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Healthy ecosystems for human and animal health: Science diplomacy for responsible development in the Arctic

The Nordic Centre of Excellence, Clinf.org (Climate-change effects on the epidemiology of infectious diseases and the impacts on Northern societies)

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Abstract

Climate warming is occurring most rapidly in the Arctic, which is both a sentinel and a driver of further global change. Ecosystems and human societies are already affected by warming. Permafrost thaws and species are on the move, bringing pathogens and vectors to virgin areas. During a five-year project, the CLINF – a Nordic Center of Excellence, funded by the Nordic Council of Ministers, has worked with the One Health concept, integrating environmental data with human and animal disease data in predictive models and creating maps of dynamic processes affecting the spread of infectious diseases. It is shown that tularemia outbreaks can be predicted even at a regional level with a manageable level of uncertainty. To decrease uncertainty, rapid development of new and harmonised technologies and databases is needed from currently highly heterogeneous data sources. A major source of uncertainty for the future of contaminants and infectious diseases in the Arctic, however, is associated with which paths the majority of the globe chooses to follow in the future. Diplomacy is one of the most powerful tools Arctic nations have to influence these choices of other nations, supported by Arctic science and One Health approaches that recognise the interconnection between people, animals, plants and their shared environment at the local, regional, national and global levels as essential for achieving a sustainable development for both the Arctic and the globe.

Introduction

Our civilisation reached the Anthropocene when the activities of *Homo sapiens* became the dominant influence on climate and the environment. This started when the first industrialisation occurred at the end of the 18th century. Early predictions of its effects came from internationally active scientists like Alexander von Humboldt and Ernst Haeckel, who developed the concepts of ecology and ecosystems. The latter includes humans as integral parts of ecosystems along with other species and has developed into the "One Health concept" describing the interconnections of people, animals and their shared environment. Charles Darwin carried these revolutionary thoughts further, while Svante Arrhenius proposed that industrialisation would lead to emissions of CO_2 that would change the climate. In 1958, Charles D. Keeling began documenting continually and rising atmospheric CO_2 levels, a crucial example of many different phenomena showing that we are living in the midst of such anthropogenic change. With changing climate, fauna and flora are on the move, bringing microbial organisms with them into virgin territory. Zoonotic pathogens, that is microorganisms transmitted between animals and humans, constitute at least 70% of emerging infections, sometimes with global spread, as illustrated by the SARS-CoV-2 pandemic. It is only through international collaboration that understanding of these rapidly ongoing processes can be deepened and that the required preparedness, and mitigation and adaptation can develop. Through the funding body NordForsk of the Nordic Council of Ministers, a Nordic Center of Excellence; Climate-change effects on the epidemiology of infectious diseases and the impacts on Northern societies, Clinf, was established.

Clinf.org has for five years focused on climate change and its impact on ecosystems, health of humans and animals, and development of societies in the North.

Here we describe how scientists from eight countries have worked to interpret nature in the Arctic and predict the conditions leading to outbreaks of climate-sensitive infections, describing possible methods illustrated with the case of tularemia, and thus support evidence-based policy aimed at preventing and mitigating their consequences.

The Arctic

The Arctic provides an extreme natural environment, manifested in many climatic, geochemical and biotic factors. The natural world and human societies have adapted to cope with these extreme conditions, but a new and major main threat to the health of people and animals in the Arctic is associated with global warming, both because of its intense effects on human and animal organisms, and the scale of the territories it covers (Isaev, 2003; Parkinson et al., 2014). Over the past few decades, the Arctic has warmed more than twice as rapidly as the rest of the world, as both sentinel for and driver of global change (Overland et al., 2020). This pattern is true for the entire territory of the Arctic. According to Roshydromet (The Russian Federal Service for Hydrometeorology and Environmental Monitoring), climate change in the Russian Arctic is more intense than in any other part of the country (Roshydromet, 2019). Over 30 years (1990–2019), the average annual temperature rose by 0.81°C every 10 years, that is 2.43°C over 30 years. Warming is also evidenced by a rapid decrease in Arctic ice cover, an increase in the thickness of the seasonally thawed permafrost layer, a decrease in the duration of the snow cover and other indicators (AMAP 2021). Likewise, the Canadian Arctic is warming at twice the rate of the rest of Canada and three times the global average, with a warming trend of 2.3^0 C over the last 68 years (Bush & Lemmen, 2019).

