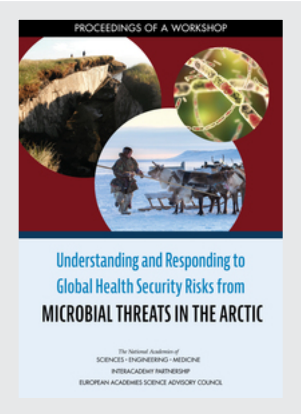

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Understanding and Responding to Global Health Security Risks from MICROBIAL THREATS IN THE ARCTIC

PROCEEDINGS OF A WORKSHOP

Lauren Everett, Rapporteur

Polar Research Board
Board on Life Sciences
Division on Earth and Life Studies

Board on Global Health
Health and Medicine Division

In collaboration with the InterAcademy Partnership and the European Academies Science Advisory Council

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This Proceedings of a Workshop was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published proceedings as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We thank the following individuals for their review of this proceedings:

Robyn Barbato, Cold Regions Research and Engineering Laboratory
Emily Jenkins, University of Saskatchewan

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the content of the proceedings nor did they see the final draft before its release. The review of this proceedings was overseen by Barbara Schaal, Washington University in St. Louis. She was responsible for making certain that an independent examination of this proceedings was carried out in accordance with standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the rapporteur and the National Academies.

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Contents

Overview

Background and Context

Arctic temperatures are rising more than twice as rapidly as the rest of the world, with myriad impacts on ice sheets, sea ice, snow cover, and many other crucial aspects of Arctic ecosystems and communities (Richter-Menge et al., 2019). One impact of this warming is the widespread thawing of permafrost—the thick subsurface layer of soil that (historically) remains frozen throughout the year. Permafrost thaw has many implications of importance to human society such as exacerbating climate change through the release of stored carbon, and posing risks to infrastructure as the permafrost gives way. There is also a growing realization of the possibility of adverse impacts on human health. Many reports discuss the potential impacts of increasing temperatures on tropical infectious diseases becoming more prevalent as the habitable zones for disease vectors expands (e.g., USGCRP, 2016). In recent years, a few scientists have begun to raise questions about whether infectious disease risks could possibly emerge or re-emerge from higher latitudes, including from melting Arctic ice and thawing permafrost (NRC, 2014).

This interest grew when, in summer 2016 (a year that shattered records for Arctic-region warmth), a remote part of Siberia known as the Yamal Peninsula saw an outbreak of anthrax, which killed a 12-year-old boy, infected dozens of people, and killed more than 2,300 reindeer. While the combination of factors that led to this outbreak is debated, one theory is that it may have resulted from the thawing of a frozen reindeer carcass infected with anthrax, which released spores into nearby water and soil. It is well known that anthrax forms spores (*Bacillus anthracis* is the bacterium that causes anthrax) that can persist for decades and remain viable to cause disease, but this phenomenon may now be exacerbated by permafrost thawing.

In addition to this known, observed threat, there is growing speculation about other types of bacteria and viruses that could emerge from ice and permafrost. In 1997, researchers obtained tissue from corpses buried in permafrost in Alaska that yielded influenza RNA fragments that facilitated recreating the sequence of the 1918 influenza virus (Taubenberger et al., 2007). While that work did not retrieve live virus, a 2005 NASA study revived bacteria that had been encased in Alaskan permafrost dated to the Pleistocene epoch (~12,000-2.5 million years ago) (Pikuta et al., 2015). Another research team in 2007 took ice from Antarctic mountains, two samples that had a minimum age of 100,000 years and the other of 8 million years, and resuscitated multiple bacterial populations and postulated that lateral gene transfer could occur by extant organisms upon thawing (Bidle et al., 2017). A 2014 publication reported on two types of "giant viruses" trapped in Siberian permafrost for 30,000 years and revived in the lab (Legendre et al., 2014). Although, these viruses were infectious only to single-celled amoeba, this work did raise concerns about the survival and emergence of viruses that are infectious to humans. Such concerns are bolstered by the facts that fragments of DNA and RNA from diseases such as smallpox, bubonic plague, as well as the 1918 influenza virus have been recovered from permafrost (Theves et al., 2011, 2017; Zhang, 2006), and that many areas around the Arctic have buried human and animal remains harboring such pathogens. Looking back further in time, permafrost may harbor infectious viruses or bacteria that have been dormant for thousands or even millions of years (Houwenhuyse et al., 2018), for which local populations lack immunity and no countermeasures exist.

Given the vast and sporadic geographic distribution of these events and the lack of a robust surveillance system to identify cases in these regions, only limited numbers of studies have been published thus far. It is therefore difficult to reliably characterize the magnitude and nature of these potential risks. They may in fact be quite small compared to known risks from existing infectious agents that are prevalent at lower latitudes, however, understanding and preparing for “low-probability, high-consequence” events is one of the hallmarks of a robust public health protection strategy.

The National Academies of Sciences, Engineering, and Medicine (National Academies) in collaboration with the InterAcademy Partnership (IAP) and the European Academies Science Advisory Committee (EASAC) held a workshop in November 2019[1] to bring together researchers and public health officials from different countries and across several relevant disciplines to explore what is known, and what critical knowledge gaps remain, regarding existing and possible future risks of harmful infectious agents emerging from thawing permafrost and melting ice in the Arctic region. In total, 56 leading researchers from 15 different countries including representatives from Arctic indigenous communities were in attendance. The workshop included 11 individual talks, interspersed with 6 panels and group guided discussions, as well as 2 breakout sessions to examine case studies such as the specific case of Arctic-region anthrax outbreaks, as a known, observed risk as well as other types of human and animal microbial health risks that have been discovered in snow, ice, or permafrost environments, or that could conceivably exist. The workshop primarily addressed two sources of emerging infectious diseases in the arctic: (1) new diseases likely to emerge in the Arctic as a result of climate change (such as vector-borne diseases) and (2) ancient and endemic diseases likely to emerge in the Arctic specifically as a result of permafrost thaw. Participants also considered key research that could advance knowledge including critical tools for improving observations, and surveillance to advance understanding of these risks, and to facilitate and implement effective early warning systems. Lessons learned from efforts to address emerging or re-emerging microbial threats elsewhere in the world were also discussed.

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[1] This Proceedings of a Workshop was prepared by a workshop rapporteur as a factual summary of what occurred at the workshop. The planning committee’s role was limited to planning and convening the workshop. See the appendixes for the Statement of Task, planning committee biosketches, workshop agenda, and participant list.

Figure 1 Map illustrating the extent of circumpolar permafrost. Source: Reprinted with permission; copyright 1998, UNEP/GRID-Arendal.

Opening Remarks

Following welcoming remarks from the planning committee Chair, Diana Wall, Colorado State University; Vice Chair, Volker Ter Meulen, InterAcademy Partnership; and Henrike Hartmann, Volkswagen Foundation, a series of three keynote speakers set the stage for workshop discussions. **Dr. Vladimir Romanovsky, University of Alaska Fairbanks**, shared context-setting remarks on the history and current dynamics of permafrost. Permafrost[2] includes any earth material at or below zero degrees Celsius for two or more consecutive years. Figure 1 shows the distribution of permafrost in the northern hemisphere, mostly located in the high latitudes and high elevations. The "active layer" is the layer above permafrost that thaws and freezes on a yearly cycle. Permafrost typically ranges from very small thicknesses near zero in discontinuous

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[2] "Permafrost is a permanently frozen layer below the Earth's surface. It consists of soil, gravel, and sand, usually bound together by ice." Source: https://www.nationalgeographic.org/encyclopedia/permafrost/.

permafrost regions to more than 1,500 meters thick in parts of Siberia, and the active layer thickness typically ranges from 30 centimeters to 1.5 meters from the surface.

Permafrost is a product of cold climates and is therefore sensitive to climate change. Dr. Romanovsky noted that recent changes in climate and warming temperatures on a global scale, especially in the high latitudes, have led to increased average temperatures that can be 2-3 times larger in high latitudes than temperatures in low latitudes. Permafrost reacts to these changes and temperature increases, which in some cases, has been as high as 2-3 degrees Celsius over the past few decades. A significant event in the polar regions, permafrost thaw can potentially have severe impacts on local communities, infrastructure, and ecosystems (Richter-Menge et al., 2019; Schuur et al., 2015). Future permafrost changes can be more readily understood in the context of past permafrost change.

For the purposes of this workshop, Dr. Romanovsky pointed out that researchers are primarily interested in permafrost from the last interglacial cycle (Figure 2). Permafrost that is currently in danger of thawing includes: (1) permafrost from the previous glacial period (approximately 12,000 – 126,000 years ago), (2) permafrost that resulted from cooling after the climatic optimum about 10,000 years ago, or (3) very recently formed permafrost as a result of cooling during the Little Ice Age (14th through 19th centuries). After the maximum extent of permafrost ~20,000 - 18,000 years ago, the climate began to transition into a recent relatively warm period (the Holocene), when that ancient permafrost experienced degradation. Conditions in Eurasia were very different at that time and included a tree-less environment, with windy conditions, cold temperatures, and rapid deposition of dust material. Despite the cold temperatures, ample vegetation was available to sustain various types of animals. Permafrost from this period contains a great deal of organic material including the remnants of vegetation and buried animals. Understanding when and how this organic material thaws will be important.

By the Holocene optimum (~9,000 – 5,000 years ago), most permafrost disappeared from Europe because of warming temperatures, especially at the continental shelves due to sea level rise. Following that period, the climate cooled again, and for the past 5,000 years, new permafrost has formed, largely reflecting present-day distribution. During the Little Ice Age, new permafrost formed, usually near the southern boundary of permafrost extent. However, when permafrost degrades, the newest permafrost thaws first. After the conditions of the Little Ice Age ended, the most recently formed permafrost began to thaw or disappeared completely. Late Holocene permafrost was stable for some time, but it has also now started to thaw. This thaw is widespread and slow. Dr. Romanovsky noted that in some places, there is currently a layer of former permafrost that does not freeze at all during the winter, an important threshold identified by researchers. Gradually, parts of the upper permafrost are introduced to the active layer (which freezes in winter and thaws in summer), and are incorporated into this seasonal process. Although this transition of permafrost to the

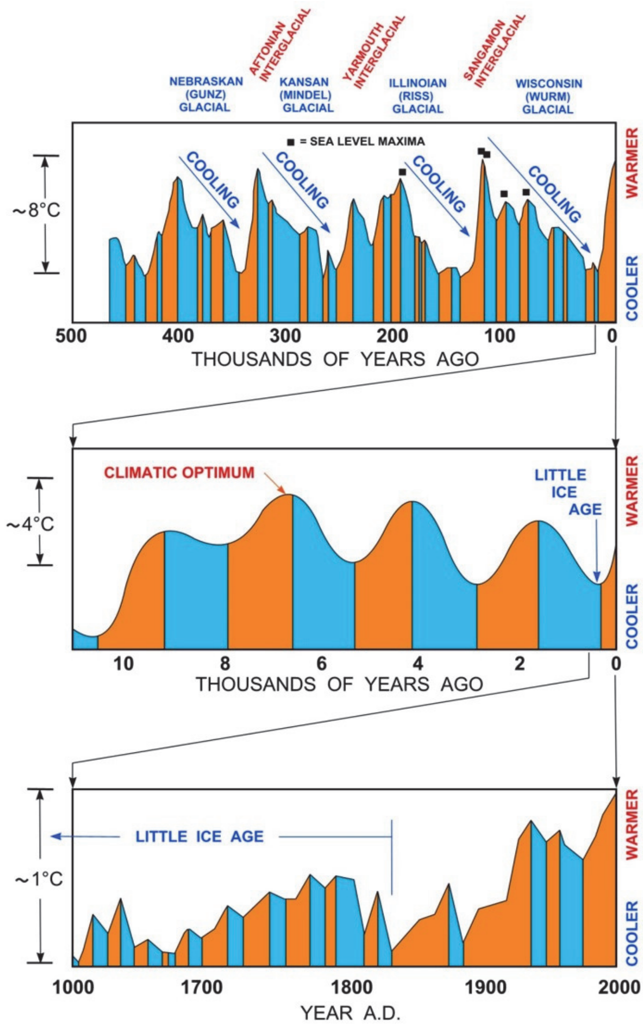

Figure 2 Timeline illustrating previous interglacial cycles. Source: Romanovsky presentation.

active layer is only on the order of a few 10s of centimeters, it is a widespread occurrence and the volume of material involved could be substantial. The changes are not linear year to year, but over the long term, there is a steady increase in the freeze/thaw depth.

