujjuaraapik, Nunavik, Quebec, CA	5	gonads	0.03 ± 0.07 (SD) µg/g dw	<0.002–0.15 µg/g dw	NA		[106]
Clam	2013	Kaipokok Bay, Newfoundland and Labrador, CA	1	whole	0.039 µg/g ww	NA	NA		[123]
	2013	Makkovik Bay, Newfoundland and Labrador, CA	1	whole	0.058 µg/g ww	NA	NA		[123]
Arctic Char	1997–2003	Cornwallis island, Devon and Somerset islands, Nunavut, CA	120	muscle	0.006–0.035 µg/g ww	0.001–0.210 µg/g ww	NA	yes	[150]
	2017–2018	European Russia (arctic and subarctic)	11	muscle	0.00526 µg/g ww	0.00099–0.00978 µg/g ww	NA	yes	[151]
Arctic Cod	1998	northern Baffin Bay, CA	1	whole	0.13 µg/g ww	NA	NA		[116]
	1998	northern Baffin Bay, CA	2	liver	0.05 ± 0.06 (SD) µg/g ww	NA	NA		[116]
Arctic Flounder	2017–2018	European Russia (arctic and subarctic)	4	muscle	0.01376 µg/g ww	0.00676–0.0233 µg/g ww	NA	yes	[151]
Arctic Grayling	2012	Christal Creek, Yukon, CA	5	whole	0.58 ± 0.06 (SD) µg/g ww[b]	NA	mine		[152]
	2012	Moose Creek, Yukon, CA	5	whole	<0.14 µg/g ww	NA	NA		[152]
Grayling	2017–2018	European Russia (arctic and subarctic)	3	muscle	0.00626 µg/g ww	<0.0003–0.0159 µg/g ww	NA	yes	[151]
Atlantic Salmon	2017–2018	European Russia (arctic and subarctic)	4	muscle	0.00299 µg/g ww	0.00249–0.0042 µg/g ww	NA	yes	[151]
Broad whitefish	2017–2018	European Russia (arctic and subarctic)	2	muscle	<0.0003 µg/g ww	NA	NA	yes	[151]
Burbot	2017–2018	European Russia (arctic and subarctic)	2	muscle	0.00121 µg/g ww	<0.0003–0.00226 µg/g ww	NA	yes	[151]
European perch	2017–2018	European Russia (arctic and subarctic)	3	muscle	<0.0003 µg/g ww	NA	NA	yes	[151]
Halibut	2005–2009	St. Lawrence Island, Alaska, US	2	muscle	<0.15 µg/g ww	NA	NA	yes	[111]
Humpback whitefish	2017–2018	European Russia (arctic and subarctic)	12	muscle	0.00226 µg/g ww	0.00068–0.00632 µg/g ww	NA	yes	[151]
Inconnu	2017–2018	European Russia (arctic and subarctic)	6	muscle	0.00098 µg/g ww	<0.0003–0.00123 µg/g ww	NA	yes	[151]
Lake Whitefish	2008–2009	Montreal Lake, Saskatchewan, CA	162[c]	muscle	0.001–0.002 µg/g ww	NA	back-ground	yes	[153]
	2008–2009	Reindeer Lake, Saskatchewan, CA	162[c]	muscle	0.001–0.044 µg/g ww	NA	back-ground	yes	[153]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	5	muscle	0.004 ± 0.002 (SD) µg/g dw	0.002–0.006 µg/g dw	NA		[106]
Navaga	2017–2018	European Russia (arctic and subarctic)	10	muscle	0.00934 µg/g ww	0.00541–0.0244 µg/g ww	NA	yes	[151]
Northern Pike	2017–2018	European Russia (arctic and subarctic)	6	muscle	0.0098 µg/g ww	0.00578–0.0143 µg/g ww	NA	yes	[151]
	2010	Montreal Lake, Saskatchewan, CA	24[c]	muscle	0.00646 ± 0.0008 (SD) µg/g dw[d]	NA	NA	yes	[154]
	2011	Montreal Lake, Saskatchewan, CA	24[c]	muscle	0.00296 ± 0.00068 (SD) µg/g dw[d]	NA	NA	yes	[154]
Peled	2017–2018	European Russia (arctic and subarctic)	3	muscle	0.00573 µg/g ww	<0.0003–0.0169 µg/g ww	NA	yes	[151]
Pink Salmon	2017–2018	European Russia (arctic and subarctic)	12	muscle	0.00862 µg/g ww	0.00045–0.0187 µg/g ww	NA	yes	[151]
Roach	2017–2018	European Russia (arctic and subarctic)	20	muscle	0.00525 µg/g ww	0.00045–0.0183 µg/g ww	NA	yes	[151]
Trout	2013	Kaipokok Bay, Newfoundland and Labrador, CA	5	unknown	0.1 µg/g ww	NA	NA		[123]
	2013	Makkovik Bay, Newfoundland and Labrador, CA	5	unknown	0.07 µg/g ww	NA	NA		[123]

(Continued)

Table 4. (Continued).

Sampled	Sampling Years	Location	n	Tissue	Arithmetic Mean[a]	Range	Lead Source	Safe?	Reference
Walleye	2010	Montreal Lake, Saskatchewan, CA	55[c]	muscle	0.00776 ± 0.00035 (SD) µg/g dw	NA	NA	yes	[154]
	2011	Montreal Lake, Saskatchewan, CA	55[c]	muscle	0.00446 ± 0.00183 (SD) − 0.02162 ± 0.03089 (SD) µg/g dw	NA	NA	yes	[154]
Greenland sleeper shark	2010	Kong Oscars Fjord – Kaiser Franz Joseph Fjord complex, Greenland	3	brain	0.014 ± 0.006 (SD) µg/g dw	NA	NA		[155]
	2010	Kong Oscars Fjord – Kaiser Franz Joseph Fjord complex, Greenland	3	liver	0.071 ± 0.016 (SD) µg/g dw	NA	NA		[155]
	2010	Kong Oscars Fjord – Kaiser Franz Joseph Fjord complex, Greenland	3	red muscle	0.132 ± 0.035 (SD) µg/g dw	NA	NA		[155]
	2010	Kong Oscars Fjord – Kaiser Franz Joseph Fjord complex, Greenland	3	white muscle	0.053 ± 0.018 (SD) µg/g dw	NA	NA		[155]

Note: n is the sample size, SD is standard deviation, dw is dry weight, and ww is wet weight. The lead source column states confirmed lead sources. If the study stated if lead levels were safe for human consumption, it was recorded here as yes or no.

[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.

[b]A fish was considered to have subclinical (elevated) levels of lead when the wet weight Pb concentration was 0.5 µg/g [165].

[c]These sample sizes are the total sample size for the study and are not separated by groups (e.g. location or year).

[d]These averages did not include the values that were below the detection limit, therefore the actual average should be lower.

Table 5. Plant and fungi lead levels in studies located in Arctic and subarctic regions that reported lead concentrations.

