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Environmental stressors and zoonoses in the Arctic: Learning from the past to prepare for the future

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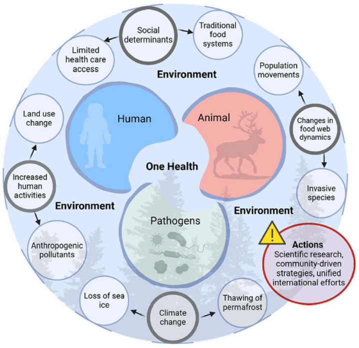
HIGHLIGHTS

- Pollution, climate change and biodiversity loss aggravate zoonoses transmission in the Arctic.
- Zoonoses transmission is elevated for Arctic people in close contact with animals, organs and tissues.
- About three-quarters of all known human infectious diseases are zoonotic including Arctic ones.
- Health care and public health services are limited in remote circumarctic regions.
- There is a need to enhance awareness and manage Arctic zoonoses with pandemic potential.

GRAPHICAL ABSTRACT



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ABSTRACT

The risk of zoonotic disease transmission from animals to humans is elevated for people in close contact with domestic and wild animals. About three-quarters of all known human infectious diseases are zoonotic, and potential health impacts of these diseases are higher where infectious disease surveillance and access to health care and public health services are limited. This is especially the case for remote circumarctic regions, where drivers for endemic, emerging, and re-emerging zoonotic diseases include anthropogenic influences, such as pollution by long-range transport of industrial chemicals, climate change, loss of biodiversity and ecosystem alterations. In addition to these, indirect effects including natural changes in food web dynamics, appearance of invasive species and thawing permafrost also affect the risk of zoonotic disease spill-over. In other words, the Arctic represents a changing world where pollution, loss of biodiversity and habitat, and maritime activity are likely driving forward occurrence of infectious diseases. As a broad international consortium with a wide range of expertise, we here describe a selection of case studies highlighting the importance of a One Health approach to zoonoses in the circumarctic, encompassing human health, animal health, and environmental health aspects. The cases highlight critical gaps in monitoring and current knowledge, focusing on environmental stressors and lifestyle factors, and they are examples of current occurrences in the Arctic that inform on critically needed actions to prepare us for the future. Through these presentations, we recommend measures to enhance awareness and management of existing and emerging zoonoses with epidemic and pandemic potential while also focusing on the impacts of various environmental stressors and lifestyle factors on zoonoses in the Arctic.

1. Introduction

Factors such as close contact with animals, traditional consumption of harvested wildlife, crowded housing, co-morbidities, severity of climate change and extreme weather events as well as poor access to health care and clean water increase risk of zoonotic infectious diseases (Barnes et al., 2020; Hennessy and Bressler, 2016; Hueffer et al., 2013; Huot et al., 2019; Revich et al., 2022). These factors occur in many Arctic communities, and several studies highlight these risks and the limited attention they are given (e.g., Campagna et al., 2011; Dudley et al., 2015; Goyette et al., 2014; Huot et al., 2019; Jenkins et al., 2013; Lévesque et al., 2007; Parkinson et al., 2014; Revich et al., 2012; Sampasa-Kanyinga et al., 2013). Traditional circumpolar food systems are both of immense importance in the Arctic and highly vulnerable to pathogens and contaminants. This creates accentuated exposure risks to Indigenous communities, while at the same time, these risks are a challenge to survey and zoonotic infections are likewise a challenge to detect (Keatts et al., 2021; Stimmelmayr and Sheffield, 2022).

Disease dynamics in the Arctic are already changing due to climate driven range expansion and in some circumstances subsequent major epidemics have occurred (Forde et al., 2016; Kafle et al., 2020; Kutz et al., 2015; Mavrot et al., 2020; Seru, 2023). Global warming, toxic biomagnifying industrial long-range transported pollutants, biodiversity loss and increasing human activities in the Arctic (e.g., mining, overfishing, and increased ship traffic) are likely to amplify endemic disease transmission and facilitate invasion and establishment of invasive hosts and pathogens (Davidson et al., 2011; Desforges et al., 2016; Dudley et al., 2015; Greatorex et al., 2016; Jenkins et al., 2013; Keatts et al., 2021; Kutz et al., 2009; Liang et al., 2022; Mahon et al., 2024; Pfenning-Butterworth et al., 2024; Waits et al., 2018). For example, wildlife species may expand their habitat range northwards due to climate change causing an increase in transmission of endemic pathogens or introducing pathogens novel for local, pristine Arctic species (Revich et al., 2012; van Oort et al., 2022). This occurs concurrent with other contemporary wildlife stressors, mentioned above, some of which may be reaching levels of immune-suppression (Aguirre, 2017; AMAP, 2021; Baker et al., 2022; Dietz et al., 2019, 2022; McKinney et al., 2013; Thomas et al., 2022).

In addition, ancient pathogens are re-emerging from thawing permafrost (Alempic et al., 2023; Christie, 2021; Council, E. A. S. A, et al., 2020; Legendre et al., 2014; Revich et al., 2022; Sajjad et al., 2020; Wu et al., 2022). A recent study by Lemieux et al. (2022) utilizing a metagenomics approach showed that viral spillover risk increases as more runoff from glacial melt occurs with e.g., global warming.

Considering the likely shifting species range of potential vectors and reservoir animal hosts northwards, Lemieux et al. (2022) suggested that the Arctic could be the origin of emerging pandemics. Keatts et al. (2021) however, argued that, thus far, the low density of humans and animals along with a cold climate has limited the risk of pandemics originating from Arctic regions. But this relatively low risk may change in the near future due to anthropogenic factors that alter host-pathogen-environment relationships. Despite this, zoonoses in the circumpolar Arctic remain neglected infectious diseases which have received lower study effort and financial support compared to diseases occurring in more temperate latitudes (Emelyanova et al., 2022; Hotez, 2010; Nelson, 2013). The reasons for this neglect may be demanding logistical conditions, relatively low population density, lack of coordinated effort and funding, and misconceptions of the Arctic as an environment possessing low microbial activity (Huot et al., 2019; Korchak et al., 2019; Neufeld and Mohn, 2005). Recent global epidemics and pandemics such as COVID-19 and highly pathogenic avian influenza (Lane et al., 2024) have underscored the significance of existing knowledge gaps with regards to Arctic zoonoses, but have also offered insight into One Health-related themes specially related to wildlife and the environment, and societal factors which complicate management of disease outbreaks (Fig. 1).

1.1. *Towards more coherent research-efforts on zoonoses in the Arctic*

An estimated 75 % of emerging infectious diseases (EIDs) are zoonotic (in origin or current transmission) and of these, around 72 % originate from wildlife (Jones et al., 2008), while ca. 63 % of all known human and animal infectious diseases are defined as climate sensitive (McIntyre et al., 2017). Microbes and their community composition, function, physiological response and evolutionary adaptation are inherently sensitive to climate change (Cavicchioli et al., 2019) and zoonotic diseases are generally more climate sensitive than infectious diseases, in part due to their wider host ranges and modes of transmission including vector-borne and environmental transmission (McIntyre et al., 2017; Naicker, 2011). Climate change is occurring at the most dramatic rate in the Arctic, and it is therefore crucial to understand the relationship between zoonotic diseases, climate, and the effects of anthropogenic activities on the epidemiology and epizootiology of zoonoses. Understanding these interactions is important to enable informed and effective interventions to mitigate human, animal, ecological, or economic loss (Rantanen et al., 2022; Waits et al., 2018).

In recent years, reviews of the current knowledge of zoonotic diseases in the Arctic covering a broad panel of zoonotic pathogens have been published (e.g., Keatts et al., 2021; Tryland, 2022; Tryland et al., 2014; Tryland and Kutz, 2018). This knowledge is however limited to scattered efforts, low diagnostic capacity in remote areas, and relatively low prioritization by Arctic health care institutions. Moreover, studies of Arctic zoonoses and has typically - until recently - lacked implementation of valuable local knowledge, e.g., from hunters (Tomaselli et al., 2018). These priorities (and lack thereof) vary across the Arctic but nevertheless leave gaps in our knowledge of current and emerging zoonotic diseases in large parts of the inhabited Arctic (Omazic et al., 2019). Scientific attention to zoonoses in the Arctic has typically been opportunistic or related to severe disease outbreaks prompting further investigation (Gigante et al., 2019; Snyman et al., 2023). With some exceptions such as academic-community-government partnered wildlife health monitoring programs (Checkley et al., 2022; Reynolds et al., 2022), systematic investigations have been lacking. Research efforts vary greatly across the Arctic, with several reports from e.g., Canada, but only very scarce information on zoonoses from e.g., Greenland. Compounding the challenges and knowledge gaps in this field are difficulties in obtaining high quality samples for prompt analysis, lack of timely communication between community stakeholders and scientists, and other challenges of trans- and multidisciplinary research. This includes inconsistent use of terminology, lack of coordinated research programs and methodology standards, and unclear data presentation across original research papers (Emelyanova et al., 2022).

Moreover, some weaknesses of traditional diagnostic modalities - which have been widely used in Arctic zoonoses research - are now being exposed by modern and ever price reducing high-throughput sequencing techniques (e.g., Tschritter et al., 2024). Some conventional diagnostic methods like serology, culture, and targeted genetic sequencing can only detect and characterize *known* pathogens, i.e., their weakness is among other that they demand some *a priori* knowledge about what to look for thus hindering the discovery and characterization of (unexpected) new pathogens. The latter is highly relevant - particularly in a permafrost-thawing environment. Conversely, metagenomic modalities present highly useful tools to investigate the presence of both known and unknown pathogens in a wide range of sample types, and future (coordinated) efforts will benefit from systematic studies looking into the pathogenic microbiome of the Arctic, e.g., in traditional foods, sewage, drinking water, invasive species, migratory species and areas with high glacial or other permafrost runoff.

As mentioned, there are still many unanswered questions related to Arctic zoonoses, e.g. 1) How will chemical pollution, biodiversity loss and habitat loss alter disease dynamics for the known endemic diseases? 2) Which pathogens remain undetected or unreported in the Arctic, and how are they affected by multiple stressors? 3) How can disease outbreaks be effectively managed? 4) Does the increase in tourism increase the risk of infections and spreading of potential zoonotic diseases? To help prioritize and coordinate surveillance and research efforts, Table 1 lists zoonoses known in the Arctic as well as specific concerns increasing their current relevance. The list also includes potentially emerging zoonoses considering likely changes in conditions. It is, however, important to remember that there is a growing number of "combined" or mixed infections in the Arctic, causing potentially heavier course of disease and additional challenge for diagnostics since many Arctic infections share the same symptoms.

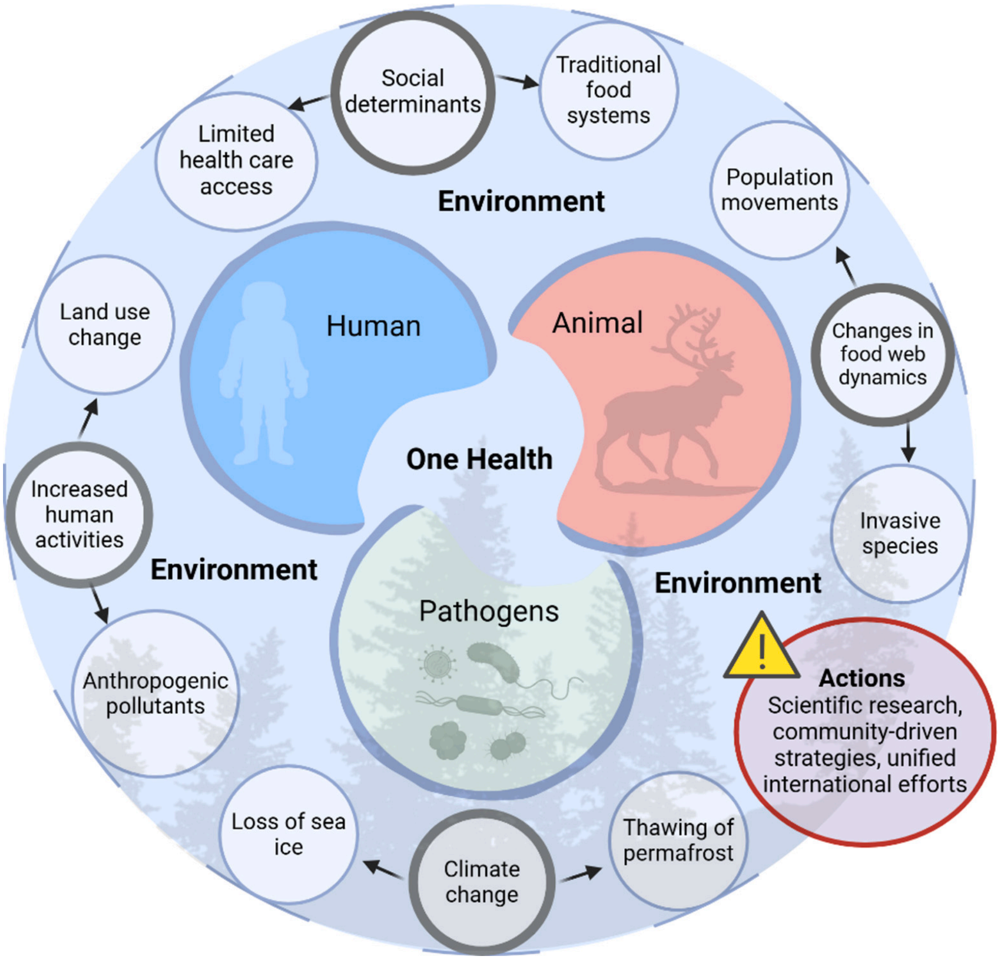

Fig. 1. The One Health concept of the Arctic showing how the large number of environmental stressors driving zoonotic infectious diseases, and where the cycle can be broken through evidence based collective action.

Table 1
Non-exhaustive overview of known zoonoses in the Arctic and their characteristic presentation, as well as why these pathogens should be included in systematic monitoring efforts. CSI = climate-sensitive infection.

Pathogen	Why is this disease important?	References
Prions and fungi	• Not covered in detail in this work due to limited reporting in the Arctic; these pathogen groups should, however, be evaluated in future as some are highly climate sensitive, pathogenic in humans and animals, and zoonotic.	
Viruses		
Lyssavirus (Rabiesvirus; RABV); established	• Nearly 100 % mortality in infected unvaccinated individuals. The main reservoir in the Arctic, the Arctic fox (*Vulpes lagopus*) may however survive rabies exposure. • Enzootic in Arctic foxes but periodically spills over into a broad range of hosts around the circumpolar north. • Increasing number of rabies cases in reindeer (*Rangifer tarandus*) across the Russian Arctic. • Climate-sensitive – e.g., reflected by a strong seasonal trend peaking in winter and spring. • Climate-driven northward shift of red foxes (*Vulpes vulpes*) may introduce more virulent strains, but loss of sea ice may decrease the spread and frequency of Arctic fox rabies outbreaks. • Rabies in Arctic foxes on Svalbard appear disproportionately affected by climatic factors in comparison to red foxes (described in case study below). • Bats, raccoons, and skunks, as other rabies reservoirs, may shift their range northwards thus increasing the infection pressure and diversity of rabies viruses in the Arctic. • Canine rabies vaccination and human post-exposure treatment is expensive and logistically challenging to deliver in many Arctic communities. • Oral vaccination of wildlife possible, but issues with residual pathogenicity, sustainability, and exposure of non-target species.	(Elmore et al., 2022; Rupprecht et al., 2002) (Hampson et al., 2015) (Kim et al., 2014) (Fehlner-Gardiner et al., 2008; Simon et al., 2021) (Hueffer et al., 2022b)
Flavivirus (e.g., Tick-Borne Encephalitis Virus, TBEV); invader	• Presentation ranges from asymptomatic to fatal neurotropic infection depending on subtype: in increasing order of virulence, European, Siberian and Far-eastern subtype, with the last causing 20–40 % fatality rate in humans, even following treatment. • Long term health deficits are common after severe infections. • *Ixodes ricinus* and *Ixodes persulcatus* are the most important tick vectors in Europe and Russia, but transmission also possible through unpasteurized dairy products. • Temperature and precipitation significantly influence the life cycle and distribution of ticks. • Both ticks and TBEV are likely to invade the Palearctic in near future due to climate change. • TBEV has spread to new areas in the recent decades and a significant increase of human cases in Europe and Russia during last 40 years has been reported, e.g., 50-fold increase in human TBEV cases in Arkhangelsk Oblast • Vaccination can reduce TBEV related morbidity and mortality in the Arctic, in addition to monitoring of vector populations and promoting self-protection from tick bites.	(Mandl, 2005; Mandl and Holbrook, 2011) (Jaenson et al., 2016; Semenza and Menne, 2009; Süss, 2008; Tokarevich et al., 2011) (Daniel et al., 2018; Heuverswyn et al., 2023; Jääskeläinen et al., 2011; Tonteri et al., 2016; Малхазова et al., 2022) (Ličková et al., 2021; Waits et al., 2018)
Influenza A; established	• Pandemic potential, high mutation rate, transmission from person-person, animal-human, and animal-animal. • Global long distance spread via migrating birds and traveling humans and goods. • Birds, particularly waterfowl that accumulate at resting sites and migrate long distances, are the main reservoir. • Since 2021 seabirds have been confirmed important vectors and colonial nesting seabirds (such as Northern gannet and great skua) have incurred very high mortality rates, resulting in a temporary moratorium on traditional gannet fledglings harvest in the Faroe Islands. Northern fulmars (*Fulmarus glacialis*), another important hunting bird has also tested positive and have been found dead in large numbers (unpublished). • Virulence ranges from asymptomatic to high morbidity and mortality according to strain. • Recent dramatic increase of wildlife die-offs related to Influenza A infection, including spread from birds to mammals e.g., marine mammals and furbearers, which are important species harvested in the Arctic.	(Bodewes et al., 2015; Kleyheeg et al., 2017; Krone et al., 2018; WHO Statement, 2023) (Banyard et al., 2022; Camphuysen et al., 2022; Lane et al., 2024) (Hofmeister et al., 2021) (Krone et al., 2018; Ramey et al., 2022)