Dr. Romanovsky also remarked on the importance of understanding abrupt permafrost thaw. With this type of abrupt change, he noted that the age of the permafrost is not as important as the processes on the surface, which have a greater impact. Some climatic and weather conditions can cause permafrost to thaw deep enough to melt ice and create ground subsidence (i.e., sinking or settling of the ground surface), the ground subsidence then fills with water, which causes the process to accelerate on itself. Weather conditions, forest fires, and other disturbances can trigger these conditions. Permafrost degradation under lakes, movement of thawed materials

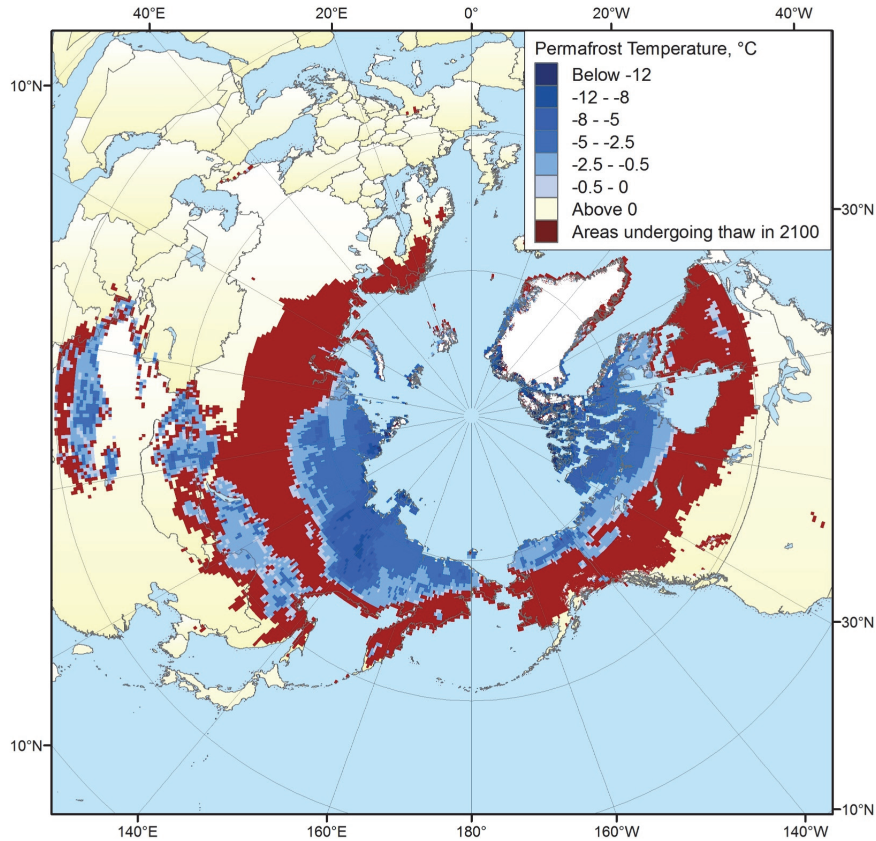

Figure 3 Permafrost temperature in the Arctic, with areas projected to thaw in 2100 shown in red. Source: Romanovsky presentation.

near riverbanks, and coastal erosion due to increasing temperatures may also contribute to abrupt thaw. These processes are local but the thaw persists and accelerates through all ages of permafrost. Questions remain regarding the significance of these two different processes (annual seasonal permafrost thaw versus abrupt events) for release of microbes or genetic material and which of these may be more likely to lead to emergence events.

Dr. Romanovsky concluded his remarks noting that ongoing modeling efforts project continued climatic warming. Even assuming relatively moderate warming, late Holocene permafrost and permafrost from the last glaciation will continue to thaw by mid-century. By the end of the century, about 60 percent of permafrost will be in the process of thawing. With higher climate warming scenarios, about 75 percent of the north slope of Alaska permafrost will be thawing by the end of the century (Figure 3).

Dr. Albert Osterhaus, University of Veterinary Medicine Hannover, discussed emerging infectious and zoonotic diseases in the context of environmental change. In past decades, there have been several viruses and zoonoses at the origin of major human disease outbreaks. The concept of "one health"[3] encompasses human and animal diseases as well as the environment and the interactions between them. Approximately 75 percent of new human infectious diseases actually come from animals (Gebreyes et al., 2014). Transmission of obligate zoonoses (such as Trichinella) requires animals and can be acquired from eating meat of infected animals. On the other hand, it is possible for humans to directly acquire facultative zoonoses (such as influenza) from animals, but they are far more likely to acquire it from another human. Historical zoonoses (like HIV) originated as a cross-over of a simian virus, but are now maintained completely by human-human transmission. Following smallpox eradication and the subsequent cessation of smallpox vaccinations, there have been cases of new animal poxvirus crossing species barriers and causing infections in humans. Because vaccinations are no longer needed against smallpox, there may be a possibility, with the thawing of permafrost, that some human or animal carcasses will pose a smallpox or other disease threat to humans, he concluded.

Dr. Osterhaus pointed out that higher ambient temperatures in the Arctic could result in increased foodborne diseases, waterborne infections in humans, and changes in the migratory pathways of animal host populations and their contacts including changing rodent and fox populations, as well as the northern range of vectorborne diseases (Parkinson and Butler, 2005). For example, a 2005 study showed that an outbreak of *Vibro parahaemolyticus* (which causes gastrointestinal illnesses in humans) occurred in farmed Alaskan oysters when the temperature of the seawater rose above 15 degrees Celsius (McLaughlin et al., 2005; Figure 4).

Other examples shared by Dr. Osterhaus include tick-borne encephalitis in Europe and Asia, primarily located in the "tick belt" that stretches across the continent. The width of the belt and the extent of viral disease spread by vector distribution is largely determined by the climate. When the climate warms, as is occurring today, the belt widens and extends disease spread into areas that have traditionally not been affected. West Nile Virus (transmitted to horses and humans by mosquitos and carried by birds), was first discovered in the U.S. in 1999 after being introduced by air travel of infected humans, and is spreading across the entire U.S., causing the death of a few hundred people every year. Importantly, the survival of the mosquitos that transmit this disease is dependent on the climate. As temperature warms, the distribution of these mosquitos has increased to parts of Canada and the Arctic (Figure 5). As noted earlier, animal populations are changing and modeling shows that this will likely continue, due in part to habitat change. As another example, some modeling studies show that Arctic fox populations are changing and that climate change will have an effect on cases of rabies in the Arctic (Huettmann et al., 2017).

[3] "One Health is a collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants, and their shared environment." Source: https://www.cdc.gov/onehealth/index.html. See also Roger et al., 2016.

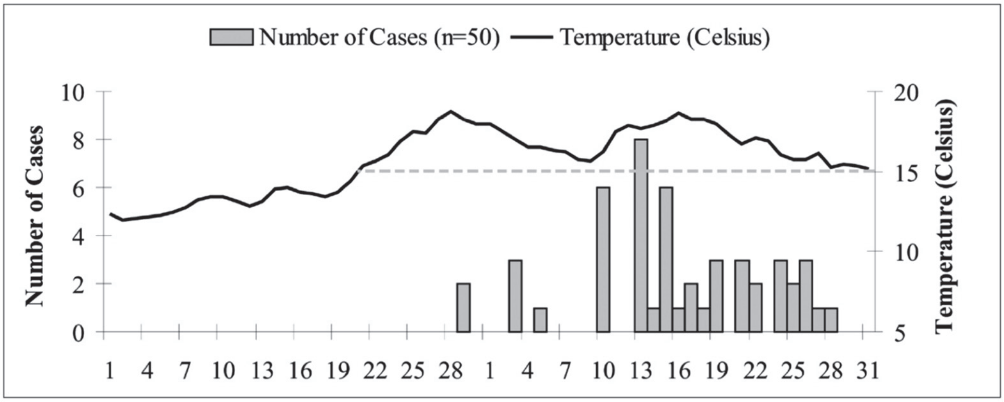

Figure 4 An outbreak of *Vibrio parahaemolyticus* associated illness following consumption of farmed oysters occurred in Alaska in 2004, when the seawater temperature exceeded 15 degrees Celsius. The figure shows the number of cases, by date of harvest of consumed oysters, and farm sea water temperature by date. Source: McLaughlin et al., 2005. Source: Reprinted with permission; copyright 2005, Massachusetts Medical Society.

New molecular techniques and technologies enable the identification of viral pathogens more effectively than previous methods of isolating viruses. Many of the viruses detected in the past few decades have some connection to changing climate and changing conditions. Dr. Osterhaus discussed an example of the changing migratory patterns of harp seals and the associated spread of Morbilliviruses, which have been detected crossing species barriers (e.g., Jo et al., 2018, 2019). Full-length sequencing of viruses can be obtained much more quickly now than in the past, and combined with phylogenetic trees, the origins of a virus can be detected. This is a powerful tool to trace where viruses originate and how they cross species barriers (e.g., Jo et al., 2018, 2019).

Using new data and sequencing, analyses can be used to detect, for example, the origin and emergence of ancient hepatitis B viruses (Muhlemann et al., 2018). Material from corpses was used to detect fragments of DNA from thousands of years ago. The key unknown is how long the viruses can actually survive in the permafrost. It is known, for instance, that poxviruses and anthrax can survive for quite a long time, on the order of hundreds of years, but the possibility of finding whole genomes is unknown.

Migratory birds are infected with Influenza A viruses in a subclinical way, and can directly transmit viruses to other species including humans. In fact, it was not considered possible for birds to spread avian viruses to humans until the late 1990s when confirmed human cases were discovered in Hong Kong. Focusing specifically on H5N1, Dr. Osterhaus demonstrated that it has mutated and spread throughout South East Asia, Europe, and Africa. Although the disease is fatal in tufted ducks (and to some extent, pochards), it appears not to be fatal for some wild duck species, particularly mallards (Keawcharoen et al., 2008). These species are capable of surviving and spreading the disease, and their migratory patterns may potentially shift due to climate

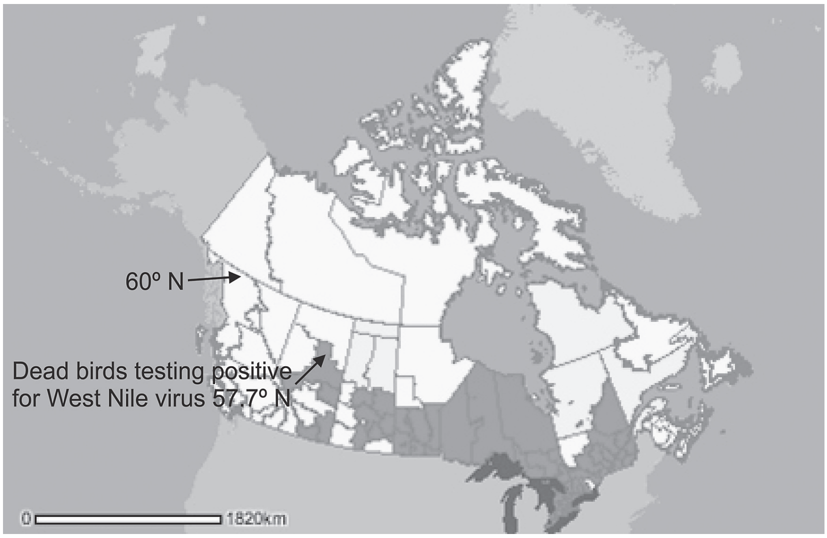

Figure 5 Figure shows dead birds submitted and tested for West Nile Virus, transmitted by mosquitos, in 2004. Migratory birds are responsible for its spread to other regions. Mosquito species known to transmit West Nile virus are now found in the Arctic. Gray shaded areas indicate the spread of the virus in birds. Source: Parkinson and Butler, 2005; Public Health Agency of Canada.

change. This has implications for the spread of this disease beyond known areas (Verhagen et al., 2015). Most of the H5N1 outbreaks in European wild birds were concentrated in areas of open water, where surface temperatures were above freezing (Reperant et al., 2010).