Expected increase of climate-sensitive infection

With regard to recent and historic epidemics and pandemics, climatic changes can lead to shifts in the geographic boundaries of pathogens, hosts and vectors, and amplify transmission of endemic climate-sensitive pathogens (Kovats, Campbell-Lendrum, McMichael, Woodward & Cox, 2001; Kutz, Hoberg, Polley&Jenkins, 2005; Parkinson et al., 2014; Pecl et al., 2017). Climate change can transform the geographic distribution and seasonal patterns of transmission of a range of infectious and parasitic diseases. Birds are known being vectors of importance. Warming causes some species to migrate to higher latitudes and altitudes, bringing new diseases; conversely, endemic Arctic-adapted species may face extinction at the top of a warming world. Both human-specific and zoonotic pathogens can cause disease in humans; however, even non-zoonotic pathogens can cause significant economic damage, threatening trade, livestock production and conservation of wildlife important for human harvest, especially in the Arctic (Evengård & Thierfelder, 2020).

Temperature and humidity affect the rate of development, survival and reproduction of pathogens and disease vectors. Higher temperatures can allow infected carriers to survive the unfavourable period of the year, thereby increasing the population size and expanding the range of the species. A role is played by changes in the timing and thickness of snow cover, which affects the conditions of overwintering for hosts and vectors (Kershengolts, Chernyavsky, Repin, Nikiforov & Sofronova, 2009; Revich, 2008). The Arctic and other high-latitude regions with low diversity of animal, plant and microbial species, and with increases of surface temperature above the global average, are excepted to experience more severe changes in infectious disease patterns than other regions (Hassol, 2004).

Reappearance of old microorganisms

There is a probability that microorganisms, including serious pathogens like anthrax, will re-appear in ecosystems due to thawing of burial places of people and animals in permafrost and glaciers in the Arctic. For example, microorganisms currently conserved in the frozen remains of mammoth fauna can be brought to the surface by permafrost thaw (Kershengolts et al., 2009). Pathogens related to modern anthrax bacteria, *Bacillus anthracis,* have been isolated from remains of mammoths. Metabolically active aerobic and anaerobic bacteria and fungi, microalgae, yeasts, moss spores, seeds of higher plants capable of germination, viable protozoan cysts and some viruses have been found in permafrost (Elpiner & Dzyuba, 2017). The danger of paleoviral and paleobacterial contamination of surface and underground water sources has been very poorly studied. Due to natural and artificial recharge of groundwater, ancient bacteria and paleoviruses have penetrated into the soil and can now, due to permafrost thaw, return to the surface, enter the atmosphere and spread over considerable distances. It is widely thought that even small climatic shifts are sufficient to change the life cycles and parasitic systems of Arctic animal pathogens and vectors that have existed for a long time under severe environmental constraints (Hoberg 2005; Strathdee & Bale 1998). The most obvious parameters that can influence the spread of natural focal infections are temperature, precipitation and fluctuations in the length of the seasons. Changes in these parameters can affect the suitability of the habitats of hosts and vectors, and their reproduction rates, distribution and abundance. These relationships are often complex, and socio-economic factors, such as human behaviour and land use, are often added to the climatic and environmental drivers involved (Hedlund, Blomstedt & Schumann, 2014).

Indigenous peoples

A range of indigenous populations lives in the Arctic region. These include Saami in circumpolar areas of Finland, Sweden, Norway and Northwest Russia; Nenets, Khanty, Evenk and Chukchi in Russia; Aleut, Yupik and Inuit (Iñupiat) in Alaska; Inuit (Inuvialuit, Nunavut, Nunavik and Nunatsiavut) in Canada; and Inuit (Kalaallit) in Greenland. All of the above-mentioned countries except Iceland have indigenous peoples living within their Arctic territory.