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
	• The thawing of ancient Influenza A viruses from the Arctic's melting permafrost and ice sheets could increase transmission pressure, particularly on waterfowl, the primary reservoir species. Millions of these birds nest in the Arctic each summer and migrate south to temperate regions in the winter. • Rapid weather variability associated with climate change may increase the risk and magnitude of influenza outbreaks, e.g. altered wetland habitat may alter density of waterfowl and interface with other species, including humans. • High need for monitoring of wildlife as both reservoirs and victims of influenza, as well as for changing transmission patterns due to climate change. • Strain-specific vaccines are effective at reducing morbidity and mortality in people, if they can be developed and deployed rapidly, but are not practical in wildlife.	
Influenza B	• Influenza B viruses are highly adapted to humans but also able to infect some animals such as pigs (*Sus scrofa*), guinea pigs (*Cavia porcellus*), ferrets (*Mustela furo*), shrews, and seals. Thus, a potential significant zoonosis and reverse-zoonosis. Transmission between humans and seals has been recorded. • Epidemiology similar to Influenza A. • High epidemic potential among humans and a globally important cause of morbidity and mortality among humans, although typically less virulent than Influenza A. • General scientific interest in the zoonotic potential of this very common influenza infection has increased because of the mutation potential and risk to vulnerable humans, such as co-morbid patients. • Similar climate sensitivity to Influenza A.	(Ohishi et al., 2002; Osterhaus et al., 2000; Pica et al., 2012; Tsai and Tsai, 2019; Yuan et al., 2019) (van de Sandt et al., 2015) (Nicholson, 1992) (Liu et al., 2020a, 2020b)
Parapoxvirus (genus, e.g., Orf virus; ORFV); established	• Distributed globally in small ruminants, occasional zoonosis in people with close contact. • Causes contagious ecthyma in sheep (*Ovis aries*) and goats (*Capra hircus*) but also in a wide range of terrestrial and marine wildlife species including muskoxen (*Ovibos moschatus*), reindeer (*Rangifer tarandus*), and seals. In Finland, recent outbreaks in reindeer have been associated with a virus similar to bovine Pseudocowpox (PCPV). • Causes lesions in the skin and particularly at muco-cutaneous interfaces at the muzzle, lips, eyelids, anus, prepuce, or vulva, teats, and oral mucosa. • Parapoxviruses, like other pox viruses, are highly environmentally resistant, • Arctic hosts may have increased susceptibility due to co-occurrence of stressors related to climate change, including other pathogens, immune-compromising environmental pollutants, and fluctuations in feed-availability. • Vaccines are effective in domestic animals. • Sensitivity to climate change has not been thoroughly investigated, however, increased susceptibility due to co-occurrence of stressors related to climate change may occur. These include alterations in infection pressure, immune-compromising environmental pollutants, and fluctuations in feed-availability.	(Klein and Tryland, 2005) (Costa et al., 2021; Dalton et al., 2023; Tikkanen et al., 2004; Tomaselli et al., 2016) (Pedersen et al., 2011) (Tryland et al., 2011)
Orthopoxvirus (genus); established	• Except for smallpox, the genus Orthopoxvirus is generally considered zoonotic, including viruses causing e.g., cowpox and mpox (also known as monkeypox). • Orthopoxvirus infections are emerging, and globally there is low immunity after smallpox vaccination programs ceased. • A new and hitherto unknown Orthopoxvirus strain was recently isolated from a female patient from inland Alaska. • Cowpoxvirus: Small rodents and shrews are regarded as asymptomatic reservoir species (Europe). Humans are exposed to infection via small rodents and cats (*Felis catus*). • A high seroprevalence of Orthopoxviruses has been found in carnivores, such as red foxes in Norway and Finland, and in brown bears (*Ursus arctos*) in Sweden. Moreover, Orthopoxvirus DNA has been detected in lynx (*Lynx lynx*) in Sweden. But apart from this, distribution and prevalence among wildlife species and populations are currently unknown. • Mpox: causes skin rash and mucosal lesions in humans. Humans typically recover but may experience severe illness. Small mammals are regarded as an important reservoir. First detected in DR Congi in 1970 but caused a global outbreak in 2022–2023 affecting 110 countries, leading to at least 87,000 cases.	(Kinnunen et al., 2015; Tryland, 2011; Tryland et al., 1998) (Shchelkunov, 2013) (Springer et al., 2017) (Pedersen et al., 2011) (Okoli et al., 2023)

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
	• Environmental resistance and sensitivity to climate change as described for parapoxvirus. Climate sensitivity is greatly dictated by changes in the distribution, behavior, and abundance of the small mammalian reservoirs species. • Vaccines are effective in people. Susceptibility of humans is related to decreased immunity (e.g. seized global vaccination against smallpox) and immunosuppression.	
Orthohantaviruses; established	• Hantaviruses are globally distributed and cause severe disease in humans. Puumalavirus (PUUV) is the most frequent type in northern Europe and emerging in Sweden and Finland. Other strains occur in the Nearctic, i.e. Sin Nombre virus.	(Borg et al., 2017; Ecke et al., 2022; Makary et al., 2010)
	• Causes Nephropatia epidemica (NE), a hemorrhagic fever with renal syndrome (HFRS), in humans in the Palearctic and hantavirus cardiopulmonary syndrome (HCPS) in the Nearctic.	(Bergstedt Oscarsson et al., 2016; Latronico et al., 2018; Voutilainen et al., 2016)
	• Rodents are asymptomatic carriers in which the virus prevalence fluctuates. The main reservoir hosts of pathogenic hantaviruses are the bank vole (*Myodes glareolus*) in the Palearctic and deer mouse (*Peromyscus maniculatus*) in the Nearctic. Both are synanthropic and found in high numbers in areas densely populated by humans. • Causes recurring clinically significant outbreaks, although cases may go unnoticed due to subclinical manifestation, or misdiagnosis. Up to half the diagnosed cases required hospitalization. • CSI linked to high autumn temperature, high precipitation, and high temperature during the wettest months of the year and mild winters with less snow cover. Climate change is seen to increase transmission of PUUV. • No licensed vaccines or specific treatment available for humans or animals. Treatment is largely supportive.	(Evander and Ahlm, 2009; Makary et al., 2010; Pettersson et al., 2008; Sipari et al., 2022)
California serogroup viruses (Snowshoe hare virus, Jamestown Canyon virus)	• High prevalence in people (27 % in Alaska) and wildlife (50–80 % of caribou) in the North American Arctic • Mosquito borne orthobunyaviruses	(Buhler et al., 2023a, 2023b; Miernyk et al., 2019)
	• Reservoirs are rabbits, rodents, and cervids. • Second most common cause of clinical encephalitis caused by arboviruses in North America	(Evans et al., 2019)
	• Highly CSI, predicted to expand northwards, experience more rapid development, amplified transmission, and longer transmission seasons in endemic regions, increase bite rates due to increased availability of breeding sites and synchrony between reproduction of reservoirs and mosquito emergence.	(Snyman et al., 2023
Bacteria		
Borrelia burgdorferi sensu lato; potential invader	• Lyme borreliosis is a zoonotic vector borne disease caused by certain genospecies of the *Borrelia burgdorferi* sensu lato complex that are transmitted by tick vectors in the genus *Ixodes*. It is generally not lethal; however, if left untreated, it can lead to serious health issues and chronic conditions. • Birds and mammals are main reservoirs of the bacterium.	(Goren et al., 2023; Jore et al., 2011; Ogden et al., 2008; Rizzoli et al., 2011; van Oort et al., 2020)
	• Humans get infected by bites from ticks that have previously fed on an infected animal. Ticks can feed on multiple host species, but the main reservoir hosts are small to medium sized mammals. • The major host groups transmit *Borrelia* genospecies with different pathogenicity. • Pathogenicity varies with genospecies; symptoms in people include fever, rash (*erythema migrans*), facial paralysis and arthritis. Dogs are often subclinical but can exhibit lameness and kidney problems. • Lyme borreliosis is the most common vector-borne disease in the northern hemisphere and is rapidly increasing in both incidence and geographical distribution in many regions of Europe and North America. *Ixodes scapularis* is not yet established north of 53 N latitude in North America. • CSI with transmission and incidence influenced by changes in climate affecting tick habitat, survival, activity patterns, host distribution, and bacterial growth. • Vaccines are not available. Preventive measures focus on avoiding tick bites and early detection, while treatment is antibiotics being especially effective during early stages of infection.	(Andersen and Davis, 2017; Mysterud et al., 2019; Waits et al., 2018)
Brucella spp.; established	• Brucellosis is one of the most frequently diagnosed zoonotic infections in humans in the Arctic.	(Cotterill et al., 2020; Dahouk and Nöckler, 2011; Faramarzi et al., 2019; Liu et al., 2020a, 2020b)

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
	• Brucellosis may cause abortions or prolonged, non-specific flu-like symptoms in humans, including undulant fever, weakness, malaise, and weight loss.	
	• Difficult to diagnose and under-reported. Unspecific and varying symptoms that are easily interchangeable with other common diseases.	(Aguilar et al., 2024; Nymo et al., 2011; Tryland et al., 1999)
	• Human infection may occur via eating or handling infected raw or inadequately cooked meat, sexual transmission, and via arthropods.	
	• Infection may be subclinical in animal hosts, including domestic animals and terrestrial- and marine wildlife important for subsistence hunting, for example caribou (*Rangifer tarandus*) muskoxen (*Ovibos moschatus*) harbour seal (*Phoca vitulina*), wild boar (*Sus scrofa*), moose (*Alces alces*) and bison (*Bison bison*). Even countries that are declared officially free of brucellosis, like Norway, have *Brucella* spp. among its marine mammals.	(Zheludkov and Tsirelson, 2010)
	• Infection can remain latent in the animal host, enabling infection and reinfection to other animals.	(Dadar et al., 2020; J. Wang et al., 2017)
	• Widespread and difficult to control because of the ecological plasticity of *Brucella* spp. and high environmental resistance.	
	• Risk of substantial economic losses due to transmission from wildlife to domesticated animals.	
	• Environmentally resistant and well adapted to both warm and cold climates; thus, increased temperatures are likely less important than changes in precipitation patterns and altered behavior and habitat of animal reservoirs and arthropod vectors. North-shifting reservoir species from the south may increase infection pressure in resident Arctic wildlife.	
	• Vaccines are used in domestic livestock in endemic regions; disease is stamped out in livestock in countries currently free of *B. abortus*.	
Bacillus anthracis; established	• Often per acute infection leading potentially to sudden death of both animals and humans. Outbreaks with sudden deaths are most seen in ruminants.	(Emelyanova et al., 2022; Malkhazova et al., 2022)
	• Because of the highly toxic nature of its bacterial spores, *B. anthracis* has been selected as a potential biological weapon as well as been used in previous terrorist attacks.	
	• In the Arctic, the most vulnerable animals to anthrax are reindeer and muskoxen.	(Ezhova et al., 2021)
	• Highly virulent spores which are extremely environmentally resistant. Can survive in the soil for decades, and possibly much longer in permafrost.	(Salb et al., 2014)
	• The main problem is the danger of reactivation of anthrax spores due to the thawing of permafrost and the exposure of old cattle burial grounds against a backdrop of the cessation of reindeer vaccination. The large anthrax outbreak of 2016 in Yamal, Russia, is an example of the climate sensitivity of *B. anthracis* with 2650 reindeer and 1 human dead (see case study on *B. anthracis* for more on this).	(New et al., 2017)
	• Large natural foci located in northern latitudes, e.g. Siberia (Sakha republic - Yakutia, Yamal, and Taimyr Peninsulas) and northern and northwestern Canada (Mackenzie Bison and Wood Buffalo National Park and more).	
Erysipelothrix rhusiopathiae; established	• Infection can cause significant morbidity and in some cases mortality e.g., in the case of septic endocarditis – *E. rhusiopathiae* has an affinity for heart valves.	(Medway, 1980; Reboli and Farrar, 1989; Woods and Gutierrez, 1993)
	• Able to infect a wide array of species, but may be a commensal in some species, e.g., predators such as Arctic seals. Thus, bites or cuts during butchering of seals are risk factors for infection in people of the Arctic.	(Dunbar and Clarridge, 2000; Robson et al., 1998)
	• Varying clinical signs challenge diagnosis.	
	• Antibiotic resistance (ABR) is seen with infection but is unlikely in wildlife reservoirs.	(Venditti et al., 1990) (Wood and Steele, 1994)
	• Long survival time in soil where it exists as a saprophyte. It can also be spread by ticks, mites, and flies.	
	• Identified as an emerging wildlife pathogen in terrestrial and marine systems in the Arctic.	(Aguilar et al., 2024; Forde et al., 2016; Mavrot et al., 2020; Seru, 2023)
	• A unique clonal strain associated with multiple epidemics with high rates of mortality in muskoxen in the Canadian Arctic Archipelago.	
	• Increased temperature and moisture lead to increased survival in soil and has been associated with increased rate of infection among caribou and other mammals. It also persist in aquatic environment, meat, and animal remains.	(Aleuy et al., 2022; Hong-Yu et al., 2020; Spraker and White, 2017)
Francisella tularensis; established	• When inhaled, one of the deadliest human pathogens, Category A bioterror agent with 30–60 % mortality rate if untreated.	(Conlan, 2011)

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
	• Arctic strain (type B, or *F. tularensis* ssp. *holarctica*) may be less virulent than type A (*F. tularensis* ssp. *tularensis*).	(Hennebique et al., 2019; Kravdal et al., 2021)
	• Humans are mainly infected via arthropod vectors (Sweden) or via direct contact with infected animals, by aerosol or waterborne (North America). Although *F. tularensis* infects a wide range of animals as well as humans, no cases of human-to-human transmission have ever been convincingly documented.	(Eliasson and Bäck, 2007)
	• Human outbreaks are recorded, e.g., 10 simultaneous cases in the Nenets AO, Russia.	(Hestvik et al., 2017; Kudryavtseva, 2017)
	• Extremely low infective dose, plague-like and highly fatal to leporids e.g., Arctic hares (*Lepus arcticus*).	
	• Rodents and hares are primary reservoirs, insects (ticks and biting flies) act as important vectors.	
	• Cold climate does not restrict transmission and tularemia is widespread in the Arctic, e.g., with up to 50 % seroprevalence in animals and 18 % in humans in Alaska. Likewise, a high seroprevalence has been recorded in terrestrial mammals in Iceland and Canada.	(Buhler et al., 2023a, 2023b; Hansen et al., 2011; Pilfold et al., 2021)
	• Evidence for climate sensitivity includes higher exposure in foxes following high precipitation during the summer, increased snow cover and colder temperatures in May, and higher exposure in polar bears (*Ursus maritimus*) following decreased sea ice and increased time spent on land.	(Desvars et al., 2015; Kravdal et al., 2021; Conlan et al., 2021)
	• A CSI. Increasing temperatures will shift the density and distribution of animal reservoirs and arthropod vectors of *F. tularensis* and may lead to type A moving northward. Increased water run-off from increased melt is also an increasing risk factor.	
	• Can be treated with antibiotics in people and domestic animals but is considered a dangerous infection.	
Clostridium botulinum; established	• High morbidity and mortality due to extremely potent nerve toxin.	(Austin and Leclair, 2011)
	• Highly environmentally resistant spores that persist for decades in soils, dust, terrestrial and marine sediments in the Arctic.	(Espelund and Klaveness, 2014)
	• Cases are several folds higher among Arctic Indigenous communities compared to other developed countries. In Alaska, incidence is 800 times higher than the rest of the U.S, and in Canada, 85 % of all cases of botulism occur in native communities.	(Austin and Leclair, 2011; Fagan et al., 2011; Leclair et al., 2013)
	• Wide range of potential wildlife carriers/host, but many foods are a source of human exposure.	
	• People can be treated with antitoxins, but this requires stockpiles and high awareness among medical professionals.	
	• A CSI. Increased temperatures will increase growth and nerve toxin production and thawing permafrost is likely to release viable and infectious spores. Both increased drought and rainfall, as well as more frequent extreme weather events, can lead to increasing cases of botulism. Outbreaks have also been associated with algal overgrowth in lakes, and overexploitation of groundwater during droughts. In the North American Arctic, cases have been linked to traditional preparation of foods in non-traditional containers (garbage bags) at warmer outdoor temperatures.	(Christie, 2021; Espelund and Klaveness, 2014; Lafrancois et al., 2011; Vidal et al., 2013)
Leptospira interrogans; established	• Certain serovars cause potentially life-threatening infections in humans and animals. Can be treated with timely use of correct antibiotics.	(Seguro and Andrade, 2013)
	• Neglected and emerging disease. Particularly neglected in the Arctic because of a traditional view of leptospirosis as a primarily tropical disease, though now known to be one of the most widespread zoonosis in the world. Less neglected in Russian research where high occurrences have been described in some areas, particularly regions of Yakutia, Murmansk, and Arkhangelsk.	(Andersen-Ranberg et al., 2016; Hartskeerl et al., 2011; Lau et al., 2010; Minette, 1983) (Revich et al., 2012; Tokarevich and Stoyanova, 2011; Zakharova et al., 2020)
	• Rodents are the most important vectors for serovars pathologic to humans, but other mammals can also act as vectors.	
	• Infection can lead to long-term asymptomatic carriers that shed the bacterium in the environment like super spreaders.	(Bradley et al., 2005; Prescott et al., 2002; Lepto-seroprevalence among Greenlanders: unpubl. Mat., Prof Anders Koch and Emilie A.-Ranberg)
	• Hunters, trappers, and reindeer herders are at increased risk of infection.	
	• Not defined as a notifiable disease by several Arctic nations but should be included in the future.	
	• High seroprevalence among Greenland Inuit, both hunters and city-dwelling people, indicate neglect in leptospirosis reporting in this part of the Arctic.	
	• Highly CSI. Waterborne transmission is the most important mode of transmission and outbreaks are as such often linked to floods. Increased thaw and water run-off as well as more frequent extreme	(Lévesque et al., 1995; Revich et al., 2012)