Dr. Osterhaus also explored the factors that make a pandemic virus. An experiment of passing a virus over the upper respiratory tract of ferrets showed that only five mutations were needed to change from a virus that does not efficiently spread, into a virus that can be easily spread (Herfst et al., 2012; Linster et al., 2014; Munster et al., 2009; Russel et al., 2012). Although this type of lab experimentation can be controversial, a similar phenomenon was detected in nature where a virus (H10N7) spilled over from ducks to seals. The original virus was purely avian, but it changed over time to a virus that spread from seal to seal (Bodewes et al., 2016).

At the conclusion of his talk, Dr. Osterhaus noted that a mix of unprecedented and complex anthropogenic (or human-driven) changes are drivers of infectious disease emergence in animals and humans. This implies that several diseases that could not spread in the past can spread today. Potential reversal or mitigating options for these changes may be topics of interest to the scientific community, and preparedness could be based on increased capabilities in terms of syndromic surveillance in humans and animals, pathogen discovery, development of diagnostics, improved animal and mathematical modeling capacity, and platforms for pathogenesis study, preventive intervention, and therapeutics.

Dr. Keith Chaulk, Stantec shared views on increasing atmospheric and oceanic temperatures in the Arctic and the connections to the people living in the region. Many indigenous communities live in the Arctic (Figure 6), with the Arctic Council estimating approximately a half million people live in these regions.[4] These Northern peoples are experiencing many rapid changes including:

- permafrost thaw, which negatively affects physical infrastructure;
- increasing rates of wildfires, which contribute to areas of poor soil and loss of critical habitat;
- changes to wildlife populations and animal distributions that may introduce new disease vectors; and
- altered freeze/thaw timing and changing ice patterns on both sea and land with effects on travel routes, safety, and access to local foods.

These types of environmental change can have negative effects on traditional land-based practices, cultural practices, and community health in general. Because northern areas lack significant agriculture, local food harvests of fish, caribou, and seals provide key sources of nutrients. However, there are issues associated with food security in the North related to poor-quality store-bought foods, limited choices, and high food prices.

Dr. Chaulk also covered the intersection of (and similarities between) traditional knowledge and science knowledge. He highlighted the key principles of traditional knowledge, as adopted by the Indigenous Peoples Secretariat[5]: traditional knowledge is (1) “a systematic way of thinking … applied to phenomena across biological, physical, cultural, and linguistic systems”; and (2) “a body of knowledge generated through cultural practices and lived experiences” … “developed and verified over millennia”. He emphasized that traditional knowledge can help further understanding of nature, through various forms of record keeping as well as a broad range of scientific undertakings that are diverse in terms of their scope, focus, and research practices. Both traditional knowledge and scientific understanding accumulate over time. Although both knowledge systems are imperfect, they are still reliable and repeatable and can be used to inform decision-making. They are also both self-correcting; traditional knowledge is highly adaptable and scientific understanding advances over time as paradigms shifts and models are improved and replaced. Knowledge transfer is another key element of both knowledge systems. Dr. Chaulk noted that teaching and learning, as well as oral communication, are fundamental to both systems. Both have experts, who are supported by third party endorsement through peer reviewers and community members.

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[4] See https://arctic-council.org/en/about/permanent-participants/.

[5] The Indigenous Peoples' Secretariat assists in creating opportunities for Arctic Council Permanent Participants to present their causes, support the provision of necessary information and materials, and communicate information about their work. Source: https://www.arcticpeoples.com/.

Figure 6 Map illustrating the indigenous communities located throughout the Arctic. Source: Arctic Human Development Report, 2004 and the Norwegian Polar Institute. Source: Reprinted with permission; copyright 2010, UNEP/GRID-Arendal.

Dr. Chaulk provided three examples of indigenous knowledge related to microbes. In the first example, he illustrated the process through which Southern Labrador Inuit place sealskins in bogs in the spring to allow microbes to remove the hair from the pelts. It is possible that changing temperatures could affect bog functioning. A second example demonstrates the importance of frost timing on the picking and gathering of *Vaccinium vitis idaea* (Lingonberry). Community elders do not allow this berry to be picked until after the first frost. The fruit ripens at this time and allows a fruit worm to emerge. Longer frost-free periods could have implications for this process. Finally, he discussed an infection called "seal finger" that is caused by bites and contact with seal products. It causes inflammation and can lead to an unusable finger, and the prevalence of this infection may be related to warming waters in the North. To improve scientific understanding of these examples and other emerging issues, there are many benefits to working with indigenous partners. It can help reduce program costs and develop capacity for long term monitoring. Scientists may also be able to leave a legacy of training and education as well as gaining insights into ecosystem and microbial processes, Dr. Chaulk concluded.

Session 1: What Do We Know?

During this workshop session, speakers and participants were asked to consider the information that is already known about the pace of permafrost thaw and where it is most prevalent, what can be expected to emerge from the thawed permafrost (e.g., animals, corpses, ancient pathogens), and the existing research efforts to help determine threats. Speakers shared information about the microbial ecology of permafrost and ice environments and their sensitivity to climatic changes as well as the viability of microorganisms in these environments.

Viruses in Permafrost

Dr. Jean-Michel Claverie, Aix-Marseille University & CNRS Mediterranean Institute of Microbiology, provided insights on viruses in permafrost. Dr. Claverie reemphasized that 24 percent of the northern hemisphere contains permafrost and most of this is very old and contains ancient frozen materials. The Arctic is warming faster than the rest of the world and leads to widespread permafrost thaw (Tollefson, 2017). This thaw may lead to additional natural consequences such as extremely large holes in the ground where soil is sinking and may even trigger spontaneous explosions.[1] Dr. Claverie also pointed out that warmer temperatures and open shipping lanes have made large industrial ventures and resource mining viable in the Arctic region, which further disrupts permafrost and associated bacteria and microbes.

Dr. Claverie discussed the potential for permafrost thaw and changes to the active layer to enable the return of anthrax outbreaks, traces of smallpox virus, and other pathogens from people and materials buried in the permafrost (Theves et al., 2014). One example is the regeneration of 30,000-year-old plants that were buried in Siberian permafrost (Yashina et al., 2012). Given that plants can be revived from the permafrost, Dr. Claverie challenged participants to consider if viruses could be revived as well. He discussed work at the Stanchikovsky Yar exposure in Chersky, Russia and the ancient permafrost that is exposed and can be accessed without digging through more recent materials. In sampling this material, it can be tested for acanthamoeba-killing viruses through a process that subjects the sample to antibiotic-adapted acanthamoeba cultures, seeks cell lysis (or breakdown of the cell), isolates the agent, and characterizes the infectious cycle, genomics, transcriptomics, and proteomics. These viruses can survive over long time periods in permafrost. Two new, previously unknown viruses were isolated from a single sample from this process (Legendre et al., 2014, 2015).

Dr. Claverie highlighted another example where a research team was given access to a skin and hair sample from frozen mammoth remains recovered from the Yana Rhinoceros Horn Site, Siberia (Pitulko et al., 2004). The sample revealed four new

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[1] See for example: https://www.nature.com/news/mysterious-siberian-crater-attributed-to-methane-1.15649.

viruses: (1) ancient Megavirus, (2) ancient Pandoravirus, (3) ancient Pithovirus, and (4) Asfar-like virus. Another example involving metagenomic[2] sequencing of cores from the Yakutia region, revealed a large diversity of bacteria as well as β-lactamas genes, a potential threat related to bacterial resistance to antibiotics. These genes could potentially be transmitted to modern bacteria as a new way of resisting antibiotics. Most of the viruses detected were already known and expected, but other viruses, less well known and in smaller quantities, were detected as well. A final example shared by Dr. Claverie illustrates the new, viable viruses discovered from Kolyma river exposures and thawing permafrost in the region near Duvanny Yar and Chersky, in addition to three new viruses discovered from the Lena river, one new virus from the thawed material, and four new viruses from the Pleistocene (or >11,700 years ago). He noted that these discoveries provide independent confirmation that some DNA viruses can remain infectious since the end of the last glacial period.

A key issue that arises from the types of discoveries shared by Dr. Claverie is the need to ensure that the samples (and associated data) are not contaminated by modern materials. Understanding the possibility of a real threat from pathogens in permafrost is crucial, especially when the topic receives a great deal of media attention. Confirmation of the results can be achieved through different sample sites, sample types, and investigation methods. Dr. Claverie concluded his remarks by emphasizing that hazards from thawing permafrost depend on the presence, viability, and resilience of known and unknown viruses pathogenic for humans, animals, and plants. However, exposure will grow due to increased human presence in the warming Arctic and potentially through increased permafrost disruption. Therefore, it could be useful for large-scale Arctic industrial projects to include on-site medical surveillance as well as on-site quarantine or isolation facilities and protocols. He also suggested that research on pathogenic permafrost microbes including protozoa is important to move forward, yet it can be extremely difficult to export potentially infectious samples out of the region. This highlights the importance of international research partnerships.

2016 Anthrax Outbreak

A deeper look at the 2016 anthrax outbreak in the Yamal peninsula was provided by **Dr. Alexander Volkovitskiy, Russian Academy of Sciences and Yamal Expedition**. The peninsula is the site for several gas extraction facilities, including sites at Bovanenkovo and Sabetta, but it is also the world's largest center of reindeer pastoralism. This is the traditional way of life for the indigenous people of Yamal. The Nenets tundra nomads work to preserve their traditional practices and the model of family migration through a synthesis of traditions and modern innovations. Approximately 6000 people live in the tundra and depend on fishing and reindeer

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[2] "Metagenomics is the study of a collection of genetic material (genomes) from a mixed community of organisms. Metagenomics usually refers to the study of microbial communities." Source: https://www.genome.gov/genetics-glossary/Metagenomics.

Figure 7 Schematic illustrating reindeer herding and industrial infrastructure in Yamal. Source: Degteva and Nellemann, 2013.

herding. They graze roughly 300,000 reindeer, about 90 percent of which are privately owned, and the other 10 percent are municipal property. Estimates of the actual number of reindeer and migration patterns are made because accurate accounting of reindeer data and tracking does not exist. As noted, these traditional practices occur within the context of intensive industrial development (Figure 7; Degteva and Nellemann, 2013).