Sampled	Sampling Years	Location	n	Tissue	Arithmetic Mean[a]	Median	Range	Lead Source	Reference
Mushroom	2001	Russian Arctic	6	whole	NA	NA	0.04–0.1 µg/g dw	NA	[119]
Lichen	2001	Russian Arctic	12	whole	NA	NA	0.9–4.1 µg/g dw	NA	[119]
	2017	Yamal Peninsula, Russia	5	whole	6.6 ± 1.6 (SD) µg/g dw	NA	NA	NA	[120]
Ground lichen	2014	Kuujjuaraapik, Nunavik, Quebec, CA	2	whole	1.03 ± 0.57 (SD) µg/g dw	NA	0.63–1.43 µg/g dw	NA	[106]
Tree lichen	2014	Kuujjuaraapik, Nunavik, Quebec, CA	2	whole	5.00 ± 4.74 (SD) µg/g dw	NA	1.64–8.35 µg/g dw	NA	[106]
Moss	2001	Russian Arctic	11	whole	NA	NA	2.6–4.5 µg/g dw	NA	[119]
	2016	Adventdalen, Svalbard	41	whole	7.68 ± 0.54 (SE) µg/g dw	NA	3.38–12.16 µg/g dw[b]	background	[121]
	2016	Ny-Ålesund, Svalbard	33	whole	8.37 ± 1.09 (SE) µg/g dw	NA	3.33–18.59 µg/g dw[b]	background	[121]
Grass	2017	Fort Greely, Alaska, US	21	root	481.6 ± 184.6 (SE) µg/g dw[b]	NA	NA	old military sites	[122]
	2017	Fort Greely, Alaska, US	21	shoot	29.17 ± 10.19 (SE) µg/g dw[b]	NA	NA	old military sites	[122]
Water Sedge	2013	Kaipokok Bay, Newfoundland and Labrador, CA	7	unknown	0.96 ± 0.54 (SD) µg/g ww	NA	NA	NA	[123]
	2013	Makkovik Bay, Newfoundland and Labrador, CA	8	unknown	4.12 ± 6.40 (SD) µg/g ww[b]	NA	NA	lead in bedrock	[123]
Forb	2017	Fort Greely, Alaska, US	24	root	20.8 ± 7.0 (SE) µg/g dw[b]	NA	NA	old military sites	[122]
	2017	Fort Greely, Alaska, US	24	shoot	11.13 ± 3.54 (SE) µg/g dw[b]	NA	NA	old military sites	[122]
Bearberry	2014	Kuujjuaraapik, Nunavik, Quebec, CA	2	leaves	<0.002 µg/g dw	NA	NA	NA	[106]
Bog Blueberry	no year	Faro, Yukon, CA	20	leaves	0.1–20 µg/g dw[b]	NA	NA	lead-zinc mine	[124]
Cranberry, blueberry, cloudberry, bilberry, crowberry	2001	Russian Arctic	11	berries	NA	NA	0.01–0.05 µg/g dw	NA	[119]
Cranberry, blueberry, lingonberry	2013–2015	Athabasca Bituminous Sands Region (ABS), Alberta, CA	51	unwashed berries	0.011 ± 0.084 (SD) µg/g dw	0.0080 µg/g dw	0.0034–0.03657 µg/g dw	dust deposition – ABS	[125]
	2013–2015	Athabasca Bituminous Sands Region, Alberta, CA	29	washed berries	0.0045 ± 0.0022 (SD) µg/g dw	0.0044 µg/g dw	0.0016–0.011 µg/g dw	dust deposition – ABS	[125]
	2013–2015	near Edmonton, Alberta, CA	5	berries	0.0026 ± 0.0012 (SD) µg/g dw	0.0021 µg/g dw	0.0020–0.0047 µg/g dw	NA	[125]
Crowberry	2014	Kuujjuaraapik, Nunavik, Quebec, CA	1	leaves	0.16 µg/g dw	NA	NA	NA	[106]
Labrador Tea	no year	Faro, Yukon, CA	20	leaves	0.1–53 µg/g dw[b]	NA	NA	lead-zinc mine	[124]
	2014	Kuujjuaraapik, Nunavik, Quebec, CA	2	leaves	0.01 ± 0.01 (SD) µg/g dw	NA	<0.002–0.02 µg/g dw	NA	[106]
	2014	Utikuma Bog, Alberta, CA	1 site	leaves	0.0266 µg/g dw	NA	NA	NA	[126]
	2017	Fort McMurray, Alberta, CA	2 sites	leaves	0.3281–0.5453 µg/g dw	NA	NA	dust deposition – reclaimed bitumen mine	[126]

(*Continued*)

Table 5. (Continued).

Sampled	Sampling Years	Location	n	Tissue	Arithmetic Mean[a]	Median	Range	Lead Source	Reference
Sweet Gale	2013	Kaipokok Bay, Newfoundland and Labrador, CA	7	unknown	0.72 ± 0.28 (SD) µg/g ww	NA	NA	NA	[123]
	2013	Makkovik Bay, Newfoundland and Labrador, CA	8	unknown	0.92 ± 0.56 (SD) µg/g ww	NA	NA	background	[123]
Shrub	2017	Fort Greely, Alaska, US	9	root	5.78 ± 2.61 (SD) µg/g dw	NA	NA	old military sites	[122]
	2017	Fort Greely, Alaska, US	9	shoot	0.82 ± 0.18 (SD) µg/g dw	NA	NA	old military sites	[122]
Spruce	2013	Kaipokok Bay, Newfoundland and Labrador, CA	6	unknown	0.53 ± 0.11 (SD) µg/g ww	NA	NA	NA	[123]
	2013	Makkovik Bay, Newfoundland and Labrador, CA	8	unknown	0.56 ± 0.16 (SD) µg/g ww	NA	NA	NA	[123]
Alder	2013	Kaipokok Bay, Newfoundland and Labrador, CA	6	unknown	0.71 ± 0.30 (SD) µg/g ww	NA	NA	NA	[123]
Willow	no year	Faro, Yukon, CA	20	leaves	0.1–15 µg/g dw[b]	NA	NA	lead-zinc mine	[124]

SD is standard deviation, SE is standard error, n is the sample size, dw is dry weight, and ww is wet weight. The lead source column states confirmed lead sources.
[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.
[b]A plant was considered to have elevated levels of lead when the dry weight was greater than 10 µg/g [276].

matrices to have low levels of lead. For example, fish in two remote lakes in northern Saskatchewan had low muscle lead levels (range of means: 0.001–0.044 µg/g ww; Table 4), but as there were no industrial operations nearby, the low concentration of lead was probably background levels and/or due to long-range transport [153]. Lead concentrations in animals can be more accurately identified as background levels if the lead isotope ratios of the animal tissues are similar to the ratios in local aspects of the environment [149,173,174].

Biological long-range transport. This scoping review uncovered many instances of birds transporting lead through migration (Table 6). For example, Gurney et al. [203] found that breeding female white-winged scoters (*Melanitta deglandi*) that wintered along the Atlantic Ocean had higher BLLs than those that wintered along the Pacific Ocean, suggesting that wintering grounds present different exposure sources and risks. Additionally, migratory tundra swans (*Cygnus columbianus*) breeding in Alaska have higher BLLs than those that are only semi-migratory [144]. Mallory et al. [137] also reported common eiders that wintered in Greenland had higher liver lead levels on their breeding grounds than those that wintered in Newfoundland and Labrador, Canada. In Svalbard, migratory common eiders from Norway and Iceland had higher mean egg lead concentrations than sedentary birds in Norway and Iceland [186].

Table 6 includes more studies with birds that could migrate with lead in their system. These birds do not necessarily migrate to the Arctic or subarctic, but all of these studies included live captured migratory birds or migratory birds that died in a way that lead poisoning was unlikely to have impacted (e.g. shot by hunters, mass death due to botulism). According to Table 6, multiple birds were exposed to lead at subclinical or higher levels and were still capable of flying and migrating. Out of the 133 rows of species, years, and studies in Table 6, 69 had means or ranges of lead concentrations exceeding subclinical levels or a percentage of samples contained lead fragments. One study with multiple species measured the presence of embedded lead pellets in birds during the breeding season (16–53% of birds) [130]. Table 6 also includes seven studies that counted lead pellets in birds at wintering or stopover sites. All of the lead pellet studies reported that each species had a proportion of samples with lead pellets either embedded in the tissue (4.9–44%) or ingested (0.5–76%).

Local environmental sources other than traditional food

Natural water. Lead levels in natural (untreated) water (WLLs) were generally lower than Canadian drinking water guidelines (0.005 mg/L) in Arctic and subarctic regions (Table 7). However, there were several instances where the range included elevated WLLs above guidelines (5/14 water bodies; Table 7). Most of these elevated WLLs were known to be a result of mines or were in areas where mining operations were nearby. Zinc and lead mines and oil sands can contaminate nearby snow and water [172,214]. In the Peace River of northern British Columbia, Canada, (1963–2015), WLLs exceeded the federal guidelines for aquatic life in 50% of surface water and 15% of groundwater samples [215]. In other instances, WLLs were below guidelines near oil and gas operations (Hay River Basin, AB and NWT) or other potential pollutants such as sewage lagoons (Snare Lake, NWT) [216,217].

Most of the lead in the Arctic Ocean is from international anthropogenic sources [218]. Lead can persist in surface waters of oceans and be transported from the Nordic Sea or north Atlantic Ocean to the Arctic Ocean [219,220]. However, the only study that we came across measuring ocean lead reported low levels overall [210] and marine animals have low lead concentrations (Tables 2 and 4). Therefore, long-range transport of lead in water does not appear to be a significant pathway of exposure for humans living in Arctic and subarctic regions.

Air. Natural sources of lead in the atmosphere include volcanic emissions and soil dust [221,222]. However, most of the atmospheric lead in the circumpolar region is due to anthropogenic processes [119,223]. Although lead in the Arctic atmosphere is low compared to more densely populated areas in the south, levels are still higher than background levels due to long-range transport [223–225]. Zhu and Chen [223] reported that 90% of the lead in the atmosphere of the Arctic Chukchi Sea was the result of industrial emissions.