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
	weather events will therefore increase the risk of infection. Moreover, increased temperatures may lead to increased survival in the environment (e.g., water bodies) and increased occurrence of important vectors e.g., synanthropic rodents in Arctic settlements. Similarly, a marked increase in dogs was recorded in Ontario after a record warm and wet fall.	
Chlamydia psittaci (previously *Chlamydophila psittaci);* established	• "Parrot fever" can lead to significant morbidity and mortality in humans as well as animals, even disease outbreaks. Infection can however be treated with timely antibiotic intervention. • There has been a corollary relationship proposed between the transatlantic exotic pet trade and the emergence of *C. psittaci* among North Atlantic scavenging seabirds – Northern fulmar. • Broad host spectrum, with birds as most important source of human disease, but host spectrum also includes an array of mammals of which Alaskan fur seals, muskrats and snowshoe hares are noteworthy in an Arctic context. Muskoxen and reindeer have also tested positive in a zoo setting, and wild muskoxen have been recorded positive for *Chlamydophila* sp. • Infections in the Faroe Islands are associated with fulmar hunting. Occurrence remains high and stable (10 %) among Northern fulmar, but for the Faroe Island where this bird is plentiful, very few cases of systemic infection humans have been recorded over the past years, but underdiagnosis is likely due to symptom overlap with other common diseases such as the common flu. • High occurrence among Arctic Indigenous people, but the most important source(s) is (are) unknown. • Increased temperatures will likely affect survival in water and soil. Moreover, infection has been associated with climatic factors and climate change induced shifts in bird migration patterns. Moreover, the bacterium can be found in soil, and increased drought or changing regional hydrology will alter the risk of exposure to *C. psittaci*.	(Beeckman and Vanrompay, 2009; Beer et al., 1982; Ramsay, 2003) (Wang et al., 2020a, 2020b) (Eddie et al., 1966; Harper and McCarthy, 2012; Probst et al., 2011; Shewen, 1980; Spalatin et al., 1971) (Fossádal et al., 2018; Herrmann et al., 2006) (Hildes et al., 1965; Wilt et al., 1959) (Anstey et al., 2021; Hulin et al., 2016; Vanrompay et al., 2007)
Mycoplasma spp.; established	• Common infection in people harvesting marine mammals, particularly seals, in the Arctic. • Localized infection is also called "seal finger" or "spekkfinger". *Mycoplasma phocacerebrale* isolated from this infection, but exact identification is often not achieved. • Typically, a local infection in joints can become systemic. • Suspected to be significantly underdiagnosed in the Arctic since only a few laboratories possess the needed diagnostic tools for *Mycoplasma* identification, moreover, infection can be confused with *E. rhusiopathiae*, and the disease may present with only mild symptoms which do not lead to prompt diagnosis. • Often requires prompt antibiotic treatment if port of infection is near a joint or other sensitive anatomy. Choice of antibiotic is important as *Mycoplasma* spp. are resistant to penicillins (beta-lactams) and rifampins. • *Mycoplasma* spp. is generally highly climate sensitive. Changes in temperature and humidity impact transmission and environmental survival of the bacterium. For instance, respiratory *Mycoplasma* infections exhibit seasonal patterns due to climate variations.	(Baseman and Tully, 1997; Sullivan Baker et al., 1998; Tryland, 2000) (Pitcher and Nicholas, 2005; Wang et al., 2020a, 2020b) (Mazet et al., 2004; Waltzek et al., 2012) (Markham and Polk, 1979; Sundeep and Cleeve, 2011; Wang et al., 2011) (Onozuka et al., 2009)
Mycobacterium spp.; established	• An important pathogen worldwide. Causes tuberculosis and a high number of fatalities in humans on a global scale. Human tuberculosis (*M. tuberculosis*) has high incidence in some Arctic Indigenous communities and may present as a co-infection alongside HIV (i.e., immunosuppression). • Widespread resistance to common antibiotics. • The zoonotic *Mycobacterium bovis* is generally livestock associated and therefore rare in the Arctic. The occurrence of non-*Mycobacterium tuberculosis* complex (MTC) species is likely underdiagnosed. • *Mycobacterium avium* subspecies *paratuberculosis* (rarely zoonotic) is found in wild moose and reindeer, and high prevalence was observed in the Akia-Maniitsoq herd in Greenland and caribou in Nunavik, northeastern Canada. *M. tuberculosis* has been diagnosed multiple times in captive polar bears. • Arctic Indigenous communities are particularly vulnerable experiencing increased infection incidence compared to non-Indigenous societies. Epidemic potential, particularly a risk when people are displaced and crowded, such as during extreme weather events. Unsuccessful attempts to reduce incidences of human tuberculosis in Greenland and North America indicate neglected risk factors.	(Frothingham et al., 1994) (Skifte, 2008) (Kunimoto et al., 2001) (Forde et al., 2012; Tryland et al., 2004; Une and Mori, 2007) (Maharjan et al., 2021)

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Pathogen	Why is this disease important?	References
	- Long term asymptomatic carriers are super-spreaders.	
	- X-ray imaging cannot necessarily distinguish between mycobacterial granulomas and cysts caused by *Echinococcus* infection.	
	- CSI via changes in precipitation, air temperature, humidity, physiological factors such as vitamin D uptake, UV radiation, and demographic factors such as displacement of vulnerable communities in the aftermath of extreme weather events.	
Yersinia pseudotuberculosis; established	- Worldwide occurrence, including the Arctic, with morbidity in humans and animals ranges from self-limiting infection to systemic illness and septicemia.	(Blake et al., 1991; McLean et al., 1993; Vincent et al., 2008)
	- Thrives in cold climates as well as warm climates and survives freeze-thaw cycles.	
	- Asymptomatic carriers and broad host spectrum.	(Asadishad et al., 2013; Ben Ari et al., 2011; Mair, 1973; Revich et al., 2008; Vincent et al., 2008)
	- Potential for mass die-offs among wildlife.	
	- *Yersinia* sensu lato is highly climate sensitive. Outbreaks among wildlife precipitate around extreme weather events and the bacterium is sensitive to changes in temperature and humidity. Rodents are important vectors, and their populations are highly susceptible to increases in temperature with likewise increasing populations resulting.	(Blake et al., 1991; Enscore et al., 2002; Kutz et al., 2015; Schmid et al., 2015; Senior, 2008; Xu et al., 2014)
Staphylococcus aureus (e.g., Methicillin Resistant *Staphylococcus aureus*, MRSA); established	- An opportunistic pathogen ubiquitous in the environment and a common part of the human and animal skin flora but can lead to septicemia and mortality especially in the immunocompromised. Human to animal and vice versa transmission recorded.	(Archer, 1998; Peton and Le Loir, 2014; Tong et al., 2015)
	- Broad antibiotic resistance including spread of resistance genes in the environment – also (under-)reported in the Arctic.	(Gunnarsdóttir et al., 2013)
	- Microplastics, e.g., from hospital settings, are suitable fomites, and environmental plastics are a problem worldwide including the Arctic.	(González-Pleiter et al., 2021)
	- Has been recorded in a broad selection of Arctic fauna where it acts as an opportunistic infection; for example, multifocal suppurative meningoencephalitis and nephritis found in an Arctic fox caused by *S. aureus*.	(Flegr et al., 2014; Iwata et al., 2018)
	- *S. aureus* survives cold temperatures (< 5 °C) at least for a few weeks, survival increases with increasing temperatures, it is sensitive to UV-light, and it transports efficiently via wind. Thus *S. aureus* is climate sensitive.	
Parasites		
Toxoplasma gondii; established	- High exposure globally and in the Arctic causes' high disease burden through congenital infections and potentially severe clinical disease in immunocompromised individuals. Potentially lifelong infection with risk of general systemic disease, and clinical manifestations such as blindness and abortion in transplacentally exposed fetuses. Associated with mental illnesses in humans, altered behavior in animals.	(Carter, 2013; Dubey and Jones, 2008) (Gyorkos et al., 1980; Messier et al., 2009; Simon et al., 2011)
	- Some communities in Arctic Canada have higher seroprevalence (32 % in Nunavut and 43 % in Nunavik) than the general population (10–15 %). Outbreaks among Arctic Indigenous people resulting in abortions have been described and recent studies have linked human exposure to consumption of surface water, geese, seals, and other marine mammals.	(Ducrocq et al., 2021; Robert-Gangneux and Dardé, 2012)
	- A very broad intermediate host spectrum, present in many Arctic marine and terrestrial mammals, as well as in humans, even in areas without definitive host populations (felids).	(Patz et al., 2000)
	- Oocysts are extremely hardy in the environment.	
	- Severe clinical disease from infection is associated with immunosuppression, possibly putting Arctic people at increased risk since they display some of the highest concentrations of environmental pollutants with immunosuppressive potential.	(Long et al., 2023) (Bouchard et al., 2019, 2022; Elmore et al., 2012)
	- No human vaccine, but livestock vaccines exist. If new exposure detected in pregnancy, antibiotic treatment can prevent or limit the consequences to the fetus.	
	- Prevalence in wildlife varies by location, but is generally higher in carnivores (wolverine [*Gulo gulo*], fox, lynx [*Felis lynx*], polar bear), migratory geese, and marine mammals than terrestrial herbivores (i.e. caribou, rodents). Prevalence typically increases with the age of the host.	(Dubey, 2004; Pereira et al., 2010; Pilfold et al., 2021) (Gunnarsdóttir et al., 2013; Jokelainen et al., 2010)
	- Demonstrated evidence of climate sensitivity includes gradient in seroprevalence in moose and increasing seroprevalence in a polar bear population experiencing warmer and wetter conditions from the 1980s, 1990s, and 2010s, with higher seroprevalence observed following wetter summers.	(Pilfold et al., 2021)

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Pathogen	Why is this disease important?	References
	• CSI, particularly due to waterborne transmission, but also due to altered survival and marine movement of oocysts, and rate of sporulation of oocysts, related to temperature. Increased water runoff will increase the risk of outbreaks associated with contamination of drinking water. Drinking water resources are generally vulnerable in the Arctic and rely on surface water reservoirs. Shifting tree line may bring potential definitive hosts into tundra regions of the Arctic where they are not currently present.	
Trichinella spp.; established	• Clinical picture in people ranges from asymptomatic to fatal depending on infectious dose, cardiac and neurological involvement, and immune competence. Can result in chronic infections of muscle-dwelling larvae. • *Trichinella nativa*, T6, and *T. chanchalensis* (T13) are the freeze-tolerant species most often detected in Arctic wildlife, but there are reports of freeze-susceptible species such as *T. britovi, T. spiralis,* and *T. pseudospiralis*. • Broad host range in carnivores in the Arctic, e.g., polar bear, black bear (*Ursus americanus*), grizzly bear (*Ursus arctos horribilis*), brown bear (*Ursus arctos*), walrus (*Odobenus rosmarus*), arctic fox (*Vulpes lagopus*), lynx, and wolverine, with prevalence up to 88 % in the more carnivorous species. Prevalence in seals is <1 %. • Human infection and outbreaks due to food sharing are associated with consumption of raw or undercooked polar bear and walrus meat. High seroprevalence (24 % in Nunavut) indicates that more people are exposed than diagnosed with clinical disease. The likelihood of exposure increases with age. • No vaccines exist, treatment is usually supportive unless caught very early, i.e. while the nematodes are still present in the intestinal tract and before they disseminate throughout the body. • Freeze resistance enables transmission to scavengers from carcasses. *Trichinella nativa* larvae in muscle can survive freezing at —45C and fermentation processing of foods (e.g., "igunaq"). Snow cover protects against UV-light and insulates against extreme low temperatures. • High rates of both subsistence hunting and infection of trichinellosis in Russian regions Sakha (Yakutia), Chukotka, Magadan Oblast, and Kamchatka. • Evidence of climate sensitivity includes higher seroprevalence in polar bears after warmer summer and winter temperatures. Prevalence was also higher in older males and bears more closely associated with human settlements. • CSI through potential increased prevalence in game species, related to climate change-related effects on feeding habits, increased survival and accessibility of muscle larvae at warmer winter temperatures, and invasion of freeze susceptible parasite species in the Arctic.	(Emelyanova et al., 2022) (Malone et al., 2024a; Sharma et al., 2020, 2022) (Møller, 2007; Oksanen et al., 2022) (Goyette et al., 2014; Jenkins et al., 2013; Oksanen et al., 2022) (Kapel, 1997) (Forbes et al., 2003; Smith, 1987) (Emelyanova et al., 2022) (Pilfold et al., 2021; Pozio, 2016; Pozio and Zarlenga, 2013)
Cryptosporidium spp. and *Giardia duodenalis;* established	• Important gastrointestinal zoonotic infections worldwide, including in the Arctic. *Cryptosporidium* and *Giardia* are ubiquitous protozoan parasite genera with broad host spectrums and several similar epidemiological traits – therefore presented here collectively although taxonomically and morphologically distinct. • Directly transmitted by fecal oral contact among people, food-borne, and/or zoonotic (depending on parasite species/genotype), but waterborne is one of the most important routes. Arctic communities are particularly vulnerable because of poor water and sewage infrastructure and typical reliance on surface water for drinking. • Human strain endemic in muskoxen on Banks Island in the Canadian Arctic Archipelago, human infections diagnosed in same region. • Considered underdiagnosed although nationally reportable in some jurisdictions. Variable but often high infection rates per capita for northern Canada (particularly in Inuit youth), Alaska, and northern Russia. • Extended survival in the environment including cold resistance and resistance against disinfection. • Low infectious dose. • Specific antibiotic treatments are available but rarely 100 % effective, no vaccines. Sanitary means and good general hygiene are of key importance to prevent persistent contamination and reinfection. • CSI and tightly connected to extreme weather events and increased volumes of water, overwhelming water treatment infrastructure.	(Jenkins et al., 2013; Palmieri et al., 2012; Thompson, 2000) (Deksne et al., 2020; Gunnarsdóttir et al., 2013) (Kutz et al., 2008; Miernyk et al., 2019; Robertson and Debenham, 2022) (Davidson et al., 2011; Erickson and Ortega, 2006; Feng and Xiao, 2011; Hellard et al., 2000; Karanis et al., 2007; Robertson et al., 1992; Ryan and Cacciò, 2013)