Three groups of reindeer herders are divided into southern, middle, and northern zones, excluding the northern most part of Yamal. Dr. Volkovitskiy provided historical background and noted that the first recorded suspected outbreak of anthrax in the Urals region was discovered in 1848 and led to the total loss of reindeer herds in the region. Indigenous community members consumed the reindeer and became sick as well. Another suspected outbreak was recorded in 1876, closer to the Yamal region, and in 1911, anthrax officially reached the Yamal peninsula. This was the first attempt by regional officials to identify the disease. Since then, there have been several documented cases of anthrax outbreaks. Vaccination campaigns were established in 1930 and the last case of officially recorded anthrax in Yamal was reported in 1941. By the 1960s, 82.5 percent of potentially receptive reindeer were vaccinated and thus mass vaccination was stopped in 2007. However, many parts of the migration routes and reindeer herding corridors pass directly through the known anthrax areas of the past. In the summer of 2016, the air temperature and the dynamics of temperature in the soil, combined with the lack of mass vaccination, allowed anthrax to emerge. Temperatures in July are most often studied, but it is important to note that the temperatures in June, as well as July, are key for understanding the processes of active layer thawing and potential release of anthrax.

Dr. Volkovitskiy noted that 2,649 reindeer perished and 36 cases of anthrax were diagnosed in people because of the 2016 anthrax outbreak. Since then, mass vaccination has resumed and discussions are ongoing with respect to the conditions of pastures and the problem of overgrazing. According to Dr. Volkovitskiy, there is unsupported blame placed on the indigenous people in the region for the anthrax outbreak coupled with resistance within the herding community to vaccinate themselves and the reindeer.

Panel on Ecosystem Changes and Microbial Threats in the Environment

Dr. Birgitta Evengård, Umeå University, moderated a panel discussion on ecosystem changes and microbial threats that are known in the environment. The first speaker, **Dr. Thomas A. Douglas, of the U.S. Army Cold Regions Research and Engineering Laboratory**, provided additional information about permafrost and illustrated an example research site in Utqiaġvik, Alaska where the seasonally thawed "active layer" can be rich in peat. He noted there may be a potential role of peat carbon in the biological systems of interest to the workshop. In areas of mixed forest where disturbances can occur, or wetlands where water has a near constant presence, the depth of the active layer increases, providing some protection against thaw (Douglas et al., 2020). Dr. Douglas also highlighted the dynamic nature of the "transition zone" between the active layer and the frozen permafrost below, which may be of particular interest to those researching emerging materials from the permafrost (Figure 8). This zone changes throughout the seasonal cycles of freeze and thaw and may contribute to changing soil conditions, microbes, or biogeochemical processes. As noted earlier in the

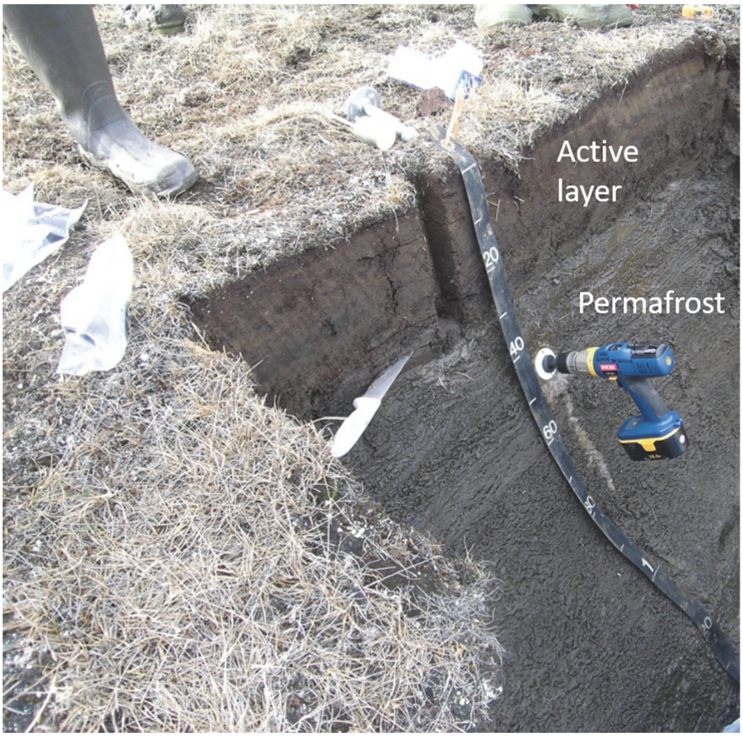

Figure 8 This image illustrates the active layer, which thaws yearly, the frozen permafrost below, and the transition zone in between. Source: Douglas presentation.

workshop, rapid thermokarst[3] landscape events can happen on the order of days to weeks and often involve water and slumps or cavities in the ground. He also highlighted ongoing and potential future work at the Permafrost Tunnel facility in Fairbanks, AK.

The second panelist, **Dr. Emily Jenkins, University of Saskatchewan**, discussed microbial threats at the interface of humans, animals, and the Arctic environment. She approached her remarks through the context of microbial risk assessment, including hazard identification, hazard characterization (or pathogenicity), exposure assessment, and risk characterization. Risk management and communication are also important, as is the inclusion of indigenous communities in associated research efforts. Dr. Jenkins provided several examples of known zoonoses in the Arctic, including the emerging prions pathogen that has only been recognized in recent years. Challenges in terms of hazard identification include gaps in surveillance, especially of wildlife, that limit the ability to determine which pathogens are circulating; lack of information about which pathogens have been there in the past; the yearly reintroduction of seasonal migratory wildlife; and other dynamics that contribute to these difficulties. Dr. Jenkins highlighted zoonoses that are particularly likely to survive for years in this environment: spore-

[3] Thermokarst refers to the process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ice. Source: https://nsidc.org/cryosphere/glossary/term/thermokarst.

forming bacteria, Mycobacterium species, protozoan cysts/oocysts, some helminth eggs, prions, non-enveloped viruses, and pox viruses. On the other hand, many types of vectorborne disease pathogens are not resistant to the Arctic environment and are unlikely to survive for long periods of time in these regions. Similarly, obligate intracellular pathogens and many viruses are dependent on host cell infrastructure and may not be resistant to this environment.

In the Canadian Arctic, bison are a source of anthrax, *Mycobacterium bovis*, and *Brucella abortus*, introduced by domestic livestock and now established in wild populations. In Saskatchewan, chronic wasting disease-infected deer are located at the fringes of the boreal caribou habitat (Figure 9), and this can be a serious challenge from a food security perspective for subsistence populations. Another example is a parasite,

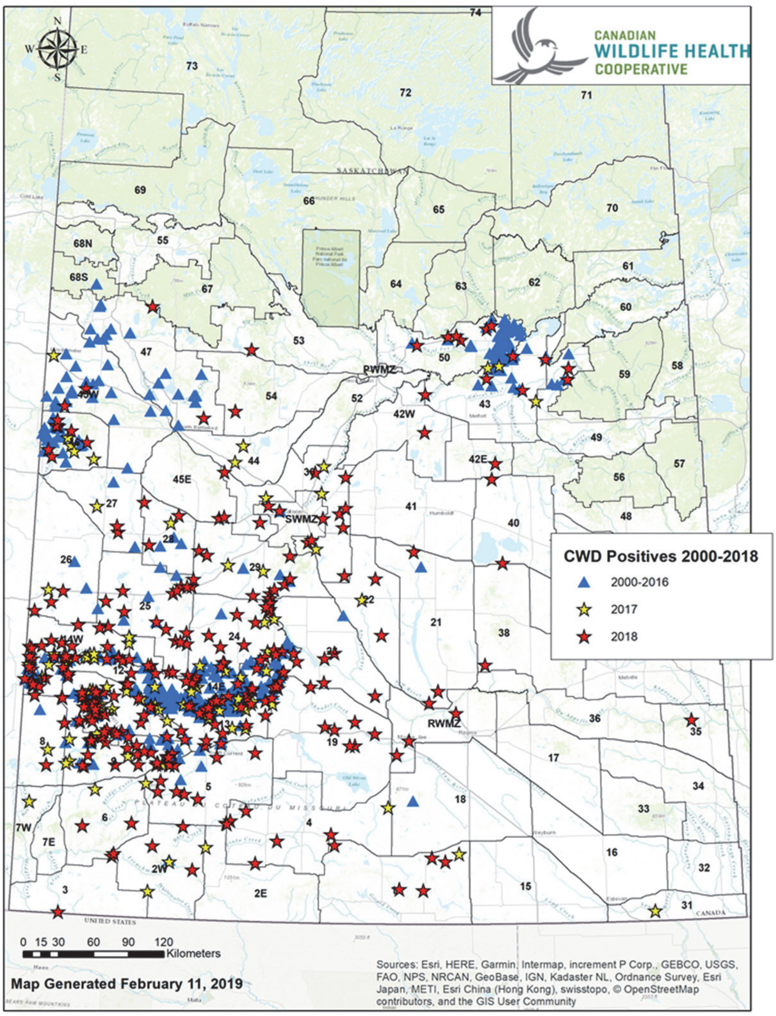

Figure 9 Map illustrating the locations of chronic wasting disease positives in Saskatchewan. Source: Image courtesy Canadian Wildlife Health Cooperative W/N.

Echinococcus, of Arctic fox that can survive for years in cold environments of the north. Dr. Jenkins highlighted the need to understand actual microhabitat conditions, the probability of survival (including environmental stages and stages inside the carcasses), and the probability of transmission (including host specificity, transmission routes, and minimum infectious doses). She noted that gaps in exposure assessment include short time spans in empirical studies, lack of information on how to preserve microbes, and differences between the freeze tolerances of Arctic-adapted strains compared to temperate and lab strains.

The final panel speaker, **Dr. Aleksandr Sokolov, Russian Academy of Sciences**, discussed terrestrial ecosystems specifically in Yamal. He highlighted three major drivers of change in the Arctic including climate change, industrial development, and herbivory grazing, all of which are occurring in Yamal. In addition, studies in Yamal allow for research into all three of these drivers in different types of geography or subzones of tundra. Logistically, it can be easier to travel to remote areas of Yamal due to the presence of a railway system and an airport, resources that are not common in other high latitude regions. Ongoing support for research stations allows for the collection of long-term data and the study of biodiversity and abundance of birds, mammals, fish, plants, and other organisms. Another key aspect of scientific research in this region involves the local communities, and he stressed the importance of interacting with the people in meaningful and robust ways to ensure true involvement in the work happening there.

Dr. Sokolov discussed the liquefied natural gas project in Sabetta above the Arctic Circle and highlighted it as an example of the logistical challenges associated with bringing thousands of people into the area. A study of the rodent and fox abundance in the area showed significant changes year to year, including a drop in both populations in 2016, followed by a rebound of the foxes but not the rodents (Figure 10). This could be related to human interventions such as providing food for the foxes, but the key

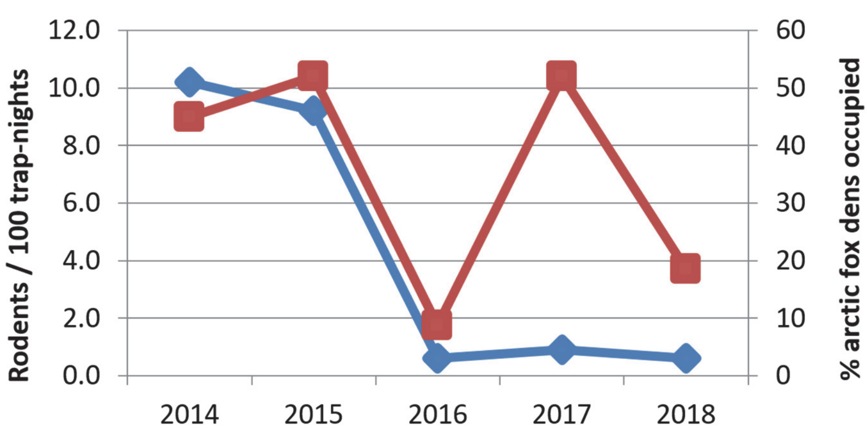

Figure 10 This graphic illustrates rodent and fox abundances and changes over time. The red line indicates arctic foxes and the blue line represents rodents. Source: Sokolov presentation.

message is that there will be associated changes throughout the ecosystem. He also illustrated the scale of migration patterns of birds that originate in Yamal and the global reach that these migrations can have. As additional examples, he highlighted the increased northern range of the Gyrfalcon, assisted by human-built railroad infrastructure where this species has increasingly built their nests. Also, increased numbers of walrus observed in Yamal, where they were seldom seen before, means increasing changes to the ecosystem.