There was a global decrease of atmospheric lead deposition after 1970 to the 1990s/early 2000s (~8–93%; Tables 7 and 8) [16228211228213228228228229,,,,]. This corresponds with the phasing out of leaded gasoline [95,213,218,229,230] and the passing of acts such as the U.S. Clean Air Act [231]. Currently, most Eurasian eagle owls from a study in Sweden had lead isotope ratios that were similar to Precambrian rock background lead, although they were more similar to leaded gasoline emissions in the past [149]. However, atmospheric lead deposition is still an ongoing process. For example, unwashed berries near the Athabasca Bituminous Sands Region in northern Alberta had higher levels of lead than washed berries (0.011 ± 0.084 (SD) and 0.0045 ± 0.0022 (SD) µg/g dw, respectively) due to dust settling onto the berries [125].

Table 6. Avian lead levels in studies that reported lead concentrations in migratory birds.

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
American Black Duck	1993	Dartmouth, Nova Scotia, CA	wintering	204	whole	NA	NA	NA	NA	18%	ammunition	[130]
	1994	Queen's/King's Cove, Prince Edward Island, CA	wintering	200	whole	NA	NA	NA	NA	12%	ammunition	[130]
Blue-winged Teal	1998–1999	Texas, US	stopover	93	liver	NA	0.12 ± 0.20 (SD) μg/g ww	NA	0.012–1.79 μg/g ww	NA	NA	[175]
	2010	El Palmar State Reserve, Yucatan, Mexico	wintering	41	whole	NA	NA	NA	NA	4.9%	ammunition	[176]
Common Teal	2010	Evros Delta, Greece	wintering	4	brain	NA	NA	0.242 μg/g dw	0.167–0.318 μg/g dw	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	4	liver	NA	NA	0.465 μg/g dw	0.370–154 μg/g dw[b]	NA	NA	[177]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	77	liver	0.19 μg/g dw (95% CI: 0.12, 0.31)	NA	NA	<0.015–52.89 μg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	43	muscle	0.11 μg/g dw (95% CI: 0.06, 0.23)	NA	NA	<0.015–20.75 μg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	170	gizzard	NA	NA	NA	NA	10.6%	ammunition	[178]
Eurasian Wigeon	2010	Evros Delta, Greece	wintering	18	brain	NA	NA	0.290 μg/g dw	0.169–1.33 μg/g dw	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	18	liver	NA	NA	1.79 μg/g dw	0.37–8.64 μg/g dw[b]	NA	NA	[177]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	11	liver	0.30 μg/g dw (95% CI: 0.10, 0.89)	NA	NA	<0.015–11.95 μg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	12	muscle	0.11 μg/g dw (95% CI: 0.06, 0.22)	NA	NA	<0.015–1.08 μg/g dw	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	16	gizzard	NA	NA	NA	NA	12.5%	ammunition	[178]
Gadwall	2010	Evros Delta, Greece	wintering	15	brain	NA	NA	0.291 μg/g dw	0.233–0.828 μg/g dw	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	15	liver	NA	NA	2.43 μg/g dw	0.74–5.27 μg/g dw	NA	NA	[177]
Mallard	1994	Moncton, New Brunswick, CA	wintering	104	whole	NA	NA	NA	NA	11%	ammunition	[130]
	1999–2000	Warmia and Mazury, Poland	breeding	38	liver	NA	0.220–0.225 μg/g ww	NA	0.05–0.892 μg/g ww	NA	local Source	[179]
	1999–2000	Warmia and Mazury, Poland	breeding	38	muscle	NA	0.088–0.136 μg/g ww	NA	0.038–0.283 μg/g ww	NA	local Source	[179]
	2009	Poland	breeding	69	blood	NA	NA	<0.2 μg/g ww	NA	NA	NA	[180]
	2010	Evros Delta, Greece	wintering	3	brain	NA	NA	0.478 μg/g dw	0.391–0.894 μg/g dw	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	3	liver	NA	NA	2.39 μg/g dw	0.64–2.48 μg/g dw	NA	NA	[177]

(*Continued*)

Table 6. (Continued).

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
	2012	southeastern Caspian Sea, Iran	wintering	30	liver	NA	1.16 ± 0.41 (SD) µg/g ww	NA	0.58–1.89 µg/g ww	NA	NA	[181]
	2012	southeastern Caspian Sea, Iran	wintering	30	kidney	NA	3.43 ± 0.91 (SD) µg/g ww[b]	NA	2.22–5.62 µg/g ww[b]	NA	NA	[181]
	2012	southeastern Caspian Sea, Iran	wintering	30	muscle	NA	0.83 ± 0.32 (SD) µg/g ww	NA	0.31–1.41 µg/g ww[b]	NA	NA	[181]
Northern Pintail	2010	Evros Delta, Greece	wintering	6	brain	NA	NA	0.699 µg/g dw	0.085–4.10 µg/g dw	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	6	liver	NA	NA	3.90 µg/g dw	0.57–225 µg/g dw[b]	NA	NA	[177]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	15	liver	41.57 µg/g dw (95% CI: 25.55, 67.64)[b]	NA	NA	6.95–161.58 µg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	15	muscle	1.40 µg/g dw (95% CI: 0.77, 2.55)	NA	NA	0.14–5.64 µg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	25	gizzard	NA	NA	NA	NA	76%	ammunition	[178]
Northern Shoveler	2010	Evros Delta, Greece	wintering	8	brain	NA	NA	0.204 µg/g dw	0.173–1.31 µg/g dw	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	8	liver	NA	NA	0.986 µg/g dw	0.650–12.7 µg/g dw[b]	NA	NA	[177]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	37	liver	0.31 µg/g dw (95% CI: 0.16, 0.60)	NA	NA	<0.015–175.20 µg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	25	muscle	0.08 µg/g dw (95% CI: 0.04, 0.14)	NA	NA	<0.015–2.91 µg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	102	gizzard	NA	NA	NA	NA	7.8%	ammunition	[178]
Common Pochard	2000, 2003, 2004	Szczecin Lagoon, Poland	wintering	24	bone	9.6 µg/g dw	14.0 ± 14.1 (SD) µg/g dw[b]	NA	1.7–56.2 µg/g dw[b]	NA	NA	[182]
	2000, 2003, 2004	Szczecin Lagoon, Poland	wintering	24	cartilage	14.9 µg/g dw[b]	27.1 ± 29.5 (SD) µg/g dw[b]	NA	2.3–101.1 µg/g dw[b]	NA	NA	[182]
	2006–2008	Medina Lagoon, Spain	wintering	4	blood	0.926 µg/g ww (95% CI: 8.0, 1067)[b]	NA	NA	0.207–6.34 µg/g ww[b]	NA	ammunition	[183]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	6	liver	1.44 µg/g dw (95% CI: 0.17, 12.06)	NA	NA	0.08–23.69 µg/g dw[b]	NA	ammunition	[178]
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	6	muscle	0.31 µg/g dw (95% CI: 0.07, 1.46)	NA	NA	<0.015–1.62 µg/g dw	NA	ammunition	[178]

(*Continued*)

Table 6. (Continued).