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
Sarcocystis spp.; established	• Sarcocystosis is a neglected human parasitic disease that may be underdiagnosed in the Arctic.	(Deksne et al., 2020)
	• Symptoms are nonspecific and range from asymptomatic or stomachache to severe necrotizing enteritis, anaphylaxis and more. Clinical signs and virulence depend on if the host is a definitive or intermediate host, and the species of *Sarcocystis.* In the intermediate host, the parasite typically encysts in striated muscle or nervous tissue for an unknown length of time.	(Chhabra and Samantaray, 2013; Fayer, 2004; Rommel and Heydorn, 1972; Van den Enden et al., 1995)
	• *Sarcocystis* spp. are prevalent in dogs, as well as marine, terrestrial and avian wildlife species in the Arctic, cycling between carnivore definitive hosts and other species as intermediate hosts.	(De Guise et al., 1993; Elmore et al., 2013; Krone et al., 2004; Kutkienė et al., 2006; Lehnert et al., 2014; Reiling et al., 2019).
	• Broad host range but limited evidence of zoonotic potential for *Sarcocystis* species in the Arctic	
	• Multiple species of *Sarcocystis* have recently been described from Arctic foxes in Alaska (sarcocysts digested from 23 %), caribou in Nunavik, Canada (DNA detected in tissue of 85 %), and beluga (*Delphinapterus leucas*) in the Eastern Beaufort Sea (DNA detected in tissue of 59 %), indicating their role as intermediate hosts.	(Fayer, 2004; Xiang et al., 2009)
	• Potential CSI because of effective waterborne transmission to intermediate hosts. Need for further studies on temperature sensitivity and environmental survival of sporocysts in environment and sarcocysts in carrion in different climatic conditions.	(Cerqueira-Cézar et al., 2017; Dubey, 2015; Hernández-Ortiz et al., 2023)
Echinococcus granulosus sensu lato and *E. multilocularis;* established	• Worldwide neglected diseases with relative high incidence in some Arctic communities.	
	• Two distinct diseases in humans: cystic echinococcosis (CE) caused by *E. canadensis* (G8 and G10, or cervid genotypes of the *E. granulosus* species complex) and alveolar echinococcosis (AE) caused by *E. multilocularis.* AE leads to higher mortality than CE among humans.	(Gilbert et al., 2010; Rausch, 2003; Sweatman and Williams, 1963)
	• On chest x-rays, CE must be distinguished from tuberculosis, another disease with relatively high occurrence in some Arctic communities, and lung cancer.	(Bygbjerg et al., 2000; Çobanoğlu et al., 2015; Gilbert et al., 2010; James and Boyd, 1937; Pohnan et al., 2017; Rausch, 2003; Sweatman and Williams, 1963; World Health Organization, 2011)
	• Believed to be underdiagnosed due to the potential for asymptomatic carriers, nonspecific symptoms, and diagnostic challenges particularly in remote regions with limited access to medical imaging.	
	• The eggs of these parasites are remarkably environmentally resistant and can be shed by infected wild canids (wolf, fox) and dogs in the Arctic. Natural intermediate hosts in the Arctic include cervids (reindeer, caribou, moose [*Alces alces*]) and rodents (lemmings, voles, deer mice). Humans can be accidentally infected by ingesting eggs in contaminated food or water.	
	• Multiple strains of *E. multilocularis* transmit in wildlife, dogs, and people in North America, with a North American Arctic strain (N1) and Asian strains in Alaska, and European and North American Prairie strains (N2) in temperate regions of Canada and the USA.	(Gesy et al., 2013; Kolapo et al., 2022; Lavikainen et al., 2006; Nakao et al., 2009)
	• *E. multilocularis* in Arctic foxes in Svalbard is genetically closely related to those found in Arctic foxes from Yakutia, Russia.	(Colli and Williams, 1972)
	• *E. canadensis* (G10) has been detected in a wild cervid (moose/reindeer) and wolf cycle in Norway, Sweden and Finland and one reported human case in Finland. Both G8 and G10 strains are present in Alaska and northern Canada. This parasite has in the last few decades colonized the island of Newfoundland in Canada, with the life cycle newly enabled by establishment of coyotes as definitive hosts.	(Deplazes et al., 2017; Gesy et al., 2013; Laurimäe et al., 2023; Malone et al., 2024a; Santoro et al., 2024)
	• *Echinococcus* spp. have a climate-sensitive environmental stage, but shifting reservoir hosts, particularly from the south, are also important factors for changing infection pressures in the Arctic. Moreover, these parasites are, among other modes of transmission, waterborne – a mode of transmission expected to increase due to increased precipitation and ice melt and a general increase in extreme weather events. Finally, livestock associated species of *E. granulosus* and some strains of *E. multilocularis* are not yet thought to be present in Arctic regions, which makes them vulnerable to introduction with dogs (*Canis familiaris*) and domestic livestock.	(Hämäläinen et al., 2015; Jenkins et al., 2011, 2013; Oksanen and Lavikainen, 2015)
Taenia spp.; established	• Worldwide occurrence and one of the oldest known parasites infecting humans. Most species present in the Arctic do not routinely infect humans.	(Craig and Ito, 2007; Konyaev et al., 2017; Le Bailly et al., 2010; Pittella, 2013)
	• Virulence ranges from asymptomatic infections (largely the norm in definitive hosts) to disruption of organ function in intermediate hosts by metacestodes (cysticercus or coenurus).	(Andreassen et al., 2017; Craig and Craig, 2005; Kapel and Nansen, 1996; Rausch et al., 1983; Unruh et al., 1973; Varcasia et al., 2022)
	• Cold-resistant northern strain of *T. saginata* is associated with reindeer as intermediate hosts and humans as definitive hosts in the Palearctic.	

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Table 1 (*continued*)

Pathogen	Why is this disease important?	References
	• *T. serialis* and *T. crassiceps* are (very rarely) zoonotic (humans are accidental intermediate hosts) and circulate in Arctic wildlife and dogs. Other *Taenia* species in the Arctic are not known to be zoonotic, e.g., *T. hydatigena and T. polyacantha.* Dogs are useful sentinels for monitoring *Taenia* occurrence in the environment. • CSI due to increased precipitation leading to greater dispersion of eggs in the environment, increased snow cover in the high Arctic and humidity leading to increased survival of eggs, and increasing occurrence of coprophilic insects leading, again, to increased dispersal of eggs. *Taenia* spp. are also likely affected/involved in parasitic host switching accelerated by climate change.	(Konyaev et al., 2017) (Booth, 2018; Brooks and Hoberg, 2007)
Hypoderma tarandi; established	• *H. tarandi,* more commonly known as the reindeer warble fly, is a parasitic insect belonging to the Oestridae family and causing zoonotic myiasis. • The life cycle of *H. tarandi* begins with adult female flies depositing eggs on reindeer during the summer. These eggs hatch into larvae that penetrate the reindeer's hide, migrating through the subcutaneous tissues and forming characteristic warbles or nodules under the skin. • Although humans are not the primary host for warble flies, accidental infections can happen when warble flies mistakenly target human skin and lay eggs in their hair. Cases have been reported from northern Norway, Sweden, Greenland, and Canada, primarily in children. Human myiasis presents as migratory dermal swellings on the head and face. • Neglected human disease and insufficient knowledge of the disease among general practitioners of medicine. • The development and activity of *H. tarandi* is strongly influenced by temperature and seasonal changes. Warble flies thrive in warmer temperatures, with pupation times decreasing with increasing temperatures. Flying activity is also temperature dependent. A warmer climate will allow for shorter pupation times and longer flying times, thereby increasing the window for warble fly exposure. In contrast, cooler summers, especially if wetter and windier, will see longer pupation times and reduced flying times. However, the risk of human infections could still be increased in this scenario, since the warble flies have a much shorter window to find their preferred reindeer hosts and might therefore select other hosts if reindeer cannot be found. Research to develop vaccines against infestations of *Hypoderma* spp. was conducted as early as the 1950s but no vaccine exists yet.	(Anderson and Nilssen, 1996) (Nilssen and Haugerud, 1994) (Landehag et al., 2017; Witter et al., 2012) (Åsbakk et al., 2019)

In addition to Table 1, we wish to draw attention to the importance of Arctic Health through concrete examples of contemporary events and studies which have spurred further scientific interest and acknowledgement. We here present 11 case studies. Case 1–3 present more general themes which are important as context in an Arctic setting, while case 4–11 increase their focus on concrete events which inform on important Arctic tendencies. Through this information, we extract experiences and knowledge which ultimately may guide and prepare stakeholders for a future, and a present, which present us with drastic changes in terms of human and wildlife health in the Arctic as well as great challenges for Arctic societies in general. The work herein was initiated by discussions at a workshop held in May 2023 at Sønderborg, Denmark. The workshop was part of an initiative by the Kingdom of Denmark and Canada to better integrate AMAP's work to monitor and assess contaminants, wildlife health and human health in the Arctic in a One Health context.

2. Case studies

2.1. Case study 1: pollution and climate change

Pollution and climate change contribute to physiological stress and weakened immune systems in hosts. Notably, high trophic predators experience an exacerbated impact from this additional stress, particularly in the case of pollution (Desforges et al., 2016; Dietz et al., 2018a, 2018b, 2019). Mercury and persistent organic pollutants (POPs, e.g., polychlorinated biphenyls [PCBs] and *per*- and polyfluoroalkyl substances [PFAS]), are long-range transported pollutants in the Arctic, typically deriving from southern industrialized countries (Dietz et al., 2019, 2022; Letcher et al., 2010). These compounds are referred to as “forever chemicals” because of their bioaccumulating properties and resistance against environmental degradation, metabolization and excretion (Sonne et al., 2018a, 2018b). Their properties along with their transportation via ocean and aerial currents explain why these chemicals are now found in nearly all Arctic wildlife sampled, as well as in humans on a global scale (AMAP, A, 2021; Desforges et al., 2018; Dietz et al., 2018b; Dietz et al., 2019). Forever chemicals lead to immune suppression in mammals and thus increase risks of debilitation and/or fatality from infections. A current example of this effect, in a contemporary pandemic context, is the positive relationship between PFAS levels in the blood and severity of COVID-19 infection (Catelan et al., 2021; Grandjean et al., 2020; Ji et al., 2021; C. Nielsen and Jöud, 2021). Studies have also demonstrated that POPs affect host-virus interactions and increase vulnerability to viral diseases such as influenza (Browning et al., 2015; Desforges et al., 2018; Teitelbaum et al., 2022). In conclusion, POPs increase the risk of outbreaks and transmission of infections including zoonotic diseases (Buelow et al., 2021; Sonne et al., 2022, 2023).

Climate change and anthropogenic immune-toxic environmental chemicals are therefore parallel and, in some cases, interactive and reinforcing problems of increasing effect and concern. It is therefore pertinent to expect at least partly synergistic effects from these factors on infectious diseases including zoonoses (Dudley et al., 2015). We, however, need to increase our understanding of how the effect of different contaminants integrate collectively within affected hosts and ecosystems. For example, PFAS bio-magnify in the food web with a factor of >1000,000 between the lowest organisms in the food web and the highest, and accordingly, the highest concentrations of PFAS in the world are found in polar bears (*Ursus maritimus*), while the highest levels of PCBs are found in odontocetes including killer whales (*Orcinus orca*) (Dietz et al., 2019; Sonne et al., 2023). Thus, accumulation is of great concern for the health of wildlife, but also for local and Indigenous Arctic communities, where these wildlife species are consumed. Despite international regulations, East Greenland polar bears still have high levels of PFAS (specifically PFOS [perfluorooctane sulfonate] – a major compound of PFAS), and novel similar compounds continue to increase to high concentrations. The loss of sea-ice due to global warming is affecting the polar bears' access to ringed seals (*Pusa hispida*) while increasing the availability of higher trophic harp seals (*Pagophilus groenlandicus*) and hooded seals (*Cystophora cristata*) increasing their POP exposure. This forced change of polar bear hunting strategy results in increased exposure to bio-accumulating POPs and is hence an example of synergistic effect on contaminants from climate change (McKinney et al., 2013).

The society of Scoresbysund (Ittoqqortoormiit) in central East Greenland has had a decade long PFAS exposure due to consumption of polar bear meat and ringed seal meat and liver. Therefore some of the highest global blood concentrations are found here (Sonne et al., 2023). This leads to risks of cancer, thyroid hormone disruptions (e.g., hypothyroidism) and immune suppression. In line with the recent toxic thresholds suggested by the European Food Safety Authority (EFSA), the observed blood concentrations, along with the surpassing Tolerable Weekly Intake (TWI), place this local society at significant risk of immunosuppression. This yields an increased risk of zoonotic disease from hunted wildlife species, which are similarly affected (Sonne et al., 2023). These blood concentrations are a reminder of how much, and how urgently we need to study and learn more about the effects of contemporary and legacy environmental pollutants, so that we can begin to protect vulnerable wildlife and human communities.

2.2. Case study 2: species on the move and altered host ranges

Altered host ranges for species on the move reflect the greater need for scientific coordination of One Health in relation to climate change. Most species have a spatial-dynamic life cycle in terms of geographical range, however, recent climate changes causes a more systematic redistribution of e.g. cold-adapted species seeking new habitat northwards i.e. in terms of latitude and altitude (Pecl et al., 2017). Terrestrial species move 17 km towards the poles for each decade (Chen et al., 2011), while it for marine taxa is 72 km (Chen et al., 2009; Dulvy et al., 2008; Poloczanska et al., 2013; Sorte et al., 2010). Altered distribution of sub-Arctic animal species, resulting in a northward shift of disease vectors, may alter infection pressure and impact naïve Arctic wildlife populations (Bradley et al., 2005). Additionally, the increasing sea water temperature and melting of ice changes the distribution of both fish and marine mammals (Laidre et al., 2008, 2013). This forces predators to develop novel hunting techniques and adapt to different prey game species. This adaptation can subsequently influence their exposure to diseases. For example, Atwood et al. (2017) and Pilfold et al. (2021) found that *Toxoplasma gondii* infections have increased in polar bears of the Southern Beaufort Sea and Western Hudson Bay, respectively. These bears are spending more time on land, compared to their more ice-dwelling compatriots. The natural polar bear hunting grounds on ice sheets have diminished drastically in some areas in recent years, and the bears, in these areas, had adapted by spending more time hunting on land; in Western Hudson Bay, increasing exposure to mosquito-borne viruses (Buhler et al., 2023a, 2023b). Conversely, analyses of *Brucella*-antibodies in polar bears at Svalbard and Beaufort Sea indicates marine mammal game as the source of infection (Atwood et al., 2017; Tryland et al., 2001). So, a changing climate and habitat not only changes exposure to POPs through altered feeding strategies, as described in Case 1, it also alters pathogen exposure and infection pressure. This shift can lead to a decreased or increased exposure, with increased exposure, particularly when transitioning from no exposure to exposure, accentuating the additional impact of immune naivety towards the introduced pathogen. If this situation is paired with increased exposure to POPs as well, then it may present a very risky “cocktail” for the host (Lemieux et al., 2022). Altered feeding strategies and pathogen exposure are also likely to have played a role in a recent elucidation of temporal increase in several zoonoses among a subpopulation of polar bears in West Hudson Bay (Pilfold et al., 2021). There are however many unknowns still, such as host-pathogen interaction. This is exemplified by a study of Svalbard Arctic foxes (*Vulpes lagopus*), which did not detect *Brucella*-antibodies although these foxes are known to scavenge on carcasses initially killed by polar bears. The reason for this discrepancy between polar bears and arctic foxes remains unknown (Nymo et al., 2022a, 2022b).

The shift in species distribution affect culture, food security, health, ecosystem structure and individual livelihoods as evident from global meta-analyses and in-depth species-specific approaches (Pecl et al., 2023). However, there remains a substantial knowledge gap, necessitating an interdisciplinary approach to establish research that can detect changes in ecosystem dynamics (species interactions) and ecosystem services important for human society (Hoberg and Brooks, 2015; Manning et al., 2019). Among other, the UN Global Goals can only be applied to some extent in the Arctic, since there is a need for an increased focus on changes in ecosystem dynamics and ecosystem services including invasive and invading species which introduce potentially new disease to the Arctic (CAFF, 2021; Pecl et al., 2017).

2.3. Case study 3: Arctic sled dogs as valuable sentinels

The additive challenge of accelerating climate change and bio-accumulation of toxic long-range transported toxic industrial chemicals and elements (pollutants) on zoonoses addressed above also impacts sled dogs (*Canis familiaris*) in the Arctic. Here, it must however also be taken into consideration that pathogens, particularly parasites, have taken advantage of a very long history and connection between humans and dogs. It is believed that domestication of the dog started ca. 20,000–30,000 years ago (Sinding et al., 2020; Thalmann et al., 2013). It is therefore not surprising that infectious diseases capable of crossing species barriers, have evolved to benefit from a close human-canine relationship. Today, we know of at least 60 pathogens that can be transmitted between humans and dogs, and some of these pathogens have developed a life cycle specialized for the human-canine relationship (Bowser and Anderson, 2018; Craig et al., 2003; Ghasemzadeh and Namazi, 2015; Jacob and Lorber, 2015). Even the recent COVID-19 pandemic was an example of how a pandemic in humans spills over to our companion animals because of our proximity, potentially causing substantial brain pathology in canine hosts (Haider et al., 2020; Kim et al., 2023). An intricate, and millennia old relationship between humans and dogs can in other words hardly be denied and humans have shared more than food and specialized hunting or herding skills with dogs.

Monitoring Arctic ecosystem health is an ongoing challenge of accelerating importance. Meaningful indicator species for ecosystem health are needed as research and monitoring tools. Some Arctic wildlife species have been monitored and used as indicator species more than others, e.g., polar bears, Arctic fox and Arctic-migrating waterfowl such as eiders (*Somateria mollissima*). Sled dogs, however, represent a link between Arctic inhabitants, prey species, predators, and the environment. Although their numbers are decreasing drastically in parts of the Arctic (Sonne et al., 2018b; Statistics Greenland, 2022), they are still widely distributed in the Arctic realm; they are in relatively close contact with humans and they can as such be said to exist in an intersection between the natural environment and human civilization. Moreover, not only are sled dogs highly accessible, they can also be relatively easily sampled and handled compared to Arctic wildlife species. It is worth mentioning that Arctic dogs are increasingly used for other purposes than sledding, and for example more so for guarding (e.g., against polar bears). These Arctic dogs are also included in our perspectives herein.