Environmental and Climatic Determinants of Infectious Disease

Exposures to a number of climate change-related events (e.g., severe weather, air pollution, water contamination, changes in vector ecology, environmental degradation, rising sea levels, food supply and safety, and others) can lead to selected health risks (Semenza and Ebi, 2019). **Dr. Jan Semenza, European Centre for Disease Prevention and Control (ECDC)**, outlined the climate impacts on two infectious diseases, Chikungunya and Dengue. Europe has experienced increased outbreaks of these tropical diseases in the past decade (Lillepold et al., 2019), and researchers have begun to explore any potential links between climate change and the emergence or recurrence of these diseases. In looking at the climatic suitability for these outbreaks, the vectoral capacity (or the temperature-dependent climatic suitability) for transmission has increased in Europe since the 1970s, and the countries of the European Union may be considered a "hot spot" for the emergence of communicable disease (Suk and Semenza, 2011). Given this context, Dr. Semenza posed a number of questions: Is there a cause and effect relationship between the climatic suitability and the reoccurrence of the epidemics in Europe? What are the infectious disease threat events in Europe? What are the underlying drivers, determinants, and risk factors for these epidemic events? Is it possible to monitor upstream drivers of epidemics throughout Europe to potentially intervene in epidemic events and prevent them from happening? Can epidemic events that occur on a regular basis be predicted? Although it is extremely challenging to predict highly unlikely but catastrophic "black swan" events (e.g., HIV, SARS, MERS, etc.), perhaps improved monitoring of epidemic events will allow for more accurate prediction.

A "foresight study" outlined by Dr. Semenza attempted to anticipate future threats of infectious diseases in Europe (Suk and Semenza, 2011). This involves consideration of changes in disease drivers, which requires a systems perspective. Interactions between underlying drivers can be examined in the context of potential scenarios and subsequently into the development of public health actions to intervene against the public health threats. The study identified three main categories of drivers of epidemic events in Europe: globalization and environmental change, social and demographic change, and public health systems. Each of these categories contains sub-drivers (e.g., the globalization and environmental change categories contains sub-drivers such as climate change, travel and tourism, migration, and global trade). The drivers and sub-drivers interact, combine, and therefore precipitate specific scenarios such as shifts in the transmission patterns of vector-borne diseases, drug-resistant bacteria, sexually transmitted infections, food-borne infections, resurgence of vaccine-preventable diseases, and more. Public health experts can help prepare for these potential scenarios and other potentially serious public health events.

In an attempt to quantify this information, a validation study was undertaken to explore epidemic intelligence data collected by the ECDC through global event monitoring that could potentially pose a threat to Europe. Dr. Semenza noted that each day, a roundtable meeting in ECDC's Emergency Operations Centre assesses threats, official alerts, and epidemic intelligence from around the EU and the world. As part of the quantification study, threat data and information on drivers between July 2008 and December 2013 were derived from ECDC databases and reports including a Threat Tracking Tool, Communicable Disease Threat Report, Threat Assessment, and Rapid Risk Assessment as well as mission reports, scientific articles, and expert consultation (Semenza et al., 2016). A database of events with the associated determinants was

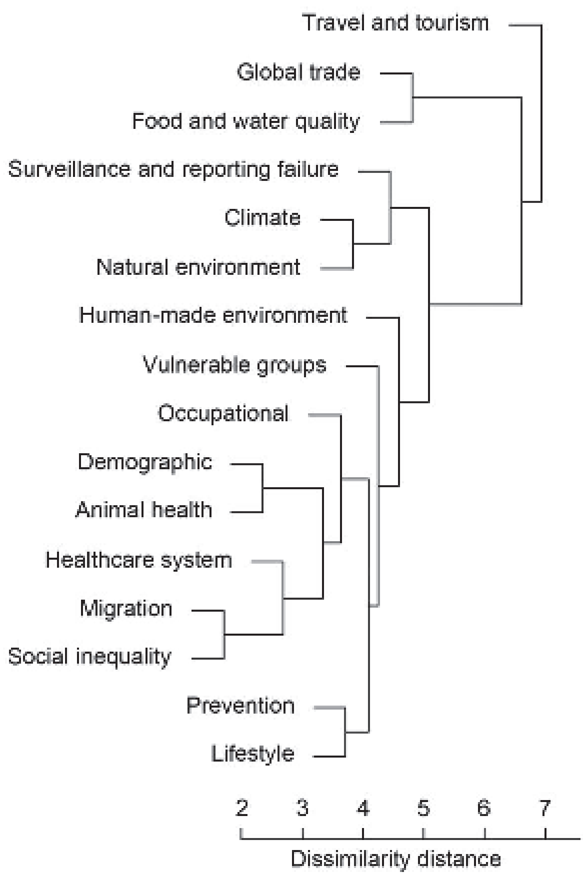

Figure 11 Cluster dendrogram from hierarchical cluster analysis of drivers of infectious disease threat events. This illustrates that travel and tourism are the most important drivers of these events in Europe. Source: Semenza et al., 2016.

developed. A minority of these events are caused by one single driver; interactions between drivers causes the majority of events. For each disease category, the drivers can be identified and then pooled into one analysis to create a cluster dendrogram that shows how multiple drivers contribute to epidemic events. For example, climate and the natural environment drivers tend to cluster together to contribute to an epidemic event. Importantly, travel and tourism are the most significant and frequent drivers of epidemic events in Europe (Figure 11).

Restricting tourism and travel is not considered a viable option to reduce the occurrence of infectious disease events in the long-run. However, Dr. Semenza noted that the relationship between diseases, like Chikungunya and Dengue, and climatic suitability could be examined together with air passenger volume for disease active areas worldwide; air passenger volume plays a key role in the occurrence of these epidemics. In 2017, there was an outbreak of Chikungunya in France and Italy. Information on global air passenger volume was used to analyze risk zones, assess importation risk and transmission potential, as well as track the local spread using unidirectional mobility of geo-located, repeated Twitter feeds (Rocklöv et al., 2019). This analysis shows that there are specific areas within Europe that are of greater concern in terms of risk of importation, including areas where the vector is present and could transmit the virus. Further, adding the climatic suitability, the risk is higher in July and August compared to other parts of the year. Combining the climatic suitability with data derived from Twitter (mobility proximity estimates) can help determine short-distance mobility and the connections between specific risk areas with the associated spread of disease (Rocklöv et al., 2019). By focusing surveillance and control strategies in high-risk areas, this information can be part of public health practices to intervene.

Dr. Semenza also considered the contribution of climate change impacts on infectious disease burden in Europe. A study ranked infectious diseases by the strength of their link to climate change as well as the potential severity of consequence to society (Lindgren et al., 2012). This weighted risk analysis revealed that some of the diseases of greatest concern did not have surveillance systems to monitor the potential pathogens. Since the study was published, some monitoring systems have been put into place, but there are still infectious diseases that are not being monitored. An improved monitoring system could take advantage of the strong climatic links established and institute monitoring mechanisms further "upstream" in the process (i.e., before the types of surveillance that are typically done for health outcomes and after direct and indirect exposures have taken place) (Semenza et al., 2015). Dr. Semenza noted that the ECDC developed the European Environment and Epidemiology Network that aims to anticipate epidemics using a climatic or environment signal to initiate active surveillance that will help to identify the first case, initiate response activities, and therefore minimize the disease burden and public health impact (Semeza and Menne, 2009). As an example, Dr. Semenza illustrated the Baltic Sea as a suitable environment for *Vibrio* species, especially given increasingly warm water temperatures and low salinity (Levy, 2015). Severe health outcomes are seen in years with heat waves, due to increased exposure to these bacteria. Early warning systems at ECDC use in situ and climatological data, remote sensing data, and models to forecast environmental suitability for *vibrio* growth and high-risk areas (Semenza et al., 2017). Given currently estimated climate change scenarios, this analysis predicts that cases of *vibrio* will increase in the Baltic region and further north into the Arctic as well.

At the conclusion of his remarks, Dr. Semenza noted that international health regulations set forth by the World Health Organization illustrate capacity in member states to advance surveillance, response, and preparedness measures for health security. Analyzing the relationship between public health capacities against infectious disease threats in Europe shows the ability of countries to respond to cross-border threat events. For example, a 10 percent increase in public health core capacities is associated with a 20 percent decrease in disease threat events (Semenza et al., 2019), and this helps to validate efforts and investments to advance public health core capacities in Europe. Returning to the earlier discussion of drivers, Dr. Semenza noted that global environmental change contributes to 61 percent of infectious disease threat events (Semenza et al., 2016), illustrating the complexity of the actual disease scenarios.

Panel on the Potential Risk of Human and Animal Exposure to Threats

Dr. Charles Haas, Drexel University, facilitated panel remarks on potential risks associated with human and animal exposure to threats. During the panel discussion, **Dr. Natalia Pshenichnaya, Central Research Institute of Epidemiology, Moscow, Russia**, noted that climate change and associated increasing air and water temperature trends are taking place throughout Russia and the circumpolar Arctic region. Permafrost thaw and degradation poses risks to human health, transportation interruptions, difficulty in accessing health care, insulation, destruction of infrastructure, and crucial for this workshop, an increased risk of anthrax (Belousov et al., 2018). There is also an increased risk of release of dangerous known microorganisms (e.g., Influenza H1N1 and anthrax) from graves. Some studies have shown that viable prokaryotic and eukaryotic microorganisms can persist in permafrost from several thousand to three million years. Examples of microorganisms isolated from permafrost include aerobes (Vorobyova et al., 1997; Zvyagintsev et al., 1985); anaerobes (Rivkina, 2007); green and blue-green microalgae (Vorobyova et al., 1997); yeast (Faizutdinova et al., 2005); mycelial fungi (Kochkina et al., 2001); and viable cysts of free-living protozoa (Shatilovich et al., 2010). Some of these may be resistant to natural antibiotics, and the released bacteria can produce carbon dioxide, methane, and other gases that may lead to additional climate warming. Dr. Pshenichnaya outlined a number of infectious diseases that are climate-dependent and are of concern in the Arctic; she used examples of tick-borne encephalitis, *Ae. albopictus*, and Dirofilariasis in Russia to illustrate current and expected expansion of disease threat to the Arctic region. In the *Ixodes ricinus* (tick) example, expanded habitat changes are estimated in relation to climate warming scenarios (Figure 12; Popov, 2016), especially in the Arkhangelsk region (Balaeva et al., 2012).