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	20	gizzard	NA	NA	NA	NA	35%	ammunition	[178]
	2012	southeastern Caspian Sea, Iran	wintering	30	liver	NA	2.36 ± 1.00 (SD) μg/g ww[b]	NA	0.97–4.25 μg/g ww[b]	NA	NA	[181]
	2012	southeastern Caspian Sea, Iran	wintering	30	kidney	NA	2.29 ± 1.07 (SD) μg/g ww[b]	NA	0.66–5.04 μg/g ww[b]	NA	NA	[181]
	2012	southeastern Caspian Sea, Iran	wintering	30	muscle	NA	0.62 ± 0.4 (SD) μg/g ww[b]	NA	0.07–1.65 μg/g ww[b]	NA	NA	[181]
Greater Scaup	1999–2000	Lake Ontario, Lake Erie, Lake St. Clair, CA	stopover	289	gizzard	NA	NA	NA	NA	0.7%	ammunition	[184]
	2000, 2003, 2004	Szczecin Lagoon, Poland	wintering	24	bone	6.2 μg/g dw	8.5 ± 7.6 (SD) μg/g dw	NA	1.8–27.6 μg/g dw[b]	NA	NA	[182]
	2000, 2003, 2004	Szczecin Lagoon, Poland	wintering	24	cartilage	10.6 μg/g dw[b]	17.8 ± 20.2 (SD) μg/g dw[b]	NA	2.5–76.8 μg/g dw[b]	NA	NA	[182]
	2002 & 2004	Szczecin Lagoon, Poland	wintering	34	muscle	2.29 μg/g dw[b]	2.30 ± 0.27 (SD) μg/g dw[b]	NA	1.82–3.01 μg/g dw[b]	NA	NA	[185]
	2002 & 2004	Szczecin Lagoon, Poland	wintering	34	liver	2.38 μg/g dw	2.43 ± 0.56 (SD) μg/g dw	NA	1.79–4.49 μg/g dw	NA	NA	[185]
	2002 & 2004	Szczecin Lagoon, Poland	wintering	34	kidney	2.55 μg/g dw	2.60 ± 0.64 (SD) μg/g dw	NA	1.81–5.57 μg/g dw	NA	NA	[185]
Lesser Scaup	1999–2000	Lake Ontario, Lake Erie, Lake St. Clair, CA	stopover	428	gizzard	NA	NA	NA	NA	0.5%	ammunition	[184]
Common Eider	1993	Sheet Harbour, Nova Scotia, CA	breeding	108	whole	NA	NA	NA	NA	35%	ammunition	[130]
	1995	Passamaquoddy Bay, New Brunswick, CA	breeding	166	whole	NA	NA	NA	NA	16%	ammunition	[130]
	1997	Ile Biquette, Quebec, CA	breeding	100	whole	NA	NA	NA	NA	37%	ammunition	[130]
	1996	Hare Bay, Grey Islands, CA	breeding	172	whole	NA	NA	NA	NA	38%	ammunition	[130]
	1995	Table Bay, Newfoundland and Labrador, CA	breeding	55	whole	NA	NA	NA	NA	53%	ammunition	[130]
	1997–1998	Southampton Island, Nunavut, CA	breeding	252	whole	NA	NA	NA	NA	24%	ammunition	[130]
	1997–1998	Cape Dorset, Baffin Island, CA	breeding	152	whole	NA	NA	NA	NA	24%	ammunition	[130]
	1997–1998	Baltic Sea by Finland	breeding	245	blood	0.09 μg/g ww	NA	NA	0.02–1.56 μg/g ww, outlier: 14.2[b]	NA	NA	[131]
	2000–2002	Nuuk, Greenland	wintering	219	whole	NA	NA	NA	NA	15%	ammunition	[134]
	2000–2002	Nuuk, Greenland	wintering	510	whole	NA	NA	NA	NA	27%	ammunition	[134]
	2007	Amchitka and Kiska Islands, Alaska, US	breeding	30	feather	0.456 μg/g dw	0.530 ± 0.0665 (SE) μg/g dw	NA	NA	NA	NA	[136]

(*Continued*)

Table 6. (Continued).

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
	2007	Amchitka and Kiska Islands, Alaska, US	breeding	30	egg	0.0809 µg/g dw	0.306 ± 0.0995 (SE) µg/g dw	NA	NA	NA	NA	[136]
	2008	Tern Island, Nunavut, CA	breeding	30	liver	NA	0.181 µg/g dw	NA	0.060–0.586 µg/g dw	NA	NA	[137]
	2008	East Bay, Nunavut, CA	breeding	30	liver	NA	0.089 µg/g dw	NA	0.060–0.263 µg/g dw	NA	NA	[137]
	2008	Table Bay, Newfoundland and Labrador, CA	breeding	30	liver	NA	0.088 µg/g dw	NA	0.060–0.737 µg/g dw	NA	NA	[137]
	2000–2014	Alaskan coast: near Barrow and in Prudhoe Bay, US	breeding and fall migration	17	kidney	0.07–0.09 µg/g dw	0.07–0.10 µg/g dw	NA	0.03–0.15 µg/g dw	NA	NA	[138]
	2000–2014	Alaskan coast: near Barrow and in Prudhoe Bay, US	breeding and fall migration	40	liver	0.04–0.33 µg/g dw	0.04–5.39 µg/g dw	NA	0.02–8.14 µg/g dw; two outliers: 89.6 & 14200[b]	NA	NA	[138]
	2013 & 2014	Mittivik Island in Northern Hudson Bay, CA	breeding	193	blood	0.008 (0.001 SD) µg/g ww	0.009 ± 0.006 (SD) µg/g ww	NA	0.005–0.043 µg/g ww	NA	NA	[139]
	2014–2015	Cape Dorset, Nunavut and Ivujivik, Quebec, CA	breeding	21 lakes	feces	NA	1.05 ± 0.07 (SD) µg/g dw	NA	NA	NA	NA	[140]
	2017	northern Norway	breeding	14	egg	NA	0.001 µg/g ww	NA	NA	NA	NA	[186]
	2017	Northeast Iceland	breeding	24	egg	NA	0.0004 µg/g ww	NA	NA	NA	NA	[186]
	2010–2012 & 2017	Storholmen, Kongsfjorden, Svalbard – winter in Norway	breeding	12	egg	NA	0.11 µg/g ww	NA	NA	NA	Svalbard breeding grounds	[186]
	2010–2012 & 2017	Storholmen, Kongsfjorden, Svalbard – winter in Iceland	breeding	52	egg	NA	0.004 µg/g ww	NA	NA	NA	Svalbard breeding grounds	[186]
King Eider	2001	Karrak Lake and Adventure Lake, Nunavut, CA	breeding	63	blood	0.011 µg/g ww (95% CI: 0.009, 0.013)	NA	NA	NA	NA	NA	[142]
	2002	Karrak Lake and Adventure Lake, Nunavut, CA	breeding	69	blood	0.021 µg/g ww (95% CI: 0.019, 0.024)	NA	NA	NA	NA	NA	[142]
	2003	Karrak Lake and Adventure Lake, Nunavut, CA	breeding	74	blood	0.021 µg/g ww (95% CI: 0.019, 0.023)	NA	NA	NA	NA	NA	[142]
	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	17	kidney	0.10–0.12 µg/g dw	0.10–0.15 µg/g dw	NA	0.03–0.37 µg/g dw	NA	NA	[138]
	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	19	liver	0.04–0.10 µg/g dw	0.05–0.18 µg/g dw	NA	0.02–0.40 µg/g dw	NA	NA	[138]
Long-tailed Duck	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	18	kidney	0.04–0.08 µg/g dw	0.04–0.27 µg/g dw	NA	0.02–0.98 µg/g dw	NA	NA	[138]
	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	46	liver	0.16–0.28 µg/g dw	0.58–2.35 µg/g dw	NA	0.01–41.0 µg/g dw[b]	NA	NA	[138]

(*Continued*)

Table 6. (Continued).