Although parts of the Arctic, such as northern Scandinavia, have living standards comparable to the rest of the Scandinavian countries, Indigenous populations in many parts of the Arctic experience health disparities (Yansouni, Pernica & Goldfarb, 2016). Infectious diseases remain the leading source of infant mortality in parts of the Arctic as Greenland and Denmark as investigated using data until 1997 (Friborg J, Koch A, Stenz F, Wohlfahrt J & Melbye M., 2004). Arctic communities are often disadvantaged by socio-economic disparities such as inadequate drinking water, sanitation and housing, decreased access to medical and educational facilities, and high levels of unemployment and food insecurity. In the Nenets Autonomous Okrug of the Russian Arctic, these contribute to the spread of various parasitic diseases (Bobyreva & Degteva, 2015; Bobyreva, Korneeva & Degteva, 2016).

The most vulnerable groups are those living in remote areas where adaptation to climate change is most difficult, for example due to insufficient economic support or lack of infrastructure (Hedlund et al., 2014). At the same time, research on these conditions is insufficient, especially in the most remote regions. In addition, comparison of data on incidence of certain diseases in different countries is often hindered by differences in reporting systems and regulatory documents due to the lack of international standardisation of data (Omazic, Berggren, Thierfelder, Koch & Evengård, 2019; Orlov et al., 2020).

In addition to infectious diseases transmitted among humans in most societies, a range of zoonotic infections, many of which are climate-sensitive, occur among in particular indigenous populations of the Arctic (Jenkins et al., 2013). The Saami people are unique among the indigenous peoples in the world in having the same public health standard as citizens in the Nordic countries (Sjolander P, 2011; Anderson et al., 2016). However, due to climate change, an increased susceptibility to infectious disease among semi-domesticated reindeer – an important Saami food source – is an increasing threat to food security and safety (Haider, Laaksonen, Kjær, Oksanen & Bødker, 2018). In the indigenous populations of the North American Arctic and Northern Russia, transmission of some zoonoses is associated with the unique food practices and habits of the indigenous population. For example, the consumption of raw meat from marine mammals, especially walruses and bears, is associated with recurring outbreaks of trichinellosis in Greenland and Northern Canada (Hotez, 2010), and the preparation of fermented walrus or seal meat ("igunaq") is associated with outbreaks of botulism in Alaska, Northern Canada and Greenland (Austin & Leclair, 2011). These unique fermentation practices can bring in unique microorganisms that give the food a special flavour (Aviaja et al., 2020). Human seroprevalence for toxoplasmosis is 2–4 times higher in Inuit in regions of the Canadian Arctic than in the rest of North America, with risk factors including consumption of harvested wildlife as well as contaminated drinking water (Jenkins et al., 2013; Messier et al., 2009). On the other hand, consumption of traditional foods of wildlife origin is critical for food security, cultural continuity and intact relationships with the land for Inuit. The benefits of these close relationships among people, animals and the land are generally considered to outweigh the risks; however, rapid climate change may alter pathogen distribution, prevalence, transmission routes and diversity in Arctic wildlife, and environments faster than Arctic residents, however innovative, can adapt. Knowledge is urgently needed in many parts of the Arctic on the prevalences and impact of zoonoses in humans, given the sparse populations and the lack of microbiological laboratories and other diagnostic facilities. In addition to building local capacity for food safety, veterinary and human diagnostics, more work is needed integrating scientific and indigenous knowledge to monitor, detect and mitigate old and new threats in the Arctic.

According to a recent analysis of policy documents from the Arctic Council, traditional ecological knowledge has only been incorporated to a limited extent in policy documents so far, and co-production of knowledge is recommended to improve integration of traditional ecological knowledge into research activities in the North (Sidorova, 2020).