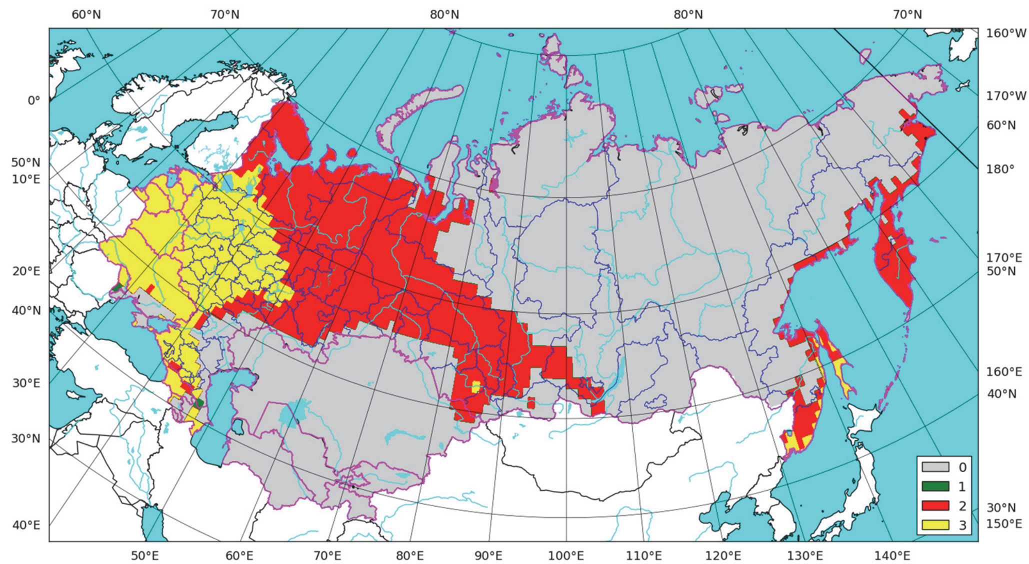

Figure 12 Expected changes in the climatic habitat of *Ixodes ricinus* in the territory of Russia and neighboring countries by the period 2080-2099 compared to 1981-2000. This work uses multimodel climate in the extreme scenario Representative Concentration Pathways (RCP) 8. 5, defined by the IPCC as "one high pathway for which radiative forcing reaches greater than 8.5 W m-2 by 2100 and continues to rise for some amount of time." Color Legend: 0 (gray) indicates that *Ixodes ricinus* will be out of habitat, 1 (green) indicates a reduction in the habitat, 2 (red) indicates expansion of the habitat, and 3 (yellow) indicates common habitat for both periods. Source: Popov, 2016. Reprinted with permission; copyright 2016, Igor O. Popov.

Dr. Pshenichnaya closed her remarks by noting that several other factors influence infectious diseases in the Arctic. These include the occurrence and expansion of ozone holes, increased air pollution, the emergence of new species of flora, increasing duration of high temperatures, and the increasing number of heat waves. These factors could lead to additional impacts such as increased allergies, reduction of innate immunity, and stress that may increase susceptibility to infectious diseases of the respiratory tract. She suggested that adaptation measures, mitigation of climate change,monitoring and prognosis of infectious threats, and preventive measures for Northern populations may be needed.

Dr. Anne Jensen, University of Alaska Fairbanks, noted that there are sites throughout the Arctic where large numbers of people with infectious diseases have been buried, including some relatively recent gravesites. Very few people know where these, often nonobvious, mass graves are located. When these graves are being excavated by archeologists, precautions are taken, but are usually intended to keep the researchers DNA off the buried remains rather than to protect the researcher from infectious disease. Dr. Jensen remarked that other (non-burial) excavation sites might not prompt the same level of precaution, because the contents of the soil are largely unknown. For example, excavation of a site from the 1940s revealed a mummified ring seal containing domoic acid (a neurotoxin associated with harmful algal blooms) in its intestines, which extended the known existence of harmful algal blooms back in time. During this study, one of the researchers contracted an infection that responded to antibiotics. This highlights gaps in our current diagnostics and surveillance and raises the question of protection against infectious disease at these sites. This is also an example that illustrates how a One Health approach may be warranted, where medical experts, animal health experts, social scientists, and community based researchers would likely benefit from sharing protective knowledge.

In terms of traditional knowledge, Dr. Jensen confirmed that many hunters examine their catches for diseases or infected areas, and the North Slope Department of Wildlife Management often takes samples when there appears to be something wrong with an animal. She noted that many traditional foods are prepared using fermentation. However, rather than using more traditional containers such as wood or hide, there has been an increased use of plastic containers for fermentation, potentially leading to anaerobic conditions and botulism. In addition, ice cellars are commonly used for food storage and are an important part of the culture, but could potentially become a method of exposure to harmful bacteria as permafrost warms and the temperatures in the cellars rise. Another example of potential exposure comes from permafrost slumps or collapse sites where ancient organic materials such as whale bone and other artifacts are exposed. It is possible for people to encounter these materials and increase their risk of exposure to diseases.

During his remarks **Dr. Dmitry Orlov, Lomonosov Moscow State University**, shared information about recently published medico-geographical research, which includes mapping of Russia's natural-focal diseases, distribution of diseases, and morbidity and its dynamics (Malkhazova et al., 2019). Dr. Orlov's work on nosogeography (the distribution of diseases) in Russia produces these types of maps of infectious disease hosts and vectors using a variety of techniques. For example, detailed maps can be produced that show areas at risk for tick-borne encephalitis throughout Russia including distribution of potential vectors. He noted that climate change and associated increases in mosquito and tick spread as well as infections transmitted by rodents are already having an impact on population health. To provide another example, Dr. Orlov shared a prognostic model of malaria risk based on climate scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2000). The results illustrate an increased probability of malaria transmission in Russia by the end of the century (Figure 13). He also pointed out that West Nile has been detected in Russia relatively recently and maps have been produced to estimate potential distribution within specific regions. These mapped projections have largely been shown to be accurate. Dr. Orlov concluded his remarks by sharing a list of currently important natural focal diseases for the Russian Arctic including anthrax, tularemia, leptospiroses, opisthorchiasis, diphyllobothriases, trichinosis, echinococcosis, and toxocariasis.

Dr. Jay Butler, US Centers for Disease Control and Prevention, shared several observations on current infectious disease threats in Alaska related to higher

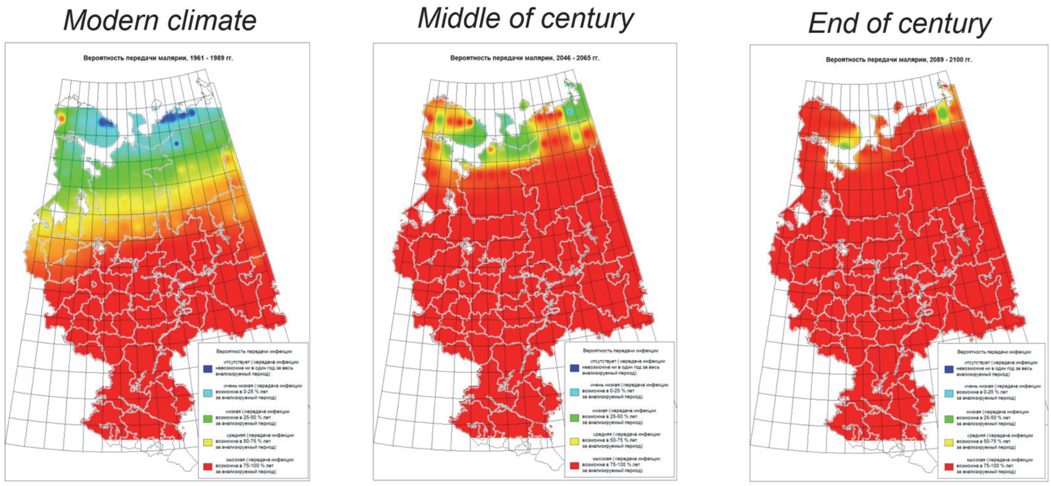

Figure 13 Changes in the probability of malaria transmission in Russia showing the modern climate, the middle of the century (2046-2065), and the end of the century (2089-2100). Red colors indicate increased rates of transmission, spreading north over time. Source: Orlov presentation.

previous presenters, Dr. Butler noted the increased air temperatures in Alaska associated with climate warming and specifically highlighted the expanded range of *Ixodes scapularis* and *I. pacificus* in the United States (Eisen et al., 2016). Increasing northward spread of ticks has been reported anecdotally, including observations of ticks on animals as well as humans. There is some concern that previously unobserved species may be emerging in Alaska, and the State Division of Environmental Health has initiated a "submit-a-tick program"[4] online as a method for sentinel surveillance for tick species previously not observed in Alaska. As another example, Dr. Butler discussed the outbreak of *Vibrio parahaemolyticus* in oysters that was observed in Prince William Sound following a prolonged period of water temperature above 15 degrees Celsius (McLaughlin et al., 2005). The research indicated that a general upward trend in surface water temperature has been observed in Prince William Sound and in the open ocean at Gulf of Alaska National Oceanic and Atmospheric Administration buoys. This warming likely contributed to the outbreak of foodborne disease caused by a pathogen not previously detected this far north in Alaska.

Two final examples illustrate the importance of permafrost thaw and loss of sea ice. Warming and loss of permafrost has been observed throughout Alaska (Thoman and Walsh, 2019, Figure 14), and Dr. Butler reiterated earlier concerns about food safety and thawing ice cellars, a traditional method of preserving food. Sea ice loss and an increasing number of days with open water has the potential to affect coastlines, especially during storms, which may damage crucial infrastructure such as sewage

[4] See https://dec.alaska.gov/eh/vet/ticks/submit-a-tick/.

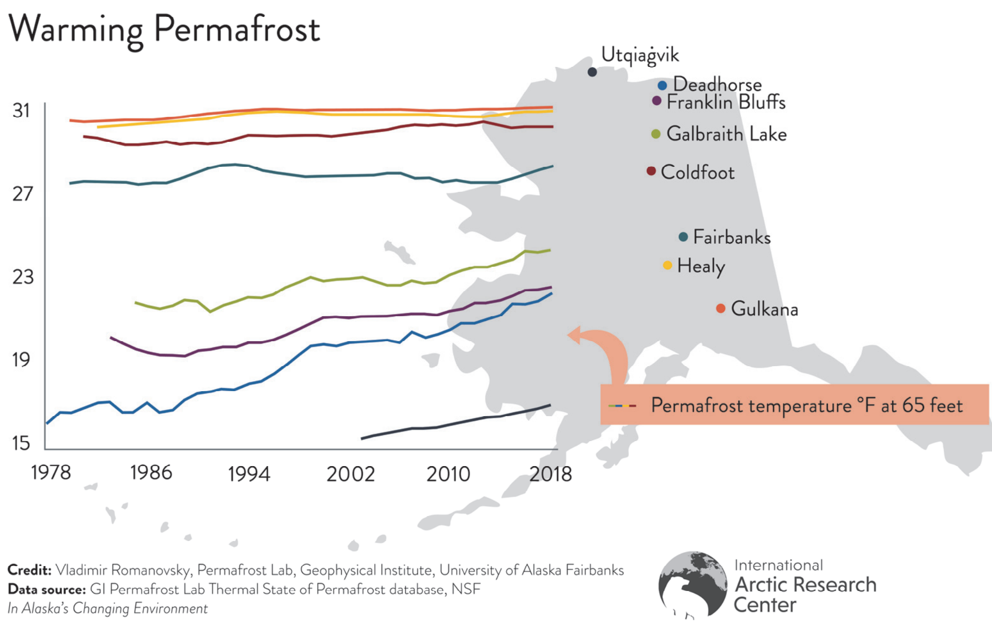

Figure 14 Permafrost temperatures (measured in degrees Fahrenheit at depths of 30 to 65 feet, shown on the y-axis) are increasing at different sites throughout Alaska, shown here from 1978 to 2018. Source: Thoman and Walsh, 2019.

treatment plants. Data are available that show a relationship between limited access to wash water and higher rates of respiratory tract infections and skin infections (Hennessy et al., 2008), and there is therefore some risk for these types of events to have implications for human disease. Dr. Butler also noted the increasing impact of tourism in these remote areas, and shared information about a Health Impact Assessment for the State of Alaska.[5]

Dr. William Bower, US Centers for Disease Control and Prevention, discussed concerns related to anthrax emergence in the Arctic. It is a naturally occurring zoonotic disease caused by *Bacillus anthracis*. This spore forming bacteria can survive in a temperate environment for decades, and it can presumably survive in permafrost indefinitely. It is also a pathogen of economic and public health concern as it has a high mortality rate in domesticated animals and wildlife. Humans can become secondarily infected by contact with infected animals or contaminated animal products, and there are currently an estimated 2,000 to 20,000 cases per year worldwide. Herbivores ingest spores when grazing or drinking contaminated water. Infection results in rapid death with a large amount of bacteria circulating in the blood stream at the time of death. The bacteria can be shed in blood and discharges, or openings in the carcasses that expose the bacteria to the environment. The bacteria shed into the environment form spores.