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
Spectacled Eider	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	19	kidney	0.04–0.18 µg/g dw	0.06–0.29 µg/g dw	NA	0.02–1.20 µg/g dw	NA	NA	[138]
	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	19	liver	0.04–0.10 µg/g dw	0.04–0.19 µg/g dw	NA	0.02–0.89 µg/g dw	NA	NA	[138]
Steller's Eider	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	13	kidney	0.26–0.44 µg/g dw	0.26–16.38 µg/g dw[b]	NA	0.03–81.40 µg/g dw[b]	NA	NA	[138]
	2000–2014	Prudhoe Bay, Alaska, US	breeding and fall migration	25	liver	0.18–0.22 µg/g dw	0.25–0.72 µg/g dw	NA	0.04–4.73 µg/g dw	NA	NA	[138]
Canada Goose	1994	Summerside, PEI, CA	breeding	111	whole	NA	NA	NA	NA	35%	ammunition	[130]
	2009	Kansas, Oklahoma, Missouri, US	breeding	28	liver	NA	<0.024–1.72 µg/g ww	NA	NA	NA	zinc and lead mines	[187]
	2009	Kansas, Oklahoma, Missouri, US	breeding	28	kidney	NA	0.20–7.03 µg/g ww[b]	NA	NA	NA	zinc and lead mines	[187]
	2009	Kansas, Oklahoma, Missouri, US	breeding	28	brain	NA	<0.024–0.55 µg/g ww	NA	NA	NA	zinc and lead mines	[187]
	2009	Kansas, Oklahoma, Missouri, US	breeding	28	blood	NA	0.04–0.86 µg/g ww[b]	NA	NA	NA	zinc and lead mines	[187]
	2009	Kansas, Oklahoma, Missouri, US	breeding	28	muscle	NA	<0.024–0.16 µg/g ww	NA	NA	NA	zinc and lead mines	[187]
	2009	Kansas, Oklahoma, Missouri, US	breeding	28	bone	NA	0.88–72.86 µg/g ww[b]	NA	NA	NA	zinc and lead mines	[187]
Greater White-fronted Goose	2010	Evros Delta, Greece	wintering	4	brain	NA	NA	0.328 µg/g dw	NA	NA	NA	[177]
	2010	Evros Delta, Greece	wintering	4	liver	NA	NA	0.282 µg/g dw	0.267–3.50 µg/g dw	NA	NA	[177]
	2012–2014	Evros Delta, Greece	wintering	118	feces	2.39 µg/g dw (95% CI: 2.07, 2.75)	3.49 µg/g dw	NA	0.66–25.09 µg/g dw[b]	NA	soil	[188]
	2012–2014	Lake Kerkini, Greece	wintering	74	feces	6.90 µg/g dw (95% CI: 5.93, 8.03)[b]	8.67 µg/g dw[b]	NA	1.33–42.26 µg/g dw[b]	NA	soil	[188]
Greylag Goose	1994–2004	Andalusian wetland, Spain	wintering	45	whole	NA	NA	NA	NA	44.40%	ammunition	[189]
	1994–2004	Andalusian wetland, Spain	wintering	161	gizzard	NA	NA	NA	NA	3.70%	ammunition	[189]
	2001–2002	Guadalquivir Marshes, Spain	wintering	50	intestinal content	0.71–7.6 µg/g dw[b]	NA	NA	0.18–18 µg/g dw[b]	NA	spill from a pyrite mine	[190]
	2001–2002	Guadalquivir Marshes, Spain	wintering	50	blood	0.06–0.8 µg/g ww[b]	NA	NA	0.04–3.3 µg/g ww[b]	NA	spill from a pyrite mine	[190]
	2001–2002	Guadalquivir Marshes, Spain	wintering	50	liver	0.27–1.6 µg/g dw	NA	NA	0.18–13 µg/g dw[b]	NA	spill from a pyrite mine	[190]
	2001–2002	Guadalquivir Marshes, Spain	wintering	50	muscle	0.20–0.22 µg/g dw	NA	NA	0.12–0.45 µg/g dw	NA	spill from a pyrite mine	[190]
	2001–2002	Guadalquivir Marshes, Spain	wintering	50	bone	4.8–11 µg/g dw[b]	NA	NA	0.45–45 µg/g dw[b]	NA	spill from a pyrite mine	[190]

(*Continued*)

Table 6. (Continued).

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
	2001–2002	Guadalquivir Marshes, Spain	wintering	270	feces	2.5–15 µg/g dw[b]	NA	NA	0.6–43 µg/g dw[b]	NA	spill from a pyrite mine	[190]
	2004–2008	Doñana Natural Park, Spain	wintering	282	feces	2.16–5.22 µg/g dw	NA	NA	0.57–48.96 µg/g dw[b]	NA	sediment contaminated from mine spill	[191]
Lesser White-fronted Goose	2012–2014	Evros Delta, Greece	wintering	25	feces	6.24 µg/g dw (95% CI: 4.69, 8.32)[b]	8.16 µg/g dw[b]	NA	1.97–28.61 µg/g dw[b]	NA	soil	[188]
	2012–2014	Lake Kerkini, Greece	wintering	145	feces	7.34 µg/g dw (95% CI: 6.78, 7.93)[b]	8.32 µg/g dw[b]	NA	1.78–36.68 µg/g dw[b]	NA	soil	[188]
Tundra Swan	2007–2008	Alaska, US	breeding	653	blood	NA	<0.2 µg/g ww	NA	NA	NA	wintering and staging grounds	[144]
Red-necked Grebe	2011	Wasaga Beach Provincial Park, Ontario, CA	stopover	21	liver	0 µg/g dw (95% CI: −0.01, 0.01)	NA	NA	<0.02–0.06 µg/g dw	NA	NA	[192]
Common Snipe	2007–2008 & 2010–2012	Ebro Delta, Spain	wintering	18	gizzard	NA	NA	NA	NA	5.6%	ammunition	[178]
Pacific Dunlin	2010–2011	Fraser River Delta, British Columbia, CA	wintering	15	feather	0.8 µg/g dw	0.9 ± 0.1 (SE) µg/g dw	NA	0.3–1.8 µg/g dw	NA	NA	[193]
Red Knot	1991–1992	Delaware Bay, New Jersey, US	stopover	16	feather	NA	0.139 ± 0.013 (SE) µg/g dw	NA	NA	NA	NA	[194]
	2011–2012	Delaware Bay, New Jersey, US	stopover	30	feather	NA	0.484 ± 0.067 (SE) µg/g dw	NA	NA	NA	NA	[194]
	2011–2012	Delaware Bay, New Jersey, US	stopover	30	blood	NA	0.07538–0.10540 µg/g ww	NA	NA	NA	NA	[195]
Sanderling	1991–1992	Delaware Bay, New Jersey, US	stopover	12	feather	NA	0.268 ± 0.052 (SE) µg/g dw	NA	NA	NA	NA	[194]
	2011–2012	Delaware Bay, New Jersey, US	stopover	20	feather	NA	0.367 ± 0.052 (SE) µg/g dw	NA	NA	NA	NA	[194]
	2011–2012	Delaware Bay, New Jersey, US	stopover	19	blood	NA	0.0336–0.145 µg/g ww[b]	NA	NA	NA	NA	[195]
Semipalmated Sandpiper	1991–1992	Delaware Bay, New Jersey, US	stopover	12	feather	NA	0.849 ± 0.165 µg/g dw	NA	NA	NA	NA	[194]
	1995	Delaware Bay, New Jersey, US	stopover	28	feather	NA	0.553 ± 0.070 µg/g dw	NA	NA	NA	NA	[194]
	2010–2012	Delaware Bay, New Jersey, US	stopover	19	muscle	0 µg/g ww	0.007 ± 0.002 (SE) µg/g ww	NA	NA	NA	NA	[196]
	2010–2012	Delaware Bay, New Jersey, US	stopover	19	liver	0.03 µg/g ww	0.03 ± 0.004 (SE) µg/g ww	NA	NA	NA	NA	[196]
	2010–2012	Delaware Bay, New Jersey, US	stopover	19	feather	0.42 µg/g ww	0.49 ± 0.07 (SE) µg/g ww	NA	NA	NA	NA	[196]

(*Continued*)

Table 6. (Continued).

Sampled	Sampling Years	Location	Site Type	n	Tissue	Geometric Mean[a]	Arithmetic Mean[a]	Median	Range	Lead pellets	Lead Source	Reference
	2010–2012	Delaware Bay, New Jersey, US	stopover	19	brain	0.06 µg/g ww	0.07 ± 0.01 (SE) µg/g ww	NA	NA	NA	NA	[196]
	2010–2012	Delaware Bay, New Jersey, US	stopover	3	fat	0.002 µg/g ww	0.002 ± 0.0005 (SE) µg/g ww	NA	NA	NA	NA	[196]
	2011	Delaware Bay, New Jersey, US	stopover	30	blood	NA	0.0598 ± 0.0105 (SE) µg/g ww	NA	0.001–0.320 µg/g ww[b]	NA	NA	[195; 197]
	2011–2012	Delaware Bay, New Jersey, US	stopover	30	feather	NA	0.411 ± 0.046 (SE) µg/g dw	NA	NA	NA	NA	[194]
	2013	Commewijne District, Suriname	wintering	71	blood	NA	0.109 ± 0.0132 (SE) µg/g ww	NA	0.0080–0.500 µg/g ww[b]	NA	NA	[198; 197]
	2016	Icapuí, Ceará, Brazil	wintering	62	blood	NA	0.097 ± 0.0236 (SE) µg/g ww	NA	0.0001–0.990 µg/g ww[b]	NA	NA	[197]
Black-headed Gull	2019	Tokyo Bay and Mikawa Bay, Japan	wintering	93	blood	NA	NA	0.0273–0.0468 µg/g ww	0.0094–0.2605 µg/g ww[b]	NA	wintering grounds	[199]
Bald eagle	1994–1995	Galloway Bay, South Saskatchewan River, CA	stopover	66	blood	NA	NA	NA	<0.05–0.585 µg/g ww[b]	NA	NA	[200]
Greater Spotted Eagle	2008–2018	El Hondo Natural Park, Spain	wintering	26	pellets	NA	NA	NA	NA	27%	ammunition	[201]
American Dipper	1999–2001	Chilliwack River, British Columbia, CA	breeding	82	feather	0.59 µg/g dw	0.88 ± 0.18 (SE) µg/g dw	NA	NA	NA	NA	[202]
	2001	Chilliwack River, British Columbia, CA	breeding	14	feces	2.5 µg/g dw	3.65 ± 1.03 (SE) µg/g dw	NA	NA	NA	NA	[202]

Note: Some of these studies are also in Table 3. n is the sample size, SD is standard deviation, SE is standard error, CI is confidence intervals, dw is dry weight, and ww is wet weight. Lead pellets indicate the percentage of birds that had at least one lead pellet either ingested or embedded in their body (see Tissue column). The lead source column states confirmed lead sources.