Co-production of knowledge

There is no uniform definition of traditional knowledge, often described as knowledge conveyed narratively or through practical learning from one generation to the next for a long period of time. A key element is also that it is embedded in a cultural framework. Traditional knowledge on how to survive and thrive in the Arctic has been passed on since time immemorial among Indigenous and Local people in the North. Climate change requires major reconsideration of this knowledge. Already, reindeer herders in Sweden and Finland have described changed herding conditions and animal behaviours and health, especially in winter (Furberg, Evengård & Nilsson, 2011; Rasmus et al., 2020).

Indigenous theory emphasises unequal power relations in society; however, indigenous cultures do naturally not theorise in the same way, and each culture needs to be respected in a dialogue. Co-produced knowledge is a central concept. Reciprocity is emphasised as an important ethical aspect: knowledge is expected to be produced in dialogue with the respective Indigenous society. Research designed for co-produced knowledge, where academic and traditional knowledge meet with respect, is important in a world with an increasing climate crisis (Rasmus et al., 2020).

In the Arctic Council, the Indigenous peoples of the Arctic are represented as permanent participants by six Non-Governmental Organisations (NGOs): the Aleut International Association (the islands in the Bering Sea between the US and Russia), the Arctic Athabaskan Council (Canada and USA), the Gwich'in Council International (Canada and USA), the Inuit Circumpolar Conference (Greenland, Canada, USA and Russia), the Saami Council (Norway, Sweden, Finland and Russia) and the Russian Association of Indigenous Peoples of the North, Raipon (representing 40 different Indigenous peoples in Russia). The structure of these NGOs differs regarding true representation of these Indigenous Arctic communities, which is important to consider in research aiming at dialogue with a specific Indigenous community.

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For example, the Inuit Circumpolar Council (ICC) is designed to represent the entire Inuit population either by parliamentarian representation (ICC Greenland and ICC Canada) or by Indigenous organisations working on a direct mission from the local communities (ICC Alaska and ICC Chukotka). Other Indigenous NGOs of the Arctic Council are less representative of an Indigenous people‘s perspective – for example the Saami. The Council is dominated by reindeer herding interests. Consequently, it only represents approximately 10 - 40 % of the Saami community. Saami parliamentarians representing the entire registered Saami population in Fennoscandia have neither influence nor representation in the Saami Council. Thus, researchers aiming at a community dialogue based on the full registered Saami population should address the Saami Parliamentarian Council instead, a governmental collaboration body consisting of representatives of the Saami Parliaments of Norway, Sweden and Finland, including Russian non-parliamentarian Saami observers. However, collaboration with the Saami Council would be better for research focusing on the sub-community of reindeer herding Saami, especially since lack of trust means some are not registered as Saami according to the parliamentarian system.

These examples demonstrate the need to be well informed about the different structures and organisations of Indigenous peoples and governmental bodies in the Arctic before approaching and building a relationship with an Indigenous community, aimed at co-production of knowledge. Depending on the research question, organisations recognised by the Arctic Council are not guaranteed to be representative from a research – or international law – perspective.

There are only a few examples of Saami community-based co-production of knowledge, as needed for research on environmental and climate change. One example from Russia is about how to improve dialogue among researchers, locals and Indigenous peoples and decision-makers (Callaghan et al., 2020), and another one is about mountain birch utilisation in a research project in northern Finland. Saami perceptions and practices were published both in scientific papers and books of the EU-funded project HIBECO (e.g. Aikio & Muller-Wille, 2003, 2005), and joik, music and videos. In recent research, Eriksen, Rautio, Johnson, Koepke & Rink, (2021) support the need to develop formalised ethical protocols and use of community-based participatory approach in Saami research to the co-production of knowledge and mutually beneficial research for all involved. The importance of compulsory feedback to the communities from the academic world cannot be too overstressed and should be a part of protocols.