[5] See http://epibulletins.dhss.alaska.gov/Document/Display?DocumentId=1962.

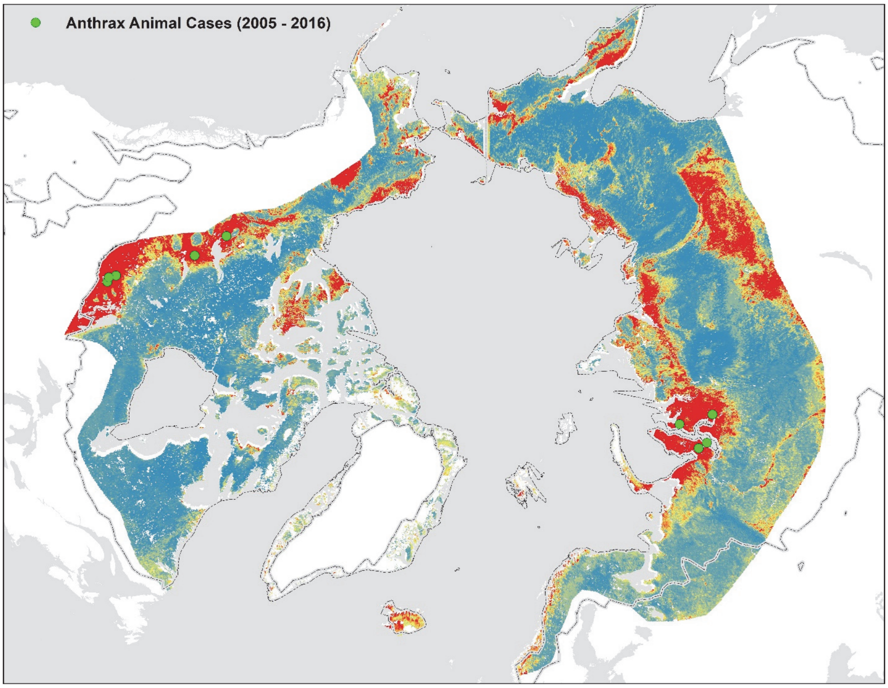

Figure 15 Ecological niche modeling allows for the mapping of areas where conditions are most suitable for anthrax and where it is most likely to emerge. Green dots indicate anthrax animal cases between 2005 and 2016, used to build the anthrax ecologic niche model. Probability of occurrence: red colors are high and blue colors are low. Source: Bower presentation.

Certain environmental conditions, such as a high soil pH, and high calcium, moisture, and high organic matter content are more favorable for long-term spore survival. Spores can be found in the vegetation where they are ingested by grazing animals, starting the cycle again. There is some evidence to suggest that insects may serve as mechanical vectors as well.

Dr. Bower illustrated the potential risk of anthrax in the Arctic region based on ecological niche modeling. Ecological niche modeling is the process of using computer algorithms to predict the geographic distribution of pathogens based on ecologic and environment variables. Variables used to create these models include environmental measurements (e.g., temperature and precipitation), ecological inputs (e.g., soil characteristics), and locations of previous outbreaks. These models can reveal areas where anthrax is more likely to occur. For example, combining the predicted areas suitable for anthrax spore survival with the distribution of permafrost and previous anthrax cases reveals areas where ecologic conditions are most suitable for anthrax and thus where anthrax is most likely to persist or reemerge in the Arctic region (Figure 15). Access to this information can increase the ability to prepare for anthrax reemergence. Capacity building is an important part of developing surveillance and detection capabilities in these areas. This likely involves input from both veterinary and human health-care providers as well as appropriate laboratory support and efficient reporting mechanisms at regional, local, and national levels. Examples of effective local capacity include the ability to detect and diagnose potential cases, and capacity at the regional level may consist of providing surge capacity to support outbreak response and confirmatory diagnostic testing. At the national level, an example of effective capacity is the formulation of policies to encourage a One Health approach. Dr. Bower noted that this might include allocation of resources to support prevention and control through vaccination programs, carcass disposal and quarantine; providing technical support; and reporting mechanisms to international authorities.

Session 2: What Do We Need to Know?

During the second workshop session, speakers and attendees considered the types of information capable of moving research forward in this area. For example, given the expected research on living organisms and disease organisms in permafrost, participants shared ideas on the specific areas of research and other activities (e.g., oil extraction) that may expose scientists or local communities to microbial risks. Speakers were asked to share their thoughts on the kinds of pathogens that might be uncovered in the permafrost, which of these might be still viable, what scientific approaches could be used, and the kinds of facilities or institutions that may have the capacity to do the research. Perhaps most importantly, attendees shared views on the critical gaps in scientific understanding as well as gaps in surveillance and observational capabilities.

Wildlife Health Surveillance

The purpose of surveillance, as outlined by **Dr. Craig Stephen, Canadian Wildlife Health Cooperative**, is to provide timely intelligence on the health of the population and to inform effective responses to emerging and ongoing issues. On the other hand, monitoring (one part of surveillance) is the ongoing, continuous, routine observation to assess the status of a population. Most wildlife surveillance takes place in the form of a survey, typically because research is time-limited and not continuous or routine. Surveillance can also come in the form of monitoring, though this is not linked to action. Dr. Stephen shared his thoughts on challenges associated with wildlife surveillance including biased population sampling (e.g., bias towards species that can be detected and those that are considered “charismatic”) and hard-to-determine trends (e.g., non-representative samples and lack of denominator data to measure prevalence). In designing effective wildlife surveillance, it is important to consider whether the goal is really tied to monitoring (e.g., characterizing a status of a population, disease, or hazard) or surveillance (e.g., a signal of change to provoke investigation or action). Both of these have distinct tradeoffs and needs to ensure a successful effort. Dr. Stephen suggested that elements for successful monitoring likely include the ability to track populations and hazards, while surveillance calls for options, thresholds, and resources to take action.

The methods through which surveillance is conducted depends on the type: health, risk, or disease surveillance. Dr. Stephen noted that currently, most wildlife surveillance takes the form of hazard surveillance (mostly infectious and parasitic surveillance, though contaminants research is emerging). Risk surveillance is very limited because researchers are rarely characterizing exposure potential. According to Dr. Stephen, there is hardly ever health surveillance of wildlife (where “health” means the capacity to cope). More often, the well-being of animals and their susceptibility to an emerging issue is tracked in population monitoring. Other crucial considerations include (1) the difference between surveillance "systems" versus time-limited projects, with implications for the identification of trends; (2) examination of specific populations versus scanning for a suite of signals, which affects ability to reveal the unexpected; and (3) looking for health outcomes versus signals of threats and hazards and who can use the data that is gathered.

A wildlife surveillance system likely aims to be an interconnected and interdependent intergovernmental enterprise done in the public good. Acknowledging the difficulty of accomplishing such a robust goal, Dr. Stephen raised a number of related questions about who may have legal authority to do so. Who has stakeholders, rights-holders, and community trust? Who has the expertise and resources to operate and sustain activities? Who has the contextual understanding to assess and communicate the findings? He also posed the important question of how one might determine that these efforts are working. A recent literature review found no systematic evaluations of wildlife surveillance systems (Stephen et al., 2019). To achieve a successful surveillance assessment, one must consider utility, acceptability, feasibility, and accuracy of the systems as well as the system's ability to meet standards. Dr. Stephen pointed out that many of these factors remain unknown (excluding perhaps utility and acceptability), impeding evaluations and quality improvement.

Dr. Stephen highlighted several key elements for surveillance success, namely a commitment among partners to work together, respect for jurisdictional roles, and emphasis on the linkages among organizations. The design of a successful system is purposeful, supportive of data sharing, accessible to a variety of stakeholders, strategic in linking people with processes and technologies, and includes a combination of epidemiological and laboratory sciences. In particular, he emphasized the importance of having clarity of goals, roles, and activities as well as equal attention towards finding and testing together with sharing data and information. In summary, development of a robust logic framework can highlight the need to support wildlife surveillance systems, especially in terms of requesting needed support and resources.

At the conclusion of his remarks, Dr. Stephen shared special considerations for threat detection surveillance. He noted that a reliable surveillance system could help provide strategic early warning in the context of scenario planning (Fink et al., 2020). Multiple sources of information are needed to move from a surveillance mindset towards one of "epidemic intelligence;" however, the holders of this information are not in the traditional wildlife health field, rather they are community members, landscape managers, meteorologists, and resource managers. It is key to engage these stakeholders in the development and use of these "intelligence-approach" systems, Dr. Stephen added.

Human Health Surveillance

Ms. Luise Müller, Statens Serum Institut, opened her remarks by defining surveillance as "systematic ongoing collection, collation and analysis of data and the timely dissemination of information to those who need to know so that action can be taken."[1] She emphasized that a key component of surveillance is data that are intended for action. Objectives of a human health surveillance system may include estimates of the magnitude of the health problem in at-risk populations, determination of disease trends, detection of outbreaks, control strategy evaluation, development of hypotheses on etiology and risk factors, detection of changes in isolation and health practices, information on microbiological evolution, and obligations to international entities (e.g., European Commission and the World Health Organization).

Acknowledging that resources are limited, Ms. Müller identified some key selection criteria for disease surveillance: frequency, severity, communicability, associated economic costs, preventability, public and political interests, and international relevance. She highlighted some examples of surveillance systems in Denmark including the clinical mandatory notification system as well as laboratory-based surveillance systems (e.g., Danish Microbiology Database [MiBa]). Other systems include childhood vaccination coverage as well as sentinel-surveillance for influenza. Focusing on MiBa, the backbone of the laboratory- based systems, she noted that it includes all national microbiological test results, in real-time, along with information on positive and negative tests. Surveillance is facilitated by data capture with person-identifiable data, which makes it possible to link to other registers.

Using a variety of mechanisms including MiBa, scientists try to capture estimates for the entire "surveillance pyramid" for influenza, from symptomatic members of the public, through the general practitioners or on-call doctors, samples taken, hospital or ICU admissions, and all the way to mortalities. Ms. Müller provided an example of the sentinel system where doctors report data on the number of consultations that include a laboratory component. This allows researchers to track these cases and review trends year-to-year (Figure 16).