[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.

[b]A bird was considered to have subclinical levels of lead when the wet weight was 0.2 µg/g for blood, 2 µg/g ww for liver and kidney [273], and 0.5 µg/g for muscle [274] or the dry weight was 6 µg/g for liver, 8.6 µg/g for kidney, 10 µg/g for bone [275], and 2 µg/g for muscle [274]. These levels are based on concentrations found in Anseriformes and Falconiformes. Other tissue types were compared to liver.

Table 7. Water lead levels in studies that reported lead concentrations in Arctic or subarctic regions.

Sampled	Sampling Years	Location	n	Arithmetic Mean[a]	Median	Range	Rate	Lead Source	Reference
Creek/stream	2012	Christal Creek, Yukon, CA	1	0.00144 mg/L	NA	NA	NA	NA	[152]
	2012	Moose Creek, Yukon, CA	1	0.000087 mg/L	NA	NA	NA	NA	[152]
Combination of ponds and creeks	2013	Kaipokok Bay, Newfoundland and Labrador, CA	13	0.00069 mg/L	NA	<0.000495–0.0059 mg/L[b]	NA	uranium mine	[123]
	2013	Makkovik Bay, Newfoundland and Labrador, CA	8	<0.000495 mg/L	NA	NA	NA	NA	[123]
River	1983–2010	Slave River, Fort Smith, NT, CA	83	NA	0.0023 mg/L	<0.0001–0.022 mg/L[b]	NA	NA	[204]
	1980–2010	Slave River, Fitzgerald, NT, CA	211	NA	0.0021 mg/L	0.00016–0.077 mg/L[b]	NA	NA	[204]
	2015	Canadian Arctic Archipelago	14	NA	NA	0.00001–0.00471 mg/L	NA	bedrock	[205]
	2018	Lower Athabasca River, Alberta, CA	36	0.000230–0.000404 mg/L	NA	NA	NA	background	[206]
	2019	Swan River, Alberta, CA	20	NA	0.000866 µg/L	0.000143–0.00243 mg/L	NA	NA	[207]
Lake	no year	Great Bear Lake, NT, CA	unknown	0.0012 mg/L	NA	NA	NA	background	[208]
	2014–2015	Cape Dorset, Nunavut and Ivujivik, Quebec, CA	21	0.000127–0.000269 mg/L	NA	NA	NA	common eider faeces	[140]
Tailings	no year	Port Radium Mine, NT, CA	unknown	0.0011–0.0046 mg/L	NA	Maximum: 0.0628 mg/L[b]	NA	mine	[208]
Groundwater wells	2018	9 communities near Anchorage, Alaska, US	22	NA	NA	<0.005–0.010 mg/L[b]	NA	NA	[209]
Seawater	2015	Canadian Arctic	17	4.6–30.5 pmol/kg (surface to 100 m)	NA	2.5–34 pmol/kg (surface to 100 m)	NA	anthropogenic source near Labrador Sea	[210]
Precipitation	1973–1974	Denmark and southern Sweden	7–10 stations	NA	NA	NA	16.1 mg/m^2/yr	atmosphere deposition	[211]
	2002–2005	Denmark and southern Sweden	7–10 stations	NA	NA	NA	1.0 mg/m^2/yr	atmosphere deposition	[211]
Ice Core	1730–1910	Mt. Logan, Saint Elias Mountains, Yukon, CA	186 metres	0.0000089 mg/L	NA	NA	NA	atmosphere deposition	[212]
	1981–1998	Mt. Logan, Saint Elias Mountains, Yukon, CA	186 metres	0.0000689 mg/L	NA	NA	NA	atmosphere deposition	[212]
	1722–2003	Greenland	115 metres	0.000051 mg/kg	NA	NA	22.0 µg/m^2/y	atmosphere deposition	[213]

Note: n is the sample size. The lead source column states confirmed lead sources.
[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.
[b]Water was considered to have elevated levels of lead when the concentration was greater than the drinking water guidelines of 0.005 mg/L [271].

Table 8. Atmospheric lead levels in studies that reported lead concentrations in Arctic or subarctic regions.

Sampled	Sampling Years	Location	Sample Size	Arithmetic Mean[a]	Range	Lead Source	Reference
Outside	1979–1980	Denmark and southern Sweden	2–6 stations	73.1 ng/m^3	NA	NA	[211]
	2002–2005	Denmark and southern Sweden	2–6 stations	6.6 ng/m^3	NA	NA	[211]
	no year	Chukchi Sea	9	0.532 ng/m^3	0.167–0.962 ng/m^3	90% industrial emissions	[223]
	2008– 2009	Iqaluit, NU, CA	21	0.24–0.39 ng/m^3	NA	soil	[226]
Inside & Outside	2016	Mining sites of Waswanipi, Quebec, CA	26	3.2 ng/m^3	NA	NA	[227]

The lead source column states confirmed lead sources.
[a]Sometimes there are a range of averages as the authors separated them into groups that were not necessary for our study.

Soil and sediment. As shown in Table 9, all studies with levels of lead above guidelines were near a mine or a shooting range. However, soil or sediment lead levels (SLLs) around mining operations do not always exceed guidelines [240]. In fact, SLLs were lower than guidelines near certain oil sands and mining sites in Canada, Svalbard, and Russia [120,121,241]. Additionally, due to the low mobility of lead in the environment, SLLs decrease with distance from mines, although lead may still be present at least 24 km away [172,238].

SLLs can also exceed Canadian guidelines near areas of sewage and waste disposal [217,228,242]. In 1990, people living by Annak Lake on the Belcher Islands, Canada were being exposed to 702 µg/person/day of lead based on calculations from sediment cores sampled from a lake that was being used as a sewage disposal for years [228]. However, sewage areas do not always results in elevated SLLs [243,244].

Pathways of exposure from household sources and lifestyles

Household sources

Out of 14 houses sampled in Nunavut in 2012, two of them had paint lead levels above Canadian guidelines (90 mg/kg [30]; see Table 10). Both paint and the presence of lead ammunition can contribute lead to household dust, which is inhaled [30]. Fillion et al. [30] found that people with high levels of lead in blood had lead isotopes more similar to dust and paint. Living in a house undergoing repairs or renovations more than doubled BLLs in humans compared to those living in houses not being repaired [30], probably due to the increase in dust.

WLLs are generally lower than guidelines prior to entering plumbing systems (Tables 7 and 10). In three communities surveyed in Nunavut in 2013–2014, the percentage of buildings that exceeded Health Canada's guidelines for lead in drinking water (0.005 mg/L) ranged from 13–43% [12]. Approximately 31% of tap water samples in Pond Inlet, Nunavut had WLLs that exceeded guidelines, although most of these were from three buildings (Table 10) [245]. In general, Nunavut tap water has higher lead content than the general Canadian population [30]. In contrast, lead levels in municipal water (including tap) are lower than Russia's allowable levels (0.01 mg/L) in Arctic Russia [127].

In northern Sweden, northern Ontario, and Denmark, the most prevalent pathway of lead exposure from store-bought food is from wine, coffee, and soft drinks [10,43,246]. In Swedish supermarkets, meat, fish, and dairy have higher lead levels than other food types [247]. However, among those eating traditional foods in northern Ontario, store-bought food contributed to only 3% of their dietary lead compared to 96% for those that did not eat traditional foods [10]. As a result, lead daily intake differed between Indigenous people that eat traditional food vs. market food (1.4–2.5 vs. 0.050–0.056 µg/kg/day [10]. Due to these patterns, lead intakes for Indigenous people in Ontario was higher than observed in the general population of Canada as well as Scandinavia [10,248]. Conversely, store-bought food might not increase BLLs [31,46,47].