Predicting disease outbreaks

Predicting potential increases in infectious diseases under ongoing climate change is a key challenge for science and society. Changes in climate and water conditions that influence the spread of disease have been observed or are projected globally (Barnett, Adam & Lettenmaier, 2005; Milly, Dunne & Vecchia, 2005) and reported to change the geographic range, prevalence and/or severity of some infectious diseases (Garrett et al., 2013; Baker-Austin et al., 2013; Harvell, Altizer, Cattadori, Harrington & Weil, 2009; Burge et al., 2014; Rodó et al., 2013). Understanding and predicting potential future changes in the spread of infectious diseases in the Arctic requires validated quantitative mechanistic or statistical disease model(s), (e.g. Balci et al., 2014; Desvars-Larrive et al., 2017; Nakazawa et al., 2007; Palo, Ahlm & Tärnvik, 2005; Rydén, Sjöstedt & Johansson, 2009; Rydén et al., 2012), which can be linked with relevant landscape and hydro-climatic modelling, data and future projections (Ma, Vigouroux, Kalantari, Goldenberg & Destouni, 2020; Leibovici et al., 2021). Such disease models can be combined with climate model projections of future temperature, precipitation, thawing of permafrost changing land cover, soil moisture, snow cover, atmospheric pollution and other disease-relevant factors in order to assess potential impacts of landscape and hydro-climatic change on future disease spreading. As far as possible, multiple alternative models should be tested for both diseases (often not available) and environmental conditions including various landscape and hydro-climatic data (often available and should be used), in order to quantify and understand multi-model uncertainty and robustness of inferred implications of future disease evolution (Bring et al., 2019; Leibovici et al., 2020).

A case study: Tularemia

Tularemia is one of the most studied zoonotic diseases in high-latitude regions, with human and wildlife outbreaks observed in, *for example*, Alaska (Hansen, Vogler, Keim, Wagner & Hueffer, 2011), Canada (Isaac-Renton, Morshed, Mak, Loyola & Hoang, 2010), the Nordic countries (Rossow et al., 2015; Larssen, Bergh, Heier, Vold & Afset, 2014; Desvars et al., 2015) and Russia (Timofeev et al., 2017). For the Nordic-Arctic region, it is one of the diseases identified as likely to be affected by hydro-climatic change (Waits, Emelyanova, Oksanen, Abass & Rautio, 2018). Tularemia is caused by the bacterium *Francisella tularensis*, which is typically spread to humans by deer flies, mosquitoes, ticks or through contacts with infected animals, for example hares, rodents or beavers. In Sweden, the geographical distribution of the disease is uneven, and the majority of the human cases occurs in seven high-risk regions (Desvars-Larrive et al., 2017). The number of human cases varies greatly between years, with local outbreaks with annual incidences of more than 500 cases/100 000 inhabitants and years with no cases in some of the high-risk regions. Seasonal variation is also large, with most cases occurring during the late summer and early autumn. The annual distribution of human tularemia cases within the high-risk regions has been modelled (Rydén et al., 2012) by considering five environmental variables: relative mosquito abundance, summer temperature in the preceding year, summer precipitation, number of cold days with low snow coverage (such weather conditions decreases the rodent and hare populations) and the number of tularemia cases in the preceding year. The relative mosquito abundance estimated from two hydro-climatic parameters, daily river flow and temperature, was then found to have the most correlation with the outcome. The highest mosquito abundance was observed when river flooding was followed by warm weather. Interestingly, all the environmental variables can be predicted from meteorological data, but the disease modelling suggests that the relation between weather data and tularemia incidences is highly complex and needs to be modelled with high temporal resolution, using daily or hourly meteorological data. Without a model that correlates tularemia cases and climate data, it will be very difficult to understand the consequences of climate change. The model proposed for tularemia has also been further adapted to various high-risk regions and was able to predict most of the outbreaks, although it failed to represent the magnitude of the outbreaks in two regions (Desvars-Larrive et al., 2017). This highlights the importance of geographically local modelling and awareness that extrapolations to other regions may not always be possible. Although we have models that explain the annual variation of tularemia cases within high-risk regions, we do not fully understand why it is endemic in these regions, nor which regions are at risk of becoming endemic in the future. This knowledge gap needs to be addressed when modelling how climate change will affect tularemia.