Bowser and Anderson (2018) suggested that dogs may bioaccumulate infectious diseases from their environment and feed, and may thus represent pathogens from a wider population of animals and/or the environment. Moreover, using dogs as sentinels prevents, to some extent, sampling bias arising from sampling and observation methods that in itself have an effect on the sampled or observed object (Bowser and Anderson, 2018). Bowser and Anderson (2018) concluded that using dogs as sentinels, or indicators for e.g., human diseases, is an underutilized potential in science and monitoring. Correspondingly, Greenland has one of the highest proportions of Indigenous people and one of the largest remaining populations, albeit rapidly decreasing, of sled dogs. At the same time, this is one of the areas where zoonotic diseases among Indigenous people have been least studied. Including sled dogs as sentinels for various environmental (incl. wildlife) exposure is as such highly relevant for an Arctic nation like Greenland (Pastorinho and Sousa, 2020; Sonne et al., 2017).

An example of how canines can be important sentinels was in the so-called “2007 pet food recalls” occurring in Europe, North America and South Africa where thousands of dogs (and cats) were affected and about 20 %, of those exposed to the feed, died (ABC News, 2007; Paulman, 2008; The New York Times, T. A, 2007). Because of a drastic increase in acute renal failure diagnosed among dogs in particular, a scandal of melamine-contaminated wheat was exposed (Bowser and Anderson, 2018; Katy Byron/CNN, 2007). A common feature of these dogs, and the cause of kidney failure, was consumption of pet-food containing meat from production animals that were given melamine contaminated feed. These production animals were also intended for human consumption and this led to increased monitoring of products intended for human consumption. Moreover, the scandal originated in wheat imported from China and led to the creation of China's first recall system for unsafe food products. It also put a spotlight on vulnerable mechanisms within food safety systems (Los Angeles Times, 2008; Paulman, 2008; Roth et al., 2008).

Sled dogs are typically fed a higher kg-raw-wildlife/kg-bodyweight ratio than their human counterparts and they have a much shorter lifecycle and gestation compared to humans. This means that they are particularly useful to monitor for infectious as well as toxic (including teratogenic effects) agents. Unlike most humans in the Arctic, sled dogs are also typically not hydrated by filtered water, but by untreated creek water, or via snow and ice lying on the ground in the immediate environment. Sled dogs are as such more exposed than humans to potential agents via the environment or wildlife. This is also relevant in terms of previously discussed viruses thawing from permafrost which may disseminate through run-off water. Other examples of sled dogs as indicators of Arctic ecosystem dynamics, here viral disease, are distemper- and rabies virus. Distemper-virus have long existed in the Arctic, particularly among predators, but transmission is sensitive to prey availability and migration patterns of e.g., Arctic fox and polar bears (Andersen-Ranberg et al., 2019; Beineke et al., 2015; Blixenkrone-Møller et al., 1989; Vernersen and Jensen, 2018). As described herein, these factors are again dictated e.g. by climatic factors. It has previously been seen that large distemper outbreaks occurred in Greenland sled dogs when certain climatic factors were fulfilled. These outbreaks likely mirror a similar condition among wildlife and the sled dogs can as such act as indicators of ecosystem changes promoting viral disease wildlife. The same is likely true for the rabies - a disease expected to increase in occurrence due to expected changes in fox and rodent populations in a drastically changing Arctic climate (Parkinson and Butler, 2005; Tabel et al., 1974). This disease is enzootic in Arctic foxes in the Arctic environment, with some evidence that Arctic foxes may survive exposure (Elmore et al., 2021) and with common spill-over events to sled dogs (Plummer, 1947). Rabid foxes lose their natural timidness and are therefore likely to engage groups of sled dogs leading to biting and viral transmission. A change in infection rate among foxes will likely also affect the number of suspected canine rabies cases. Canine rabies is already a reportable disease in most Arctic countries, meaning any changes in fox infections may be reflected in reported cases of rabies in dogs.

Several studies describe various zoonotic diseases in Arctic inhabitants and animals (Gilbert et al., 2010; Parkinson et al., 2014). Still, with regard to vastness and geographical, social/cultural, climatic and faunal variability, we still know very little in terms of epizootiology, epidemiology, occurrence and risks of Arctic zoonoses. Moreover, only very few studies have focused on sled dogs or emphasized the sentinel potential of sled dogs as a means to increase our knowledge on Arctic zoonoses (Salb et al., 2008). These few studies have however typically recorded a number of zoonotic diseases in sled dogs (Brenner, 2024; Salb et al., 2008; Andersen-Ranberg et al. pers. comm.) as well as significant negative physiological effects from toxic pollutants derived from wildlife, particularly marine mammals (Dietz et al., 2019; Letcher et al., 2010). A current study, QimmeqHealth (2024) collects and studies samples from Greenland sled dogs, in Greenland. Very little is known about these dogs that are part of an essential cultural history of the native Inuit people in Greenland. QimmeqHealth has detected several zoonotic parasites in Greenland sled dogs. For example, all 30 dogs investigated in Ittoqqortoormiit, East Greenland, were seropositive to *Trichinella nativa* (Mejer et al. *in writing*) – a zoonotic parasite most likely derived from consumption of raw walrus (*Odobenus rosmarus rosmarus*) or polar bear meat. Due to the general lack of research on zoonoses in Greenland, we unfortunately cannot say if this is a result of increased infection pressure, but it will be relevant to increase monitoring of the parasite in game species, and increase diagnostic efforts in Greenland, where there is currently no monitoring program for zoonoses. Similar studies are also needed in other Arctic areas including strict attention to the feeding regimen of the dogs. We need this knowledge to guide proper management as well as to identify contingencies from current environmental challenges. For example, increased awareness of zoonoses in the Arctic, particularly local knowledge, will improve diagnostics and treatment. A significant challenge in addressing zoonoses in the Arctic lies in the insufficient knowledge, awareness, and the need for specific diagnostic requirements. This can lead to misdiagnoses. For example, some zoonoses elicit symptoms initially resembling influenza or a common cold, thus potentially concealing more severe short or long term health consequences of a zoonotic pathogen for the clinician.

At last, a series of unique studies of the effects of a cocktail of environmental pollutants in the Greenland sled dog has also been carried out underscoring their deleterious biological effects. These studies have shown that pollutants play a role in an array of pathology in sled dogs. Pollutants such as PCBs and other POPs affected liver and kidney directly, but also disrupted the endocrine, reproductive, and immune system. Collectively, studies showed that sled dogs represented a good model for assessing health effects of bioaccumulating contaminants in top predators and humans (Dietz et al., 2019; Kirkegaard et al., 2011; Sonne et al., 2015; Verreault et al., 2009).

Taking this together, we argue that there is a potential for sled dogs as sentinels to increase knowledge of both zoonoses-related risk and epidemiology/epizootiology but also effects of bio-accumulating contaminants. Sled dogs are of significant value in securing representative samples of high quality and quantity, and from across the Arctic realm (Bowser and Anderson, 2018; Sonne et al., 2017). This approach, coupled with increased scientific focus and emphasis on zoonoses and bioaccumulating toxic pollutants in the Arctic is therefore recommended (Sonne, 2010). Concrete examples of how increased use of sled dogs as a sentinel can be achieved are: by offering veterinary services in Arctic areas where such services are scarce or non-existent (e.g., QimmeqHealth project in Greenland); monitoring dogs that are part of national vaccination schemes such as in Greenland; or by including various sled dog samples from hunters (who are often sled dog owners) that already supply research labs with wildlife samples.

2.4. Case study 4: compromised traditional foods in the Arctic exemplified by Bacillus anthracis in Russia

Traditional circumpolar Arctic food preparation methods present a risk of zoonotic transmissions due to limited frying and cooking and through carcass handling (Odland et al., 2016; Stimmelmayr and Sheffield, 2022; Tryland et al., 2014). For example, up to 80 % of Inuit consuming dried marine mammal meat tested seropositive for the disease *T. gondii*, while among Cree, who prefer cooked meat, the seroprevalence was 10 % (Messier et al., 2009).

The bacterium *B. anthracis* is a relevant example for food safety (i.e. risks of harmful effects on consumers), food security (i.e. availability and quality), and food export. It is particularly important to consider in the preparation of traditional foods, which are often not heat-treated or exposed to antimicrobial additives before curing. Under the right conditions, *B. anthracis* produces highly toxic spores. Humans get infected by handling products from infected animals, meat or by inhalation of spores. There are three forms of human anthrax: cutaneous, inhalation and gastrointestinal. Around 95 % of human anthrax is cutaneous, 5 % inhalational and <1 % is the gastrointestinal form, but this distribution will vary according to continent (Kamal et al., 2011). There have also been several outbreaks linked to food scarcity when people have been forced to eat *B. anthracis*-infected animals in lack of other options (Lehman et al., 2017). The largest known anthrax outbreak in humans occurred in Sverdlovsk, Russia, in 1979, resulting in a total of 96 registered cases and 64 human deaths (Dadakina and Khalturin, 2017; Dzhupina, 2004; Meselson, 1988). Among these cases, 79 manifested as gastrointestinal anthrax, while the remainder presented with the cutaneous form of the disease. The most recent known outbreak has been ongoing (2023) in the Republic of Tuva in Russia with five registered human cases by mid-July Lindh et al., 2023. The outbreak started with the slaughtering of a sick horse where hospitalized victims had eaten the internal organs. Four hospitalized patients with anthrax refused to be treated and left the hospital without permission (Moscow Times and служба, 2023). Meanwhile, restrictive measures in the territory were extended until 20th of July Lindh et al., 2023 due to the death of another horse.

Anthrax has been described in Russia at least since the end of the 19th century, where it was already acknowledged as common and very dangerous (Malkhazova et al., 2019). *B. anthracis* spores were initially found in Arkhangelsk and Nenets areas as well as in the Asian part of the Russian Arctic – in Taimyr, Khantu-Mansi, Yamalo-Nenets Autonomous Okrug (AO), and Evenky area. Historically, these areas have had large outbreaks since the 19th century and the soil has been able to store infection for many decades. In the Yamalo-Nenets AO alone, as many as 400,000 reindeer died in 1889–1915 from anthrax outbreaks. In 1911, during the summer, 100,000 reindeer were reported to have succumbed due to anthrax on the Yamal Peninsula (Skjenneberg and Slagsvold, 1968). Moreover, there was a large outbreak in this region in 1941, which caused ca. 6700 reindeer deaths (Bogdanov and Golovatin, 2017). Outbreaks were caused by grazing of non-vaccinated livestock in territories of stationary anthrax points where anthrax outbreaks had occurred and resulted in contaminated pastures, as well as by slaughter and selling of meat and meat products without veterinary inspection. The perhaps most unfavourable recorded anthrax epicentre has been in Sakha (Yakutia, Russian Far-East) with annual cases every year from 1811 to 1959 and 19 larger outbreaks with deaths of 1000–7000 of animals. The total number of animal deaths in the Sakha republic in 1811–1993 was about 85,000 with the last outbreak registered in 1993. In the European North, the last outbreak was registered in 1937 (Hueffer et al., 2022a, 2022b). Anthrax is still highly relevant in the Arctic, particularly in Sakha Republic (Yakutia), Yamal and Taimyr Peninsula, where large reindeer populations exist, and the bacterium has been more extensively monitored and studied.

A recent anthrax outbreak in the Yamal Peninsula during the summer 2016, in the Arctic part of Russia, was one of the largest in the recent past. Apart from this outbreak, anthrax was last recorded in this area in 1941. In 2016, a record-breaking, month-long, temperature of 35 °C in the southern Yamal region led to the deaths of over 2300 reindeer from anthrax, triggered by the melting of the top layers of permafrost. Apart from the mass deaths of reindeer, 90 local people were hospitalized, and one died. Quarantine was introduced on July 25 in 2016, and a massive reindeer vaccination campaign was undertaken with 450,000 animals vaccinated with urgency and with annual continuation (Ryazanova et al., 2017; Yasjukevich and Yasjukevich, 2016). The dead animals were individually burned by biological protection units of the Russian Armed Forces. The Yamal Government maintained mandatory vaccination of reindeer against *B. anthracis* until 2007, when it was discontinued based on scientific data showing insignificant risk of *B. anthracis* in the local soil – a decision which was later regarded as a mistake (Shestakova, 2016). Currently, there is a risk of revival in northern regions of Russia including Kolyma, Indigirka and Yana rivers due to flooding and large-scale mining and gas and oil exploration requiring preventive measures among livestock animals (Liskova et al., 2021). Anthrax has been acknowledged as a possible re-emerging problem as record permafrost thawing exposes and releases spores, along with changes in regional hydrology (Parkinson et al., 2014; Revich et al., 2012; Revich and Podolnaya, 2011). The long survival time of spores means that the high historical prevalence of the disease is likely to have built uplinked to high concentration of spores in frozen soil via e.g., animal carcasses fallen from decades or even centuries ago or even millennia. From an ecological point of view, anthrax can bring a conflict for ambitious regional authorities' plans and Indigenous mentality towards an expansion of reindeer herding (Bogdanov and Golovatin, 2017).

Many challenges remain e.g., how to build cooperation of various responsible stakeholders most effectively; identifying and safely maintaining anthrax burial places, especially under climate change; exploring new industrial and natural resources' sites; maintain a reasonable vaccination level; inform the general population about anthrax prevention; and educate medical and veterinary practitioners more about the disease and its symptoms (Layshev et al., 2011; Layshev et al., 2015; Shestakova, 2016). Handling anthrax outbreaks on the tundra is challenging. There is typically no road-infrastructure so it is nearly impossible to transport infected carcasses away from the area where it might reinfect other animals or humans. It is therefore recommended that each animal carcass is burned individually at the location it was found dead, although this is difficult in the absence of wood fuel and without risking wildfires. Another problem is the widespread leakage of blood/fluids prior to death which can lead to spread of the bacterium to the environment. Insects (tabanid flies) and other scavengers can also further contribute to the transmission. A paper by Dragon et al. (1999) gives a detailed guide to different methods of dealing with anthrax outbreaks in remote locations.

2.5. Case study 5: Country Foods for Good Health project – Inuvialuit Settlement Region, Canada

In February 2020 the project “Country Foods for Good Health” was launched in Paulatuk and Tuktoyaktuk. The project expanded to all six communities of the Inuvialuit Settlement Region (ISR) in the Northwest Territories (NWT), Canada, in 2021. A team of academic, government and Indigenous researchers are working together using a One Health lens that includes Indigenous, qualitative, and quantitative methodologies to respond to the overarching questions “How good is this food to eat?” and “How can information about food and health be communicated”. The project centers around the analysis of country food samples collected by Community Research Leads in each community. Additional samples of polar- and grizzly bear (*Ursus arctos horribilis*) provided by the

Government of NWT Department of Environment and Natural Resources, salmon (*Oncorhynchus* spp.) and beluga whale (*Delphinapterus leucas*) samples from the Department of Fisheries and Oceans and ringed seal samples from Environment and Climate Change Canada were also included. Samples are analysed for nutrients, contaminants and seroprevalence of antibodies against *Erysipelothrix rhusiopathiae*, DNA of *T. gondii* and *Sarcocystis* spp., and larvae of *Trichinella*, to characterize the benefits and risks associated with consuming specific country foods. Engaging with diverse perspectives, the study employed interviews with Elders and a photovoice project with youth to comprehensively explore the values and knowledge of country foods in the ISR to gather insights on how local stakeholders contribute to culture-centred messaging in Tuktoyaktuk, NWT (Gyapay, 2022). A survey was used in each community to record local perspectives on food quality and safety, and to learn about the preferred methods of communicating messages about country foods and health. Results from the analysis of country foods were co-interpreted with community representatives through intensive focus groups. Inuvialuit harvesters provided feedback on the significance of the results related to food safety and quality, the perceived risks from zoonotic diseases present in Inuvialuit country foods and proceeded to co-develop messages together to share this information in the community in a non-alarming way (Gyapay et al., 2023).

Thus, through our collaborative processes, local perspectives and experiences of gaps in healthcare associated with zoonotic disease exposure were discussed. We are exploring ways by which local, regional, and territorial resources recommendations to the Government of NWT Department of Health and Social Services can address and mitigate potential zoonosis exposure in the ISR. For example, there appears to be a need for improved surveillance of illnesses associated with harvesting and handling fish, birds and wildlife to improve treatment and local experiences at community health centers (Gyapay, 2022). In addition, country food knowledge holders may also play an important role in leading local communications about country foods (Gyapay et al., 2023).