Behaviours

People that hunt or participate in target practice with lead ammunition may be exposed to lead through inhalation [30,47]. In northern Quebec, hunting frequency was correlated with human BLLs in Indigenous people [8,44,48]. In Alaska, indoor firing ranges with inadequate ventilation that regularly swept with a dry broom (increasing dust in the air) had participants with higher BLLs than ranges that had adequate ventilation and did not dry sweep [249]. In addition, children can be exposed to lead when using air-pellet guns with lead pellets, as they tend to store the pellets in their mouth during use [49].

Smoking was associated with increased BLLs [40,44,47,50,51,250], similar to more southern

Table 9. Soil and sediment lead levels in studies that reported lead concentrations in Arctic or subarctic regions.

Sampled	Depth	Sampling Years	Location	n	Arithmetic Mean[a]	Median[a]	Range	Lead Source	Reference
Soil	Surface	2012	Nunavut communities, CA	12	10.2–16.8 mg/kg	5.4–11.8 mg/kg	NA	NA	[30]
	Organic horizon	no year	Abisko, Sweden	44	NA	6.53 mg/kg	1.76–19.5 mg/kg	mines	[232]
	Organic horizon	2003	Hollola, Finland	30	75–18,800 mg/kg[b]	NA	NA	old shooting range	[233]
	Organic horizon	2016	Adventdalen, Spitsbergen, Svalbard	22	15.46 ± 0.46 (SE) mg/kg	NA	8.80–19.31 mg/kg	background	[121]
	Organic horizon	2016	Ny-Ålesund, Spitsbergen, Svalbard	13	11.84 ± 0.89 (SE) mg/kg	NA	3.84–25.77 mg/kg	background	[121]
	F horizon	2005–2006	Hälvälä shooting area, southern Finland	10	44–23,175 mg/kg[b]	NA	NA	shooting range	[234]
	H horizon	2005–2006	Hälvälä shooting area, southern Finland	10	125–28,328 mg/kg[b]	NA	NA	shooting range	[234]
	Mineral horizon	no year	Abisko, Sweden	21	NA	14.2 mg/kg	6.65–18.3 mg/kg	mines	[232]
	A horizon	no year	Alaska, US	1081	21.1 ± 41.1 (SD) mg/kg	13 mg/kg	2–720 mg/kg[b]	mines	[235]
	Above C horizon	2016	North European sector of Russia to East Siberia	25	16.3 mg/kg	NA	NA	background and anthropogenic	[236]
	0–5 cm	2015–2018	Ny-Ålesund, Svalbard	6	19.56 ± 3.55 (SD) mg/kg	18.55 mg/kg	14.02–25.17 mg/kg	NA	[237]
	0–10 cm	no year	Laesoe, Denmark	32	15 mg/kg	NA	NA	NA	[211]
	0–20 cm	2017	Fort Greely, Alaska, US	54	NA	NA	5.6–4650 mg/kg[b]	old military sites	[122]
	0–20 cm	no year	Nanisivick lead-zinc mine, Nunavut, CA	8	NA	33.8 mg/kg	21.9–220.5 mg/kg[b]	lead-zinc mine	[104]
	0–20 cm	no year	Arctic Bay, Nunavut, CA	8	NA	15.9 mg/kg	3.2–30.3 mg/kg	background	[104]
	10–20 cm	no year	Laesoe, Denmark	32	3.2 mg/kg	NA	NA	NA	[211]
	10–50 cm	2017	Yamal Peninsula, Russia	20	3.9–35.1 mg/kg	NA	NA	NA	[120]
	unknown	no year	Port Radium Mine, Northwest Territories, CA	unknown	48.4 mg/kg	NA	NA	mine	[208]
Sediment	0–0.5 cm	2014–2015	Cape Dorset, Nunavut and Ivujivik, Quebec, CA	21	4.9–8.3 mg/kg	NA	NA	common eider faeces	[140]
	0–1 cm	2013–2015	Yellowknife Bay, Northwest Territories, CA	9	16–35 mg/kg	NA	NA	gold mine	[238]
	0–20 cm	2006–2008	Ulkebµgten, West Greenland	15	1.3–33.1 mg/kg	NA	NA	NA	[239]
	Subsurface (below 1 cm)	2013–2015	Yellowknife Bay, Northwest Territories, CA	9	NA	NA	Maximums: 71–351 mg/kg[b]	gold mine	[238]
	0–40 cm	1993	Imitavik, Belcher Islands, CA	3	1980: 325 ng/cm^3	NA	NA	atmospheric deposition	[228]
					1993: 300 ng/cm^3	NA	NA	atmospheric deposition	[228]
	0–40 cm	1993	Annak, Belcher Islands, CA	3	1970: 250 ng/cm^3	NA	NA	sewage disposal	[228]
					1991: 1242 ng/cm^3	NA	NA	sewage disposal	[228]
	unknown	2018	Lower Athabasca River, Alberta, CA	48–80	2.06–9.08 mg/kg	NA	NA	background	[206]
	unknown	no year	Port Radium Mine, Northwest Territories, CA	unknown	84–1187 mg/kg[b]	NA	NA	mine	[208]

SD is standard deviation, SE is standard error, and n is the sample size. The lead source column states confirmed lead sources.

[a]Sometimes there are a range of averages or medians as the authors separated them into groups that were not necessary for our study.

[b]Soil was considered to have elevated levels of lead when the concentration was greater than the Canadian Council of Ministers of the Environment (CCME) residential guideline of 140 mg/kg [277], although this is under review. Sediment was considered to have elevated levels of lead when the concentration was greater than the CCME freshwater guideline of 35 mg/kg dry weight [278].

Table 10. Household lead levels in studies that reported lead concentrations in Arctic or subarctic regions.

Sampled	Sampling Years	Location	n	Arithmetic Mean[a]	Median[a]	Range	Reference
Paint	2012	Nunavut, CA	27	76.8 ± 168.0 (SD) mg/kg	NA	0.002–565.6 mg/kg[b]	[30]
Tap water	2012	Nunavut, CA	28	0.0147 ± 0.0397 (SD) mg/L[b]	0.0019 mg/L	NA	[30]
	2018–2019	Pond Inlet, Baffin Island, Nunavut, CA	274	NA	0.002 mg/L	0–0.76 mg/L[b]	[245]
Pumphouse	2018–2019	Pond Inlet, Baffin Island, Nunavut, CA	36	NA	0	0–0.009 mg/L[b]	[245]
Water Truck	2018–2019	Pond Inlet, Baffin Island, Nunavut, CA	36	NA	0	0–0.003 mg/L	[245]
Cistern	2018–2019	Pond Inlet, Baffin Island, Nunavut, CA	29	NA	0	0–0.005 mg/L	[245]
Dust	2012	Nunavut, CA	19	108.5–433.1 mg/kg[b]	32.6–141.9 mg/kg	NA	[30]
Ammunition	2012	Nunavut, CA	10	431.4 ± 387.2 (SD) g/kg[b]	NA	NA	[30]

SD is standard deviation and n is the sample size.
[a]Sometimes there are a range of averages or medians as the authors separated them into groups that were not necessary for our study.
[b]Paint was considered to have elevated levels of lead when the concentration was greater than 90 mg/kg [279]. Water was considered to have elevated levels of lead when the concentration was greater than the drinking water guidelines of 0.005 mg/L [271]. Dust was considered to have elevated levels of lead when the concentration was greater than 250 mg/kg [280].

communities [251,252]. Heavy smokers have higher BLLs than those that smoke less [103] and people that have quit smoking have higher BLLs than those that have never smoked [52]. Smoking during pregnancy can also result in higher BLLs in umbilical cords [53,54]. However, other studies have found that smoking is not related to BLLs [8,31,253].

Discussion

Human health in the north

The decrease in human lead levels in Arctic and subarctic regions has been attributed to educational campaigns, partial bans of lead ammunition, and the phasing out of leaded gasoline. In addition, the more substantial decrease in BLLs in northern populations compared to the general population of Canada may point to a difference in the pathways of exposure between southern and northern communities. As lead levels continue to be higher in northern communities compared to southern [8,10,30,254], it is important to determine potential lead sources and pathways of exposure within the Arctic.

While education programs have been generally successful, lead ammunition continues to be sold in stores [255]. Due to the multiple exposure pathways that can result from the use of lead ammunition, a shift to alternative ammunition (e.g. steel shot, copper bullets, bismuth shot) may decrease lead exposure substantially. However, switching to non-lead ammunition may be more expensive [256].

This study did not uncover many adult health effects in northern communities as many studies focus on children. However, the lead-induced neurodevelopmental effects found in children could possibly be carried over into adulthood [55]. Furthermore, epidemiological findings among exposed communities also suggest a role of lead affecting mental health [257–259].