Projection of disease evolution under climate change

In general, a combination of climate and water conditions (hydroclimate) can directly or indirectly influence important disease mechanisms by affecting the abundance of disease vectors, such as mosquitoes and ticks (Rogers & Randolph, 2006), and pathogen survival outside the host (Lowen, Mubareka, Steel & Palese, 2007). Hydro-climatic conditions can also influence host-pathogen interactions, related to community ecology and biodiversity (Altizer, Ostfeld, Johnson, Kutz & Harvell, 2013; Callaghan et al., 2004), and environmental contamination and exposure to water-borne infections (Reiner et al., 2012). Other possible hydro-climatic factors include damping of host immunity (Foxman, Storer, Vanaja, Levchenko & Iwasaki, 2016), disruptions of health status due to malnutrition linked to droughts or floods and disruption of health care systems by disasters such as floods (Kouadio, Aljunic, Kamigaki, Hammad & Oshitani, 2012).

For the example of tularemia, Ma, Bring, Kalantari & Destouni (2019) linked a statistical disease model with the historically observed ranges of relevant hydro-climatic variables, in order to quantify the sensitivity of future disease evolution to measured variations in the variables. This revealed that relatively small variations and changes in the variables could greatly shift the level of tularemia outbreaks. Ma et al. (2020) further tested multiple disease model versions relevant to different high-risk areas across Sweden. This showed that the impacts of climate change on tularemia can differ greatly among geographic regions and that predictions depend on the specific disease models and hydro-climatic models used. Overall, Ma et al. (2020) quantified high uncertainty levels in projections of future disease scenarios, which poses significant challenges to related policy, management and diplomacy for the Arctic (Azcárate, Balfors, Bring & Destouni, 2013).

A few other studies have also attempted to quantify the impacts of projected hydro-climatic change on tularemia outbreaks (Nakazawa et al., 2007; Palo et al., 2005; Rydén et al., 2009). Consistent with the findings of Ma et al. (2020), their results vary due to different models assumptions and perspectives adopted in the different studies. For example, Rydén et al. (2009) concluded that a future increase of approximately 2°C in monthly summer temperature would increase the duration of tularemia outbreaks in Sweden. In contrast, Palo et al. (2005) concluded that a future warmer climate will not lead to higher frequency of tularemia outbreaks in Sweden. Such contradictions often emerge in projections of diseases with highly localised transmission (Desvars-Larrive et al., 2017). A focus on smaller geographical scales may mean higher accuracy for local disease models, but generally implies higher uncertainty and lower accuracy for climate models. Going to larger spatial scales instead implies likely lower applicability of local disease models, but considerably more robust and accurate projections by climate models. The choice of geographic problem and model scale thus involves tradeoffs, which need to be acknowledged and accounted for in projections of coupled future disease and climate change scenarios: Arctic science diplomacy will be most effective when it considers, and uses, such model projections based on best climatic and disease data. The information required for projection of disease evolution under climate change includes systematically procured long-term data on environmental indicators, increased understanding of the ecology of the disease-causing agents, appropriate indicators to monitor (including traditional knowledge) and information on the occurrence of infections in humans and animals. Different countries host various databases containing a wealth of such information, but often in incompatible forms, making it difficult or impossible to extract consistent data for urgent cross-border comparisons. Rapid development of new harmonised technologies and databases is needed to access relevant data from rich, but currently highly heterogeneous data sources. Furthermore, the largest uncertainties in modelling climate change scenarios are not scientific, but sociological, with the future of contaminants and infectious diseases in the Arctic depending on what paths the majority of the globe chooses to follow. Diplomacy is a powerful tool Arctic nations have to influence the choices of other nations and should have at its core recognition of the interconnection between people, animals, plants and their shared environment at the local, regional, national and global levels.

Recommendation

International harmonised databases and forecasts like those for tularemia should be pursued and made openly and routinely available to support decisions aimed at keeping humans and animals healthy and societies sustainable in the Arctic. This requires diplomatic efforts to establish a solidly based network for international collaboration, including Indigenous theory as mentioned above and community-based participatory research. With a strong enough mandate, such an organisation/network would be able to rapidly share results, strengthen the input of resources from different nations and reinforce swift exchange of information across nations for the benefit of a globally sustainable environment that benefits human and animal health.

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