2.6. Case study 6: hunting and tourism in the circumpolar Arctic: contemporary challenges and contingencies

Hunting, handling, and consumption of wildlife have been identified as the origin of several highly important recent epidemics and pandemics (Cantlay et al., 2017; Greatorex et al., 2016; Karesh et al., 2005; Kurpiers et al., 2016; Travis et al., 2011). Focus on hunting and zoonotic risk was accelerated with the global outbreak of COVID-19 as one of the strongest theories for the origin of the virus was the exploitation of wildlife (Aguirre et al., 2020; Huong et al., 2020). Generally speaking, a relatively low influx and efflux of people internationally, low animal and human density, as well as extreme low temperatures all decrease the risk of epidemics in the Arctic (Keatts et al., 2021), but some of these characteristics are changing. For example, climate change has been demonstrated to increase viral spill-over within lake sediments that are linked both via direct and indirect pathways to the sea. This is particularly concerning given that a significant proportion of game, such as seals and whales, are harvested from the marine environment (Lemieux et al., 2022). Freshwater fishing is of interest for hunters traveling to the Arctic, but because viruses are rarely reported to transmit between fish and people, the viruses in lake sediments (potentially including thawed ancient human viruses) may incorporate other bridging species before reaching mammals and humans. Conversely, numerous bacterial fish-related zoonoses are known, and if the results of Lemieux et al. (2022) can be extrapolated to bacteria, we may face a greater risk of direct fish-to-human transmission of zoonoses.

Tourism is a significant economical player in several Arctic

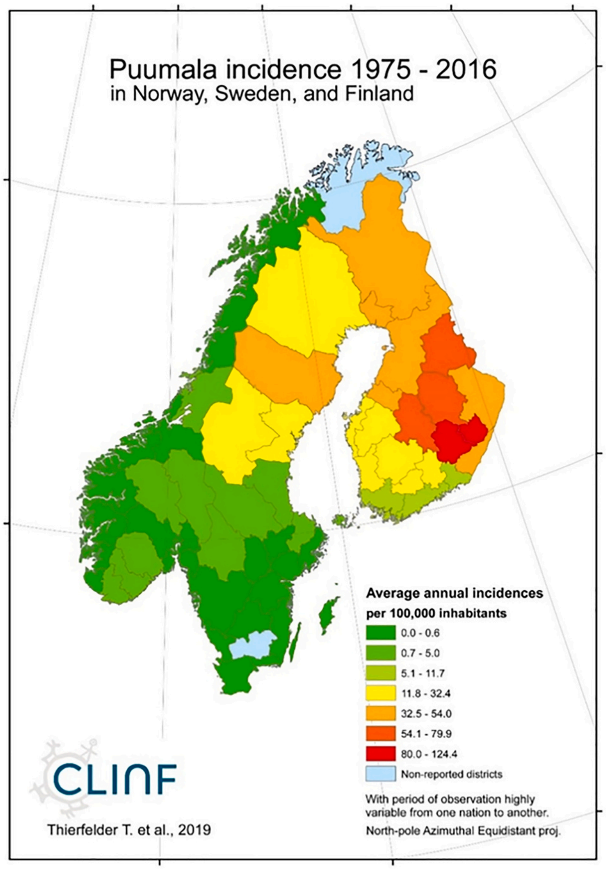

Fig. 2. Average annual *Nephropathia epidemica* (NE, Puumala) incidences as observed through the approximate thirty-year climate reference period, across Norway, Sweden, and Finland. Modified from Thierfelder and Evengård (2021).

communities. In northern Canada, tourism contributes with around 400,000,000 $ in the economy (Maher et al., 2014). Correspondingly, the development of tourism in Iceland can almost be described as exploding. Tourism in Iceland has increased with an annual average of 8 % in 2000–2014 (Maher et al., 2014). Tourism has likewise grown significantly in Greenland, Arctic Sweden and Faroe Islands (Greenland Statistics, 2022; Maher et al., 2014). Arctic tourism often relates to outdoor wilderness activities, i.e., 'nature experiences', such as dog sledding, hiking, canoeing, Arctic survival experiences, hunting, fishing, and visiting national parks and reindeer herds (Lemelin et al., 2012). Sometimes the 'full Arctic experience' includes the traditional cuisine of among other raw animal products, with concomitant increased risk of zoonotic transmission (i.e. trichinellosis, see Malone et al., 2024a, 2024b; Malone et al., 2024a). Moreover, the Arctic tourism sector places an emphasis on offering a wilderness experience that involves potential close encounters with wildlife and livestock, including semi-domesticated reindeer and sled dogs. This, however, poses a risk concerning zoonoses and the potential resurgence of pathogens with epidemic potential in the Arctic. The risk is accentuated by international travel and relocation of tourists that are potential carriers of latent disease as well as antimicrobial resistant microbes (Griekspoor et al., 2009; Hernández and González-Acuña, 2016).

Climate change leads to reductions in sea ice. This shift includes changing accessibility to traditional game species and an increase in iceberg hazards due to glacier melting (Gössling and Hall, 2017). Although tourism such as resort skiing and dog sledding may be challenged in the future due to increased rainfall and shorter seasons with snow (Nilsson and Demiroglu, 2024; Schrot et al., 2019), cruise tourism may on the other hand find novel routes that was previously blocked by sea ice. New tourism opportunities should be carefully assessed in relation to human health risks, both in terms of infectious diseases, the risk of search and rescue missions and accidents associated with pollution. Moreover, new opportunities should be assessed in relation to social, economic, and environmental sustainability. As mentioned, the changing climate may also affect hunting opportunities which both affect hunting tourism, but much more so the Arctic subsistence hunter. The indigenous hunters have already adapted extensively to the changing climate, e.g. more use of boats, different game species, traveling to new hunting and fishing areas, and seeking alternative income sources. Subsistence hunting has also become more dangerous because of e.g. sudden break-up of ice sheets; unpredictable and extreme weather; and unstable ice which is relied upon for seal hunting among others (Ford et al., 2006; Ford and Goldhar, 2012; Hauser et al., 2021). This is particularly dangerous when using snowmobiles compared to dog sleds because they e.g., travel faster and are heavier and cannot remount to the ice sheet once entered the water, such as is possible for dogs. Inuit sled dog owners also report that sled dogs are able to detect problematically thin ice and stop prior to potential breakage of the ice, and if the ice breaks, it more often occurs under the heavier sled, not under the light weight and fan distributed dogs, which leaves the dogs able to wholly or partly pull up the sled (Ford et al., 2006; Ford and Goldhar, 2012). The SIKU mobile app is a North American initiative by Arctic Eider Society that works as a platform for local and Indigenous knowledge about the current and changing ice and weather conditions, but also local knowledge about game species and wildlife (SIKU initiative, 2024). This is a succesful initiative which could serve as inspiration to other similar Arctic nations, e.g., Greenland.

In summary: In many parts of the Arctic, there is a widespread lack of understanding concerning the prevalence and risks of zoonotic diseases in game animals. Although a few projects have effectively involved local hunters and tapped into their knowledge, this success has not been widespread enough to address the overall lack of awareness (see e.g., Reynolds et al., 2022). This is relevant for both local hunters, but also for visiting tourists trying local traditional foods and hunting tourists. Moreover, there is a lacking capacity to diagnose such infections due to the sometime restricted availability of health care in the Arctic. History including travel and/or hunting is also valuable information for the health professional in the homeland of tourists. The ability to act on this information goes, however, hand in hand with local knowledge of zoonoses in the area the tourist visited. We recommend increased awareness of Arctic zoonoses in the Arctic tourism industry as well as among hunters and not least among health care professional in the Arctic and those receiving recent tourists returned from their Arctic experience. The latter includes increased medical awareness of specific diagnostic needs for relevant zoonotic pathogens.

2.7. Case study 7: hantavirus hemorrhagic fever with renal syndrome (HFRS/NE) in Northern Europe

Hantavirus hemorrhagic fever with renal syndrome (HFRS) is a group of clinically similar illnesses caused by hantaviruses from the family Hantaviridae, order Bunyavirales. Hantaviruses causing HFRS are found in Europe, Asia, and Africa, while hantaviruses in the Americas cause the more severe hantavirus cardiopulmonary syndrome. In

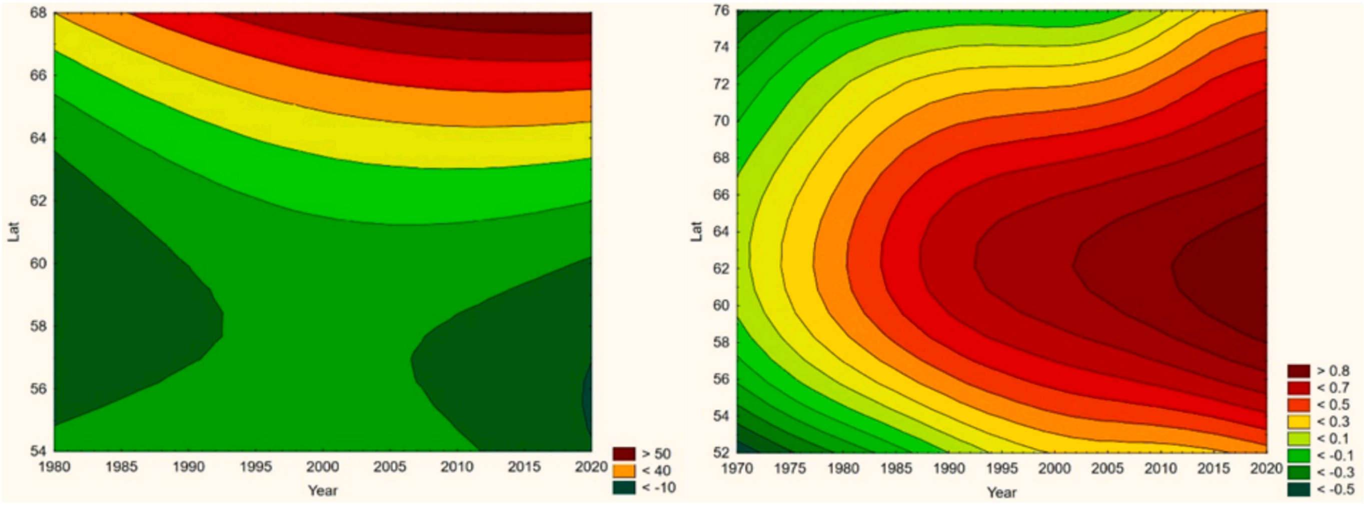

Fig. 3. As illustrated with Sweden (left, primary incidences), NE populations have migrated southwards while incidences have stayed rather unchanged through the observed period. In European Russia (right, ordinal incidences), the NE population has stayed latitudinally stationary while incidences have increased. Third-degree spline interpolations including interpolation artefacts (like negative incidences). Geographical latitude shown on y-axis, time (1970–2020) on the x-axis. Modified from Thierfelder and Evengård (2021).

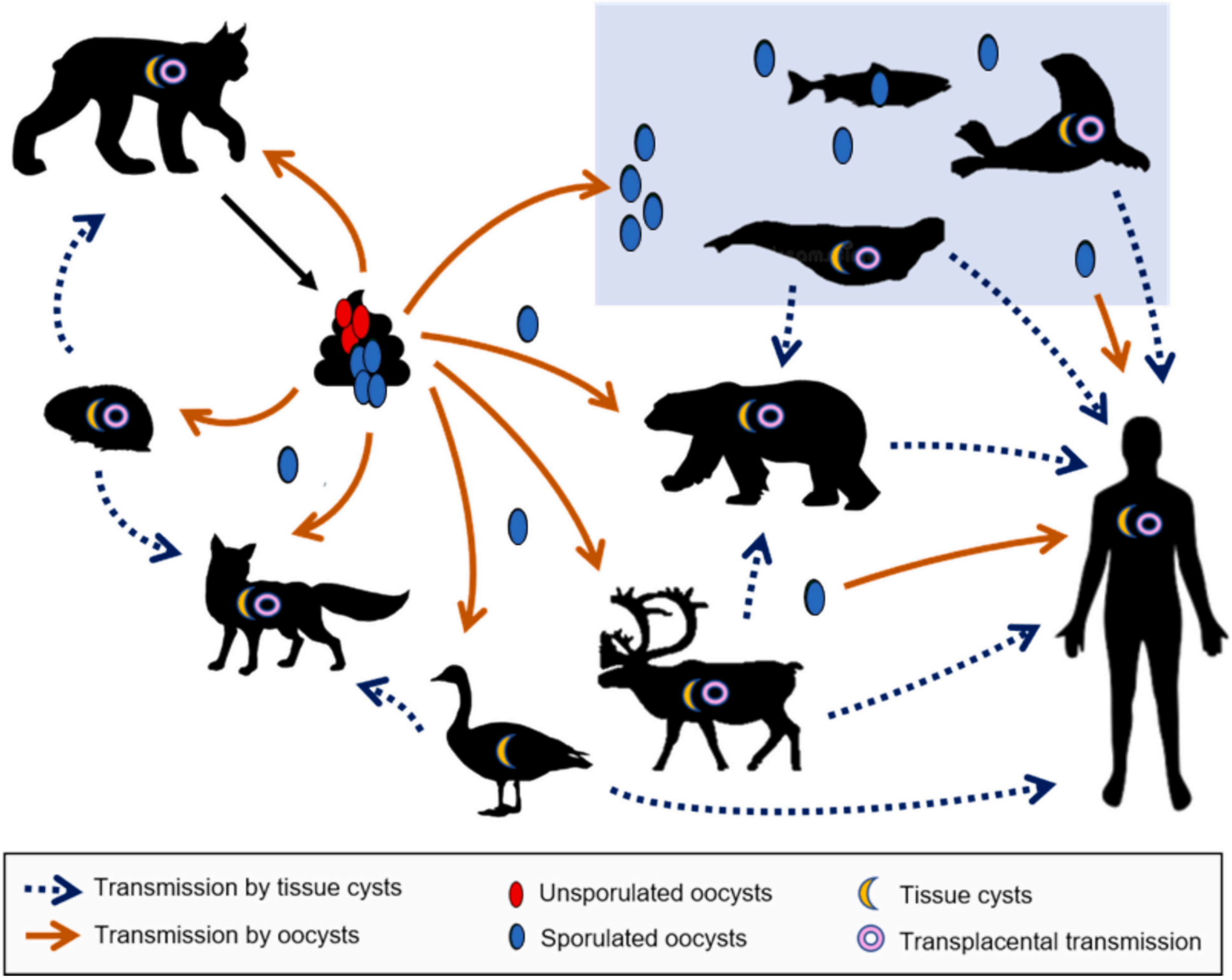

Fig. 4. Potential routes of transmission of the zoonotic parasite *Toxoplasma gondii* in the North, with focus on free-ranging wildlife hosts and the shared environment. (Reprinted and modified with permission from Springer Nature: Springer, Toxoplasmosis in Northern Regions. Source: Bouchard et al. (2022). Adapted under a Creative Commons Attribution License CC BY 4.0.)

northern Europe and Russia, HFRS is primarily caused by the Puumala virus (PUUV), named *Nephropathia epidemica* (NE). Up to half of diagnosed cases are hospitalized, dialysis may be needed mostly in the acute phase, but case fatality rate is low (<1 %) in comparison to many other hantavirus diseases (Makary et al., 2010; Pettersson et al., 2008). The hantavirus diseases are often quite severe rodent-borne zoonotic disease common in large areas of northern Europe and Russia (Olsson et al., 2010), causing a significant strain on the health care system during peak years (Pettersson et al., 2008). NE is relatively well-known in northern Sweden, Norway, and Finland. Hantaviruses are typically carried and transmitted by rodents but spillover infections occur to many other species including humans (CDC, 2019; Peters et al., 1999). In northern areas, recurrent outbreaks follow the cyclic population dynamics of their rodent host being the bank vole (*Myodes glareolus*) being the reservoir host of the PUUV (Khalil et al., 2019). Humans are infected via aerosols of rodent urine, feces, and saliva. Other hantaviruses occurring in the Arctic, and related to PUUV, are Topografov Hantavirus found in Siberian lemmings (*Lemmus sibiricus*) and Hokkaido hantavirus found in grey-sided voles (*Myodes rufocanus*) and red-backed voles (*Myodes rutilus*). They have however thus far not been reported as human infections (Plyusnin et al., 1996; Yashina et al., 2015.

In northern Europe and Russia, the NE show average and maximum annual incidences of 11.4 and 309.3 per 100.000 inhabitants respectively (Fig. 2). Case fatality-rates of diagnosed and reported cases approach 1 %. The majority of Puumala virus infections are, however, not diagnosed. Seroprevalence studies point towards an increasing prevalence in Fennoscandia. In northern Sweden, the seroprevalence has increased from 5.4 % (Ahlm et al., 1994) to 13.4 % (Bergstedt Oscarsson et al., 2016) and in Finland from 5 % (Markus Brummer-Korvenkontio et al., 1999) to 12.5 % (Latronico et al., 2018). It cannot be excluded that differences in methods used by these studies are a potential confounding factor.

When testing the current thirty-year climate reference period data on NE incidence for spatiotemporal trends (Fig. 3), NE seems stable except for the European Russia (Fig. 3). Therefore, NE should be considered a climate sensitive infection, and NE outbreaks have earlier been linked to mild winters with less snow cover in northern Sweden (Evander and Ahlm, 2009; Pettersson et al., 2008) and periods of increased precipitation and high autumn temperature (Ma et al., 2021). Increasingly wet early winters have also been linked to increased PUUV transmission in the reservoir host (Sipari et al., 2022).