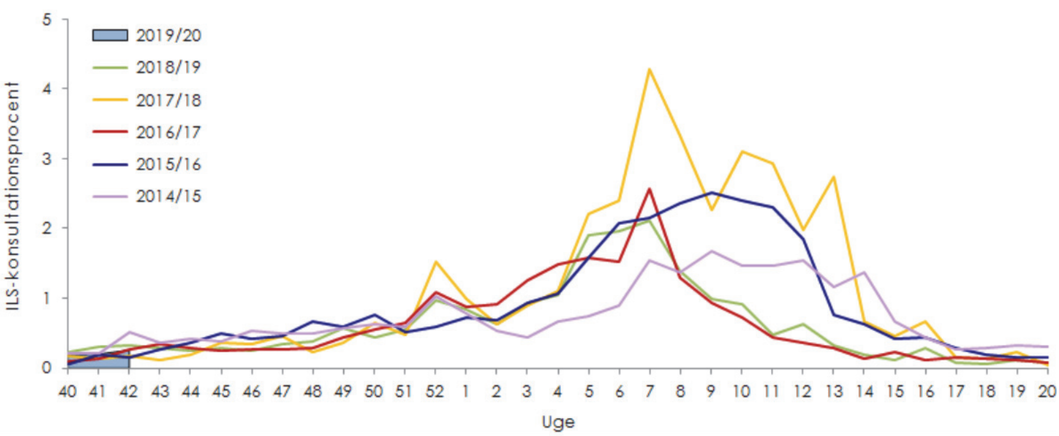

Figure 16 Reports from general practitioners on the number of influenza-like illness patients and total number of consultations weekly that included laboratory work. The x-axis indicates week and the y-axis indicates the percentage of consultations. Source: Müller presentation.

[1] See *A Dictionary of Epidemiology*. 4th edition. Ed. Last J. Oxford University Press, 2001.

Ms. Müller then focused on foodborne outbreaks in Denmark, both locally and nationally. In the case of local outbreaks (i.e., point-source outbreaks), responsible institutions include regional food offices, medical officers, and local laboratories. In national outbreaks (i.e., cases in two or more regions), responsible institutions include the Statens Serum Institut reference laboratory and Department of Infectious Disease Epidemiology as well as the Veterinary and Food Administration and Food Institute. These three institutions make up the Central Outbreak Management Group to track outbreaks and coordinate investigations using a One Health approach.

As an example, Ms. Müller discussed a 2017 outbreak of *Listeria monocytogenes* ST8, a severe disease with relatively high mortality rates, in cold-smoked salmon. A genetic cluster of four cases was identified by whole genome sequencing, one from 2015 and three from 2017, indicating that outbreaks can potentially persist for years. The Central Outbreak Management Group met to discuss the findings, and after two additional cases were identified, comparisons were made between the food and environmental isolates from 2014 to 2017 and matched to cold-smoked salmon from Poland. Interviews of the patients revealed that they had consumed the salmon, and the product was recalled from the market. Upon starting an international inquiry, notifications were issued to the European Epidemic Intelligence Information System for Food and Waterborne Diseases, Early Warning and Response System, and the Rapid Alert System for Food and Feed. Shortly after, a case was reported in France and matched with the same salmon producer in Poland, and a month later, matching cases were reported in Germany as well. Ms. Müller emphasized the importance of whole genome sequencing as a tool to detect and compare food and human isolates, especially in cross-border outbreaks. This case illustrates the usefulness of robust communication platforms in disseminating information quickly. Ms. Müller ended her presentation by reiterating some of the ongoing challenges in human health surveillance such as ensuring that data are collected for action, prioritizing diseases to monitor, detecting unexpected diseases, comparing surveillance data in humans with food and animals using a One Health approach, and harmonizing surveillance data across national borders.

Panel on Research Needs and Gaps in Scientific Understanding and Surveillance Capabilities

During a panel discussion on critical gaps in scientific understanding and surveillance capabilities, Dr. Robyn Barbato, U.S. Army Cold Regions Research and Engineering Lab, encouraged speakers to consider potential research services and programs that may help fill these needs. Reflecting on microbial survival in ancient permafrost, **Dr. Lise Øvreås, University of Bergen** noted that the Arctic system, organisms, and ecosystems are complex and diverse. Referring to the 2018 IPCC report, she highlighted the increased emissions of CO_2 and associated warming, and in particular, the impacts on the Arctic regions. As previous speakers have noted, permafrost is located throughout the Arctic, some of which is isolated and sporadic, and some of which is continuous. Thawing permafrost contributes to a shift in tundra carbon balance over time; more thawing indicates increased levels of carbon released compared to the amount of carbon that is taken in by the system. Dr. Øvreås outlined some of the changes specifically to the system near Svalbard, including rifts in the soil, lake drainage, and other impacts on local settlements. Researchers in the area have discovered that ice wedges are melting quickly, sometimes on the order of months, releasing carbon and other gases to the atmosphere.

Dr. Øvreås noted that the microbial world is a scientific frontier, with untold bacteria and microorganisms to be discovered and explored. She suggested that most have never been cultivated and their functions remain unknown. These microbes are responsible for fundamental life processes, on a global scale, including cycling of carbon, nitrogen, and other nutrients. It is known that permafrost thaw-induced microbial decomposition releases carbon dioxide and methane, and there is potentially hundreds of gigatons of carbon stored in permafrost. To begin to understand the microorganisms in permafrost, DNA is extracted and genome sequences are studied to provide information on metabolic pathways that could mediate biogeochemical cycles. Findings from this research include a stress response and antibiotic resistance in the samples (Xue et al., 2019).

Dr. Sanne Eline Wennerberg, Veterinary and Food Authority of Greenland, shared her thoughts on the need to access data and the difficulties in gathering this information in Greenland. She reiterated the importance of the research and scientific results from previous presentations, and noted that this work could be extremely helpful in determining risks to local populations. However, access to this information can be challenging. Denmark provides some of these data, but it would be especially helpful to have the ability to engage with local knowledge networks and databases when the need arises. Dr. Wennerberg also highlighted the importance of action and information that is accessible and useable within local communities. Changing climate conditions have clear impacts on the daily lives of people living in Arctic regions, and access to information about potential diseases and emerging threats would enable achievable and actionable responses.

Continuing on the themes raised by Dr. Øvreås, **Dr. Jessica Ernakovich, University of New Hampshire**, discussed some of the key unknowns within the permafrost microbiome and the role of pathogens now and in the future. She noted that several researchers, collectively known as the Permafrost Microbiome Network, are working on a database to collect, curate, and reanalyze sequencing datasets to understand microbial communities in changing permafrost landscapes. Dr. Ernakovich started broadly by discussing the influence of the landscape topography on microbial communities, emphasizing that whether permafrost landscapes are drained or inundated with water influences which microorganisms are present and can thrive. Dr. Ernakovich then highlighted some of the information that is known about permafrost microbiomes at present: Active layer and permafrost communities are not the same, and more is known about the active layer than the permafrost layer microbiome.

Diversity declines with depth (for bacteria and fungi; it is likely that diversity increases with depth for archaea). It is likely that microbes live in brine channels in frozen permafrost. Microbes in permafrost are selected (adapted or well suited) for long-term survival in harsh conditions (Bottos et al., 2018; Mackelprang et al., 2017). Community composition shifts when permafrost thaws, but the controls on community assembly are not yet known. Understanding what factors contribute to composition of microbial communities after permafrost thaw may be helpful in predicting pathogen risks.

In the microbiome following permafrost thaw, there are still several unanswered questions. Some of these raised by Dr. Ernakovich include: What proportion of the permafrost microbes survive the thaw? The sequencing techniques mentioned previously are not quantitative and thus other tools may be needed. Is there a biological or physical mechanism to determine the likelihood of a microorganism surviving permafrost thaw? Is it random? Given that permafrost microbes are selected for survival, can they compete with newly dispersed active layer microbes? Do increasing biotic interactions affect community composition? How do these change over space and time? She also shared ideas on the role of community assembly in permafrost layers after thaw. When permafrost conditions are stable (intact), permafrost acts as a "selective filter" and the community is selected specifically for life in permafrost and there is not much dispersal from the active layer. When permafrost thaws, there is a change in conditions of selective pressures, in which the community is affected by random losses of species and by dispersal from the active layer. Over time, the community continues to respond to changing niche space, but also to dispersal (Graham and Stegen, 2017) and perhaps also diversification. Additional information is needed on the permafrost microbiome before the survival of pathogens can be understood and predicted. According to Dr. Ernakovich, key information gaps include understanding (1) whether pathogens in permafrost are active or dormant, which may reveal clues about their availability to survive and thrive after permafrost thaw, (2) if they are able to thrive and grow to the required population size to be an effective pathogen, (3) whether pathogen populations will be kept in check by the effects of community, or if the low biomass and diversity of other community members allow pathogens to get a foothold, and (4) if pathogen dominance is one of many alternate stable states.

Dr. Tatiana Vishnivetskaya, University of Tennessee Knoxville, discussed microbial research on permafrost core samples that were approximately two million years old. She noted that permafrost collection techniques may need to be adjusted to ensure that the samples remain uncontaminated. It has been estimated that prokaryotic diversity in soil reaches between 6,400 and 38,000 species per gram (Curtis et al., 2002), but the absolute diversity is unknown. Dr. Vishnivetskaya presented information from a number of published papers on total cell counts, microbial biomass, and viable counts for different permafrost samples (e.g., Gilichinsky, 2005; Hansen, 2007; Rivkina, 1998; Vishnivetskaya, 2000; and others). Only 0.01 to 1 percent of the native microorganisms are able to be cultured; therefore, most of the microbial diversity in permafrost sediments remains unexplored. However, a number of studies have determined the viable bacterial community structure in different permafrost sediments. She noted that the type of media used by researchers could influence structure of the bacterial community.

Types of microorganisms that have been isolated from Siberian permafrost include prokaryotes (e.g., bacteria, archaea, cyanobacteria) and eukaryotes (e.g., yeasts, fungi, green algae, moss, protista, nematode). Dr. Vishnivetskaya noted that viruses could also be isolated from this permafrost. In all, she identified 26 strains that have been isolated from these permafrost samples (Shatilovich et al., 2018). Database information, based on 37 permafrost metagenomes and 26 active layer metagenomes, shows that the majority of biodiversity exists at levels below 1 percent. Metagenomes show differences in dominant phyla from permafrost versus the active layer, due to their differing functions in the soil.

The final panelist of the session, **Dr. David Stanton, Swedish Museum of Natural History**, discussed DNA from ice age wildlife and the possibility of pathogens emerging from these samples. A broad range of ancient species has been found in permafrost, with remarkable levels of preservation, even in samples over 50,000 years old. DNA is extracted from the samples, and a library is built and sequenced. Dr. Stanton pointed out that often there are low amounts of the actual species of interest for the research group and the rest are data that could potentially contain bacterial DNA and pathogens. These data could possibly be used to investigate pathogens.

Dr. Stanton shared an example from lion samples and mapping for the anthrax genome. This approach can reveal pathogens present in the carcasses and their dependence on location, age, or other factors. He emphasized that DNA from ice age wildlife is highly damaged and fragmented; even if pathogens are present, they are not necessarily viable. Most of the DNA that the team works with is approximately 70 to 80 base pairs. Another example from mammoth samples revealed an innocuous soil bacterium (*Azospirillum brasilense*). Some bacteria that produce toxins were discovered as well (*Clostridium botulinum*), but these would not necessarily pose a threat to researchers working with the samples, unless samples containing the toxin were consumed. He noted that knowledge gaps include an understanding of potential risks posed by pathogens that are present in the samples, and the evolutionary history of parasites as well.

Discussion on Biosafety and Biosecurity Risks

Following breakout group discussions, participants shared ideas and opportunities related to laboratory procedures, biocontainment and engineering controls, as well as risk assessments and impacts on indigenous and local communities.

Laboratory Procedures and Levels of Risk

The first group specifically considered laboratory