Sources from the environment

Traditional foods

Local food. While some populations of mammals and birds had elevated lead concentrations (e.g. moose, caribou, ptarmigan), the majority of studies reported lead levels below any level of concern, indicating that high lead concentrations are not that common in traditional food. In addition, lead does not biomagnify in higher trophic levels, but rather seems to dilute [116,162]. However, even a constant, low exposure can be critical to sensitive human subpopulations.

Focusing on birds, the majority of studies only reported lead pellets present or elevated lead levels around when lead shot was banned in Canada [26]. Lead shot was banned for hunting migratory wetland birds in North America, but lead shot, slugs, and bullets can still be legally used for large and small mammals and non-wetland birds [6]. Ptarmigan is a popular food item in northern communities in Canada [23], thus the use of lead shot for hunting ptarmigan (and other animals) could increase the lead exposure of people. In addition, two northern studies reported the number of old lead pellets found in birds, which indicates a hunter could be exposed to lead from other hunters. However, a diet consisting only of store-bought food to avoid any lead pellets might result in less nutrients and physical activity, more expenses, and a loss of traditional values [260]. This needs to be taken into consideration in future studies and outreach opportunities.

Mines and other industrial activities represent large sources of lead in Arctic and subarctic regions. Historically, mines in Northwest Territories have produced 1.8 million tonnes of lead [261]. Lead is also one of the main resources mined in Russia [93]. Additionally, 20 facilities use, produce, or process lead or lead compounds in Alaska [5]. This is reflected in our review as six studies attributed the elevated lead levels of eight different animal or plant sample populations to the proximity of mining practices.

However, mines and industry are not always a large source of lead for animals and plants as multiple studies included in this review reported low, more background levels of lead in animals and plants close to mining sites. If lead levels are low in a species and there are no distinguishable sources of anthropogenic lead, it is sometimes assumed the lead is at background levels, although it is difficult to eliminate long-range transport of anthropogenic lead as a potential source [153]. The use of lead isotope ratios allows researchers to more conclusively determine if lead is due to background lead levels or the result of long-range transport [149,173,174].

Biological long-range transport. Internationally, 51.9% of bird samples within these studies (Table 6) were capable of flight with elevated lead levels or lead pellets in at least some individuals. Franson et al. [131] reported that a common eider with a BLL of 14.2 μg/g ww (above BLL poisoning levels) was seen the year after capture. This bird would have migrated to the wintering grounds and back in that time. In one study, many birds with embedded lead pellets were collected during their breeding season [130]. As the hunting season is usually in the fall or winter, this suggests that these birds have been carrying these pellets for months, if not years. Several other studies captured birds at their wintering or stopover sites. While it is unclear if the pellets are from the current year, the birds remained capable of flight at the time of the studies. Therefore, it is possible for birds to bring lead into the Arctic and subarctic region. Although other animal taxa might also bring lead to the northern environment (e.g. fish) [262], there are little data regarding fish or mammals and biological transport of lead.

Birds can sequester lead into their feathers or bones. Sanderlings (*Calidris alba*) at a stopover site in New Jersey, USA had lower blood lead concentrations after they moulted their feathers [195]. Although lead might be lost through feathers, it is possible for sequestered lead in bones to become active in the bloodstream and tissues again. McPartland et al. [263] reported that common eiders breeding in the central Baltic Sea had increased levels of lead as the incubation period progressed. As the lead isotope ratios did not change throughout the incubation period and the eiders were fasting, lead was probably remobilising from the bones. Therefore, the lead exposure most likely happened before the breeding season. This demonstrates that these eiders can migrate after being exposed to lead and re-release it into their body when experiencing stress (e.g. fasting). As a result, even if a bird's lead exposure was not recent, if a hunter consumes a stressed bird, that person could experience elevated exposure due to the remobilisation of lead. The probability of encountering these birds cannot yet be precisely quantified, but these observations highlight the importance of international commitments to decreasing lead.

Environmental sources other than traditional food

In general, WLLs were low throughout the studies included in our review. Lead compounds can bind with organic material, or free ions, and can be soluble in slightly acidic water as compounds such as lead acetate, lead chloride, and lead nitrate [264]. However, elementary lead (metal form) does not dissolve in water under normal environmental conditions and the lead compounds usually found in water (e.g. lead carbonate, sulphate, chloride) are not very mobile [265,266]. As such, WLLs are usually low, even in samples taken right next to old lead mines. However, the disruption of soils, bedrock, and sediments through anthropogenic activities can result in elevated levels of mobile lead in a region [267], although elevated WLLs were not consistently present at mining sites in our review.

Anthropogenic inputs of lead into the atmosphere are fine enough (diameter of less than 2.5 µm [28], that the lead can either be inhaled by humans or deposited into other environmental compartments that humans could be exposed to such as surface water, soil, or plants [268]. Overall, anthropogenic contributions of lead to the atmosphere are still ongoing at present, but they are at much lower levels than a few decades ago.

Pathways of exposure from household sources and lifestyles

Lead-based paint (LBP) was phased out in both Canada and the United States. Houses built between 1960 and 1990 may have small lead levels in interior paint and higher levels in exterior paint. However, the house paint in homes built after 1990 is likely to be virtually lead-free [269]. Although LBP exposure may be less of an issue in northern Canada and Alaska, it is still used by many Indigenous people in Russia [119].

Lead contamination in northern communities' tap water is most likely due to corrosion within the buildings' plumbing or household storage tanks [12], although lead contamination can also be present in more southern communities' drinking water [270]. Lead service connections were used in drinking water systems until 1975 and lead solder until 1986 [271], so buildings that were constructed prior to 1990 are more likely to have higher levels of lead in the drinking water. All three studies that reported high levels of lead in tap water were located in Nunavut. As WLLs within the environment were generally low, the plumbing systems seem to be the source of lead in municipal water. There were limited studies on tap water outside of Nunavut.

Limitations

While we tried to make our search for literature as exhaustive as possible, there were a few limitations to our review. As has been noted for other analytes, there were relatively few studies from countries other than Canada. In addition, our review did not uncover many adult health effects. These limitations further reinforce the recommendations for the future of northern biomonitoring under the Arctic Monitoring and Assessment Programme [272].

Conclusion

Not all studies attribute lead concentrations in humans to eating traditional foods hunted with lead ammunition. Similarly, there are few studies focusing on how the use of lead sinkers in fishing affect lead levels in traditional foods. Therefore, it is still unknown how extensive lead exposure is from consuming traditional foods obtained using lead ammunition or sinkers. In addition, it is possible for migrating birds to bring lead into Arctic and subarctic regions. This phenomenon has not been studied within a human health perspective and should be a focus for future studies .

A few studies included in the review found lead concentrations in water or soil were elevated above guidelines. Most of these elevated levels were known to be a result of mines, shooting ranges, or sewage disposal. However, these findings from the literature were inconsistent and require further study. In addition, the specific contribution of long-range transport to human lead exposure after the phasing out of leaded gasoline is still unknown and should be focused on in future studies.

There are a variety of potential lead sources inside homes such as paint, dust, and tap water. There are few studies focusing on household lead alone or in combination with lead in traditional foods, although this would be a valuable addition to the knowledge about lead exposure in Arctic and subarctic communities.

Lead's effect on adult behaviour was not studied extensively in the literature within this review. It is plausible that lead-induced behaviour in children is carried over into adulthood, or that lead exposure during adulthood might result in similar cognitive adverse effects. This should be focused on in future studies in northern communities.

Overall, there are multiple possible pathways of lead exposure for humans. While lead levels in humans are decreasing in the north, BLLs still tend to be higher in Arctic and subarctic regions compared to southern locations. Therefore, it is important to have more studies actively researching the effects of certain lead sources and pathways on lead concentrations in humans. This scoping review should give other researchers a starting point as we highlight the many possible sources and pathways of exposure for humans living in Arctic and subarctic regions.

Acknowledgments

We would like to thank the federal funding agency, the Northern Contaminants Program. We would like to thank Jackie Stapleton for her assistance in creating the search strategy. We would also like to thank Steven Lam and Gabriella Luongo for comments regarding grey literature screening methods. We sincerely thank David G. MacDougall, geologist and Emeritus Members of the Saskatchewan Geological Society, for his assistance on soil lead composition.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Funding for this work (2019-2021) was provided by the Northern Contaminants Program (NCP), which is a governmental program of Crown-Indigenous Relations and Northern Affairs Canada (grant number HH-05).

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