2.8. *Case study 8: Toxoplasma gondii as a "pathogen pollutant" in the North American Arctic*

Toxoplasma gondii is a zoonotic protozoan parasite with a global distribution that can infect a wide range of vertebrates, including people, through food, water, and congenital routes. The definitive hosts of *T. gondii* are domestic or wild cats. Therefore, all *T. gondii* originates in the intestine of terrestrial felids, and the oocysts are considered a

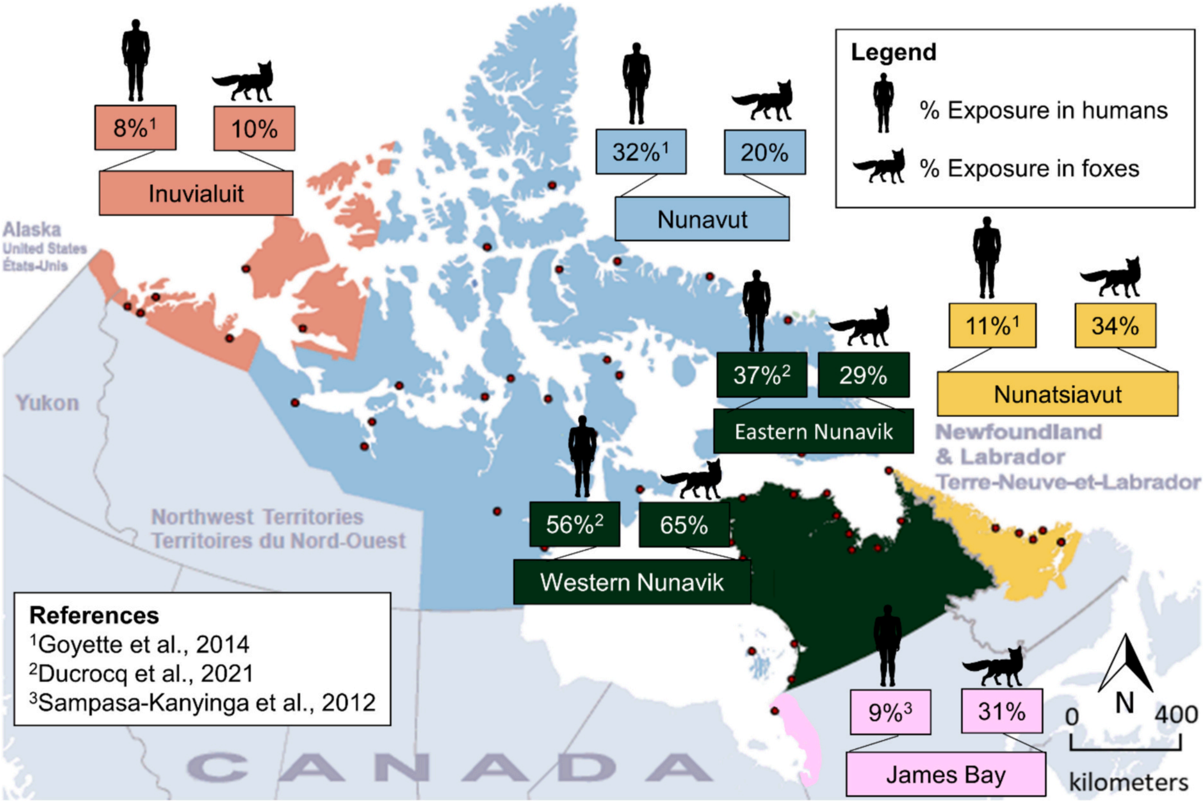

Fig. 5. Seroprevalence of antibodies to *Toxoplasma gondii* in people across Inuit Nunangat and foxes as sentinels of environmental transmission in northern Canada (Bouchard et al., 2022).
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"pathogen pollutant" in marine and Arctic systems, where felids are largely absent (Burgess et al., 2018). Similar to some chemical pollutants, *T. gondii* oocysts originate elsewhere, but are transported to Arctic ecosystems, where the parasite can bioaccumulate through its ability to chronically infect tissues of various hosts and transmit further via carnivores as well as transplacental (Elmore et al., 2012) (Fig. 4).

Possibly due to these many transmission pathways, some human populations in the central Canadian Arctic have, apparently paradoxically despite the general absence of felids, high seroprevalence of antibodies to *T. gondii*: 43 % in Nunavik and 32 % in Nunavut, at least double the seroprevalence in the general North American population, indicating higher exposure (Ducrocq et al., 2021; Goyette et al., 2014). In contrast, seroprevalence in humans in the Western Canadian Arctic (Inuvialuit Region) and the Eastern Canadian Subarctic (Nunatsiavut) is lower (estimated 7.5 % and 11.3 %). It is difficult to determine if this is due to differences in dietary preferences or genuine regional differences in infection pressure. Therefore, using a One Health approach, surveillance was conducted in foxes across the Canadian North (3600 km wide) as sentinels for *T. gondii* (Bouchard et al., 2022). At the same time, human health surveys independently explored human risk factors for exposure among northern residents. Reassuringly, these independent studies gave the same signal: seroprevalence was higher in both people and foxes in Nunavut and Nunavik in the central Canadian Arctic, and lowest in the Inuvialuit region in the west (Fig. 4), suggesting genuine geographical differences in transmission that may reflect the colder, drier climate in the western Canadian Arctic. In contrast, in the Eastern Subarctic (Nunatsiavut) and the James Bay Cree region, foxes had higher seroprevalence than people, and this is most likely to different human dietary preferences in these regions (Fig. 5). Finally, independent dietary studies in both foxes and people in Nunavik, a hotspot of *T. gondii* transmission, linked exposure to *T. gondii* to consumption of geese and aquatic wildlife (marine mammals, fish, and shellfish) (Bouchard, 2023; Ducrocq et al., 2021), rather than terrestrial herbivores such as caribou. This is further reinforced by low levels of detection of DNA of *T. gondii* in tissues of caribou harvested for human consumption in Nunavik (Hernández-Ortiz et al., 2023).

While currently reassuring for public health, the evidence for low levels of transmission of *T. gondii* in the western Canadian Arctic makes it more vulnerable to amplification of the parasite in this region, which is unfortunately also experiencing the most rapid climate warming in Canada over the past 75 years (Fig. 6). There is growing evidence that transmission of *T. gondii* is influenced by climate change and other anthropogenic factors (Meerburg and Kijlstra, 2009; VanWormer et al., 2016), including coastal run-off and changes in regional precipitation and hydrology. In the western Canadian Arctic, a multi-decadal study demonstrated that exposure of polar bears in the Western Hudson Bay population to *T. gondii* (and other terrestrial pathogens) increased from the 1980s, 1990s, and 2010s as the regional climate warmed and got wetter, and seroprevalence increased following wetter summers (Pilfold et al., 2021). Increased transport via water routes and survival of oocysts as well as survival of tissue cysts of *T. gondii* in carrion may be driven by climate change, which can have significance for wildlife health and conservation, and for human health. Further work is needed to determine possible synergistic interactions between "pathogen pollutants" like *T. gondii* and immunosuppressive chemical contaminants.

2.9. Case study 9: will climate change lead to the elimination of rabies from the Svalbard archipelago?

Rabies is an acute viral infection of the brain caused by the RNA rabies virus (RABV) belonging to the family *Rhabdoviridae*, genus *Lyssavirus*. It causes severe neurological disease and is most often transmitted by bite (Wunner and Conzelmann, 2013). There are an estimated 59,000 human cases yearly across >150 countries, with 95 % of cases

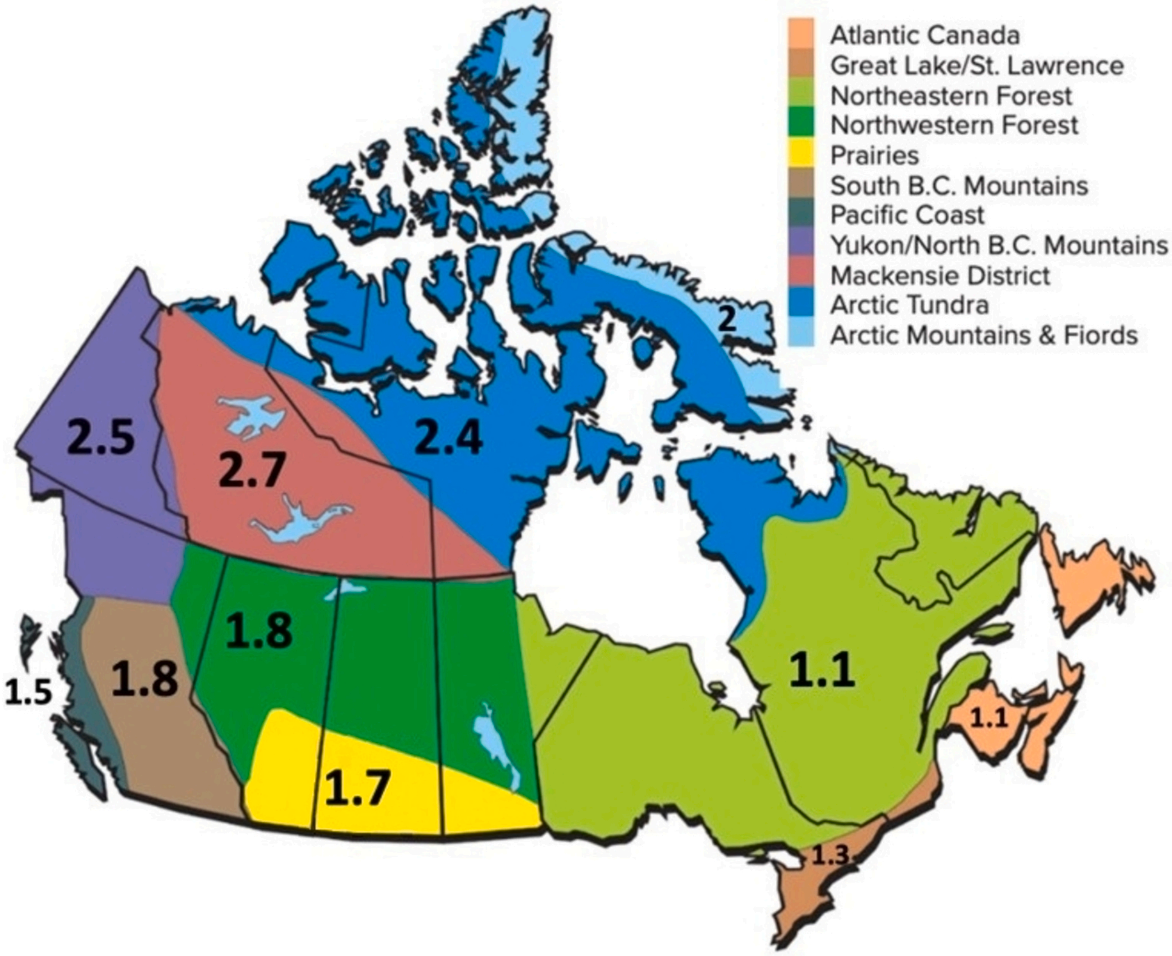

Fig. 6. Regional trends (°C) in observed climate warming over the last 75 years (1948–2022) in Canada, compared to the national warming trend of 1.9 °C. Map and data from Environment and Climate Change Canada. Open source: Government of Canada Publications (2023).

occurring in Africa and Asia. In these cases, 99 % are due to dog bites (World Health Organization, 2023). The Arctic variant of RABV, which is divided into four sub-groups (Arctic-1 to 4) (Deviatkin et al., 2017; Kuzmin et al., 2008; Nadin-Davis et al., 2021), is enzootic in the Arctic and causing rabies among wildlife and Indigenous people (Briggs and Mantini-Briggs, 2016; Hueffer et al., 2022a, 2022b). The Arctic fox is the primary host and reservoir (Hueffer et al., 2022b; Mørk and Prestrud, 2004). On Svalbard, there have been prior outbreaks in the Arctic fox population (Ødegaard and Krogsrud, 1981), with the most recent known outbreak in 2018 (Norwegian Veterinary Institute, 2018a, 2018b). Later it has sporadically been detected in both Arctic foxes and reindeer (Hueffer et al., 2022a, 2022b; Mørk et al., 2011; Ørpetveit et al., 2022.

Despite being an archipelago, sea ice connects Svalbard with other continents during the winter making the Arctic fox population non-isolated. This is supported by population genetics showing circumpolar connectivity (Carmichael et al., 2007; Cockerill et al., 2022; Dalén et al., 2005; Fuglei and Tarroux, 2019; Geffen et al., 2007; Norén et al., 2017). Phylogenetic characterization of RABV isolated from Svalbard Arctic foxes suggest that the source of infection may be Russia, coastal areas of North America or Greenland (Johnson et al., 2007; Kuzmin et al., 2008; Mansfield et al., 2006; Mørk et al., 2011; Ørpetveit et al., 2022). Screening of large numbers of Svalbard Arctic foxes indicate that there is either very low viral prevalence or that the virus is not enzootic in this population, but is introduced and causes disease outbreaks from time to time (Mørk et al., 2011; Prestrud et al., 1992).

The Arctic is warming about four times faster than the global average (Rantanen et al., 2022), and an Arctic Ocean without summer sea-ice is likely to occur around year 2030, which will affect Arctic fox foraging and movement (Fuglei and Ims, 2008; Goltsman et al., 2005; Guarino et al., 2020; Hanssen et al., 2013). However, the Svalbard Arctic fox may also benefit from becoming isolated, since it is likely that the occurrence of rabies on the Svalbard archipelago is dependent on repeated reintroduction of the virus. Climate change may ultimately contribute to the elimination of rabies from the Svalbard archipelago. This is an example of a positive effect of climate change, but the negative effects from e.g., increased energetic stress and the development of “Island syndrome” may vastly overshadow the positive health effect of decreased infection pressure from rabies. Of course, in a strictly health focused context, it is desirable to see the risk of this potentially severe disease decrease on Svalbard.

2.10. *Case study 10: anthropogenic species introduction coupled with climate change increases zoonotic infection risk, exemplified by Echinococcus multilocularis in Svalbard*

The zoonotic cestode, and causative agent of alveolar echinococcosis in humans, *Echinococcus multilocularis* was first detected in Svalbard in 1999 in the accidentally introduced sibling vole (*Microtus levis*) population in the Grumant area on Spitsbergen, i.e., Svalbard (Henttonen et al., 2001). These voles were thought to have been anthropogenically introduced to this Arctic archipelago with freight ships, possibly those delivering grain at some point during the 20th century (Henttonen et al., 2001). After this initial detection in rodents, screening of Arctic foxes has been intermittently carried out using different methods (Fuglei and

Table 2
Disease-mitigating actions that can be instigated as a response to ongoing change in disease dynamics, but also to address the potential for epidemic and pandemic of Arctic zoonoses.

Mitigating actions	Level of direct impact (wildlife = W, domestic animals = D; human = H, environment = E)	Responses
Policies	H, D, W, E	- Health policies proportionally directed at monitoring and controlling zoonoses in the Arctic using a One Health approach, regionally relevant contingency plans, and culturally acceptable interventions. - Tourism policies that reflect evidence-based strategies that continually evaluate human health risks, potential for accidents on land and sea, pollution risks, wildlife protection and general sustainability economically, socially and environmentally. - Policies that include Indigenous and local knowledge in plans for northern societies. - Policies that support equitable health care access in the Arctic as well as regional capacity to diagnose specific zoonoses in the Arctic and emerging pathogens (e.g., from thawing ice).
Surveillance and monitoring	W, D, H, E	- High efficacy, easy-to-use, and low-cost diagnostic modalities are greatly needed. For example, a greater and coordinated use of dry blood spots for zoonoses and contaminant analyses (Curry et al., 2014). - National and international strategies for monitoring and communicating risks of emerging diseases among wildlife, as well as a contingency plan. Indicator species should be selected from insights into general epizootiology, e.g., knowledge of wildlife species with high disease carrier and spread potential, trophic position, and pathogen specific modes of transmission. - One Health increased coordination and method standardization. This "One Healthness" of surveillance approaches can be evaluated to identify points that can be strengthened. - Community-based harvest and health monitoring of wildlife species will be key for a circumpolar sustainable wildlife health surveillance network. - Increased monitoring of bivalves for toxins, pollutants and zoonoses. - Investigation of wastewater's potential for biomonitoring of pollutants and zoonoses in the Arctic. - Wildlife population monitoring to detect declines and die-off events, especially relying on Indigenous and northern residents as “eyes on the land”. - Increased use of suitable animal species, such as dogs and wild canids as indicators or sentinels for human exposure of zoonoses and toxic pollutants as well as for ecosystem and wildlife health changes. - Increased monitoring of lakes carrying run-off water from thawing perma-frost/ice sheets for potential re-emerging pathogens.
Vaccination and countermeasures	H, D, W	Vaccines and other countermeasures should be quickly identified and deployed.
Information	H, D, W	- Increased education and culturally appropriate outreach concerning the handling of animals and behavior in the environment. Includes local civilians, tourists, hunters, scientists, and everyone else handling animals. Food safety messaging must, however, be carefully balanced to not cause further food insecurity among circumpolar Indigenous people. These are lessons learned from communicating on Arctic pollution threats to the communities. - Increased awareness of and ability to diagnose zoonoses in the Arctic among health care and veterinary practitioners.
Water resources	H, E	- Securing clean water and infrastructure that protects water from contamination is pivotal in disease control, particularly in areas relying on surface water for drinking reservoirs. This includes continuous monitoring of water resources in terms of both availability and biological and chemical contaminants.
Food resources	H, D, W	- Strengthening and supporting community led research on the effectiveness of traditional practices and food preparation methods to keep the hunters and communities safe from infectious disease exposure.
Movement	H, D, W	- Cost-effective resources for public and wildlife health surveillance, reflecting seasonal migrations of wildlife as well as northward shifts in species distributions and altered sea ice connectivity. - Increased collaboration between animal and human surveillance systems, and increased awareness of One Health risks through cross-disciplinary collaborations (veterinarians, biologists, soil scientists, permafrost experts, botanists, urban planners…).

Ims, 2008; Knapp et al., 2012; Stien et al., 2010). Based on these studies it was concluded that infection was probably brought to Svalbard by Arctic foxes over the sea ice from other arctic regions and that the presence of sibling voles enabled the establishment of a local infection hotspot. Infection prevalence varies between studies, and between years within studies, from 2 to over 8 %. Infection prevalence in Arctic foxes in Svalbard is inversely proportional to the distance from the core sibling vole area in Grumant, with decreasing prevalence with increasing distance (Fuglei and Ims, 2008; Stien et al., 2010). An infected fox has also been identified distant to Spitsbergen on the island of Hopen, 215 km east of the southern coast of Spitsbergen (Tryland pers. comm.).

Genetic analysis of adult cestodes from infected foxes in Svalbard has shown that they are closely related to those isolated from Arctic foxes in Yakutia (Santoro et al., 2024), supporting the initial introduction hypothesis, and highlighting that the positive fox on Hopen might as equally have come from Russia, with migration over the sea ice, as from Svalbard. Recent investigations into the burden of infection in Arctic foxes has revealed extremely high worm burdens in some individuals, ranging from 361 to almost 81,000 individual adult cestodes per infected Arctic fox across Nordenskiöld Land (Spitsbergen) (Norwegian Veterinary Institute unpubl. data). With each worm capable of producing hundreds of eggs that can infect humans as well as rodents, the environmental contamination will be considerable (Alvarez Rojas et al., 2018).

Long-term monitoring of the rodent population has shown how the population cycles in response to vegetation and climatic factors and how rodent abundance also impacts parasite prevalence in sibling voles (Stien et al., 2010). In years with favourable climate conditions (e.g., longer growth span for vegetation and winters with few rain-on-snow events), rodent distribution extends beyond Grumant into the human settlement areas of Barentsburg and Longyearbyen (Fuglei et al., 2008). Both Longyearbyen and Barentsburg have high densities of sled dogs housed in outdoor dog yards. Should these dogs gain access to infected rodents, the parasite can complete its life cycle and infectious *E. multilocularis* eggs will be shed in canine feces close to human habitations. Recent investigations of rodents trapped in Longyearbyen did not find any infected individuals ($N = 70$, Norwegian Veterinary Institute, unpubl. data) and, to date, none of the dogs on Svalbard that have been tested for this parasite since 2017 ($N = 404$) were infected (Karamon, 2022; Norwegian Veterinary Institute unpubl. data). It is not farfetched to consider that a climate favouring either year-round or just increased seasonal presence of rodents close to human habitations in Svalbard would also favour the establishment of *E. multilocularis* infection in domestic dogs and the potential for subsequent spill over to humans would therefore increase.

2.11. Case study 11: avian influenza in the Arctic – in need of increased monitoring

Avian influenza, also known as 'bird flu', is a zoonotic disease caused by influenza A viruses in the family Orthomyxoviridae. Though mostly known for its impact on poultry and waterfowl health, influenza A viruses (IAV) were associated with 4 human pandemics (e.g., Taubenberger and Morens, 2020) and are known to sporadically infect other mammals (ENETWILD Consortium et al., 2024; Runstadler and Puryear, 2024). According to its pathogenicity for poultry two subtypes are distinguished the Low Pathogenic Avian Influenza Virus (LPAIV) and the Highly Pathogenic Avian Influenza Virus (HPAIV). In 2020, subclade 2.3.4.4b HPAIV H5N1 evolved through reassortment in wild birds in Europe and spread globally. In contrast to previous HPAIV variants, this subclade has caused significant mortality in wild birds globally and has affected mammals as well (e.g., Alkie et al., 2022; Elsmo et al., 2023; Gamarra-Toledo et al., 2023; Kim et al., 2023; Lane et al., 2024; Lee et al., 2024; Leguia et al., 2023; Lindh et al., 2023; Plaza et al., 2024; Pohlmann et al., 2023; Rabalski et al., 2023; Ramey et al., 2022; Rimondi et al., 2024; Ulloa et al., 2023). Given its high fatality rate and broad host range (e.g., 502 wild avian species; 60 mammalian species) this variant has significant potential to reshape regional and local biodiversity of avian and mammalian species. Similar to other H5Nx viruses of the A/Goose/Guangdong/1/96 lineage, the current subclade 2.3.4.4b H5N1 exhibits pronounced neurotropism in infected animals and infection of the brain is common among both avian and mammalian species (Alkie et al., 2023; Bauer et al., 2023; Bordes et al., 2023) with limited detection of viral antigen in respiratory tissues despite apparent lung lesions (Puryear and Runstadler, 2024). Neurotropism appears to be absent in HPAIV infected US dairy cattle where the viral infection is self-limiting and shows a predilection for mammary gland tissue (Burrough et al., 2024).

Though active HPAIV surveillance in the Arctic and subarctic regions is likely characterized by incomplete and spotty coverage since the emergence of the current subclade 2.3.4.4b HPIAV H5N1; noteworthy detection of naturally occurring fatal highly pathogenic avian influenza virus H5N1 clade 2.3.4.4b infection have occurred in a number of Arctic and subarctic mammals including red fox (*Vulpes vulpes*) (Elsmo et al., 2023) and lynx (*Lynx lynx*), otter (*Lutra lutra*), farmed American mink (*Neovison vison*), Arctic (blue) fox, red (silver) fox and their crossbreeds (Lindh et al., 2023). Also, it is found in Kodiak brown bear (*Ursus arctos middendorffi*), black bear (*Ursus americanus*) and polar bear (Stimmelmayr et al., 2024). Among phocid and cetacean species it occurred in Caspian seal (*Pusa caspica*), northern fur seal (*Callorhinus ursinus*), harbour (*Phoca vitulina*) and grey seals (Lair et al., 2024) as well as Atlantic walrus at Svalbard, Norway (H5Nx Christian Lydersen pers. comm.) and harbour porpoise (*Phocoena phocoena*) (Thorsson et al. Lindh et al., 2023). These current records (2021–2023) likely underrepresent ongoing exposure of susceptible (naturally and/or experimentally) Arctic mammalian hosts to this subclade. Previous serological surveillance data suggests sporadic exposure of various Arctic mammals to circulating IAV's is not uncommon in Arctic wildlife, including beluga whales (Nielsen et al., 2001; Nymo et al., 2022a, 2022b), ringed seals and Pacific walrus (*Odobenus rosmarus divergens*) (Calle et al., 2002; Nielsen et al., 2001) in addition to Arctic fox (Hemert et al., 2019) and brown bear (*Ursus arctos*) (Naidenko et al., 2019; Ramey et al., 2019) as well as reindeer and other cervids (Hemert et al., 2019; Župančič et al., 2002); and muskrat (*Ondatra zibethicus*) (Gulyaeva et al., 2017). Additionally, evidence of seroconversion in both wild and domestic carnivores, as well as in a swine herd during the ongoing panzootic, suggests that infection with this subclade is not always fatal in mammals. This implies that subclinical, asymptomatic infections may occur in known susceptible hosts (Brown et al., 2024; Chestakova et al., 2023; Moreno et al., 2023; Rosone et al., 2023). Given the highly dynamic nature of this ongoing panzootic, pan-Arctic surveillance strategies are needed. This surveillance should combine active case finding efforts with standard testing of clinical animal cases which fit HPAIV case definitions, to further characterize ongoing exposure of Arctic wildlife.

For the majority of mammalian spillover cases in Arctic and non-Arctic species alike, the exact nature of transmission remains inconclusive but direct contact with infected birds or contaminated environments, and predation or scavenging of infected birds or mammals, likely play important roles in transmission (Runstadler and Puryear, 2024). Though speculative, given that cranial nerves – especially the olfactory nerve – are important routes of neuro-invasion for HPAI H5Nx viruses (Bauer et al., 2023), enhanced olfactory sensitivity coupled with olfactory foraging in carnivores (Green et al., 2012; Togunov et al., 2017) and typical carnivore behavior including scent rubbing, rolling behavior with carrion, conspecific greeting rituals, and grooming behavior including allo-grooming, may constitute unique alternative oral and/or olfactory exposure transmission scenarios among terrestrial carnivores. Evidence of onward mammal-to-mammal transmission for this subclade remains rare and includes fur farms, cat shelter, dairy farms, South American sea lion and elephant seal rookeries. However, with increasing frequency of mammalian infections, the risk for viral adaptation and reassortment is likely additive (Plaza et al., 2024; Puryear and Runstadler, 2024; Runstadler and Puryear, 2024). Spillback and cross-species transmission from cow to poultry, cow to cat, cow to peridomestic wildlife, cow to human have been documented for this subclade (Burrough et al., 2024; Garg, 2024). In the recent history of human H5N1 cases (1997–2024: 909 cases globally) most reported human (H5N1) cases were due to exposure to poultry.

Ongoing global reporting of outbreaks of subclade 2.3.4.4b HPAIV H5N1 in poultry, wild birds, and mammals suggests this panzootic will continue in 2024. Though speculative, given the ecological significance of Arctic regions for the environmental persistence and geographic dissemination of influenza A viruses in general (Gass Jr et al., 2022; Ramey et al., 2022), high pathogen pressure in the circumpolar Arctic from recurrent introduction via multiple avian migratory flyways could result in HPAIV H5N1 becoming endemic in northern regions. From a Pan-Arctic One Health perspective, endemic HPAIV would pose a significant public and wildlife health concern for northern communities and negatively impact traditional foods security and safety. Community- and hunter based participatory circumpolar wildlife health surveillance will be key to detect and monitor for this potentially emerging One Health issue. Moreover, circumpolar mitigation and management will require sustainable and broad research support by governments.

3. Recommendations and conclusions

The ongoing change of the Arctic environment highlights current knowledge gaps and that we should prepare for emerging zoonoses. The warming Arctic climate influences long-range transport and biomagnification of industrial chemicals as well as pathogens to the Arctic, which has implications for human, animal and environmental health i.e., One Health. Monitoring Arctic diseases has largely been neglected, and knowledge on their interactive effects with climate change and contaminant exposure are much needed to propel the One Health concept and its gains (Emelyanova et al., 2022; Hotez, 2010; Nelson, 2013). The lack of studies in the Arctic may be partly because of a much lower human density at northern latitudes. This should however not be a sole determinant for attention - particularly when taking into consideration fast and difficult-to-control global diseases and pandemic alertness/risk assessment. When more resources are allocated to areas with warmer climates or higher human population density there is an inherent risk of missing clues to an upcoming pandemic originating from a region where many people are in close contact with wildlife and (among other pandemic-promoting factors) a vast frozen library of historic and ancient microorganisms thawing (Christie, 2021; El-Sayed and Kamel, 2021).

There is a great need to invest in strategic One Health surveillance and research efforts in the circumpolar Arctic to concurrently address factors that affect both wildlife and public health (Fig. 1 and Table 2) (Caminade et al., 2019; Dudley et al., 2015; Ruscio et al., 2015; Tryland, 2022). In many regions, such efforts need to draw on and honour traditional local and traditional knowledge and ways of knowing (Kutz and Tomaselli, 2019) and should invest in participatory epidemiology methods for issue identification, early detection and ongoing monitoring (Mubareka et al., 2023; Peacock et al., 2020; Tomaselli et al., 2018). It is also crucial to assess additive, synergistic, or antagonistic effects between climate change and other stressors including anthropogenic pollutants, such as legacy- and emerging contaminants, especially in the marine ecosystem where the food chains are longer and contaminant levels hence are highest. Lessons learned in the Arctic, are also likely to be relevant or applicable in a global context, not least because diseases arising in the north now have more potential to spread globally than ever before (Christie, 2021; Council, E. A. S. A, et al., 2020; Partnership (IAP), the I, 2020). The COVID-19 pandemic illustrates how animal wet markets might have been ground zero for the introduction of a novel coronavirus to humans with globally devastating public health consequences and immense economic costs for society (Worobey et al., 2022). Although the trade of wildlife meat in Asian markets is dramatically different from food sharing networks in Arctic communities, harvesting game in remote areas and consuming it raw and without authorized meat-control is typical in many indigenous cultures (Keatts et al., 2021; Wegner et al., 2022). Arctic inhabitants are often in close contact with, and dependent on, wildlife for sustenance. Traditional circumpolar food systems are therefore vulnerable to the potential pathogens present in the hunted animals as well as to pathogen contamination during preparation or storage. This likely creates greater exposure risks for indigenous circumpolar communities (Keatts et al., 2021; Stimmelmayr and Sheffield, 2022).

In addition to this, Many communities in the Arctic do not have year-round road access so health care is limited to health centres staffed by nurses and nurse practitioners with periodic visits by physicians. The nursing staff is often transient and may not be familiar with locally relevant diseases and have limited resources for diagnostic workups. This means zoonotic diseases may go undiagnosed (Huot et al., 2019; Revich et al., 2012). An example of this, is a case in the western Canadian Arctic where human cases of *Giardia* are disproportionately represented and were likely missed until the human strain was detected in muskoxen, and health care providers were thereby alerted of the occurrence of this disease in the area (Jenkins et al., 2013). Arctic inhabitants are moreover required to travel by plane to larger, typically more southern, cities or regional centers for specialized treatment (when the weather conditions allow flying). For example, Inuit in need of specialized health care in Greenland travel to either Nuuk or to Copenhagen, Denmark, which may take several days. In addition, these movements could be potential routes for the introduction of unexpected pathogens in more densely populated areas at southern latitudes.

Table 2 offers a list of mitigating actions that could be instigated to control current and future disease outbreaks. Actions must be viewed as working in synchrony and cannot be individually "cherry-picked", but they must nevertheless be tailored to regional ecological conditions and unique community needs. The Arctic presents multiple challenges in terms of its vast geographical extent, hostile climate, and low density of animals (outside seasonal high-density aggregations) and diverse indigenous people's cultures. Monitoring diseases and their dynamics, therefore, commands a high degree of international cooperation between Arctic nations and their respective scientific communities for example, to increase effort to educate the relevant groups of the public regarding safe handling of wildlife, including protective traditional practices and local knowledge not often known to tourists or transient medical or veterinary personnel. Table 2 also highlights the need for cross-disciplinary and international collaboration in a circumpolar framework to mitigate the current significant lack of scientific knowledge in the literature about zoonoses in the Arctic including their relation to current global changes. A rapidly transforming environment and growing human influence position the Arctic as a critical focal point for potential global health crises, primarily through the emergence of zoonotic diseases and thawing of permafrost, including ancient pathogens. The compounding pressures of environmental toxins and shifting ecological dynamics not only endanger the unique wildlife, but also amplify health risks for the Indigenous peoples who rely on healthy and stable wildlife populations. The region's deep-rooted cultural heritage and ecological systems, epitomized by traditional food sources, are being increasingly challenged, with episodes like the Siberian anthrax outbreak painting a grim picture of potential repercussions. Navigating this complex landscape, a multifaceted, global response is of paramount importance. This involves championing international research collaborations to bridge knowledge disparities, amplifying disease monitoring in the Arctic for proactive interventions, and engaging indigenous communities to adapt to these evolving challenges. As the Arctic's global importance grows, effective guidelines on health and environmental mindfulness to respect biosecurity and protect the region's delicate balance are urgently needed. Investing more substantially in Arctic research and addressing the root environmental culprits, such as pollution and the overarching climate change, are also non-negotiable necessary actions. Ultimately, preserving the Arctic's future and averting global health crises requires a holistic One Health approach, rooted in rigorous scientific research, community-driven strategies, and unified international multidisciplinary efforts.

CRediT authorship contribution statement

Emilie Andersen-Ranberg: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ingebjørg H. Nymo:** Writing – review & editing. **Pikka Jokelainen:** Writing – review & editing. **Anastasia Emelyanova:** Writing – review & editing. **Solveig Jore:** Writing –

review & editing. **Brian Laird:** Writing – review & editing. **Rebecca K. Davidson:** Writing – review & editing. **Sonja Ostertag:** Writing – review & editing. **Emilie Bouchard:** Writing – review & editing, Visualization. **Freja Fagerholm:** Writing – review & editing. **Kelly Skinner:** Writing – review & editing. **Mario Acquarone:** Writing – review & editing. **Morten Tryland:** Writing – review & editing. **Rune Dietz:** Writing – review & editing, Funding acquisition. **Khaled Abass:** Writing – review & editing. **Arja Rautio:** Writing – review & editing. **Sjúrður Hammer:** Writing – review & editing. **Birgitta Evengård:** Writing – review & editing. **Tomas Thierfelder:** Writing – review & editing. **Raphaela Stimmelmayr:** Writing – review & editing. **Emily Jenkins:** Writing – review & editing, Visualization. **Christian Sonne:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

All data are in the Tables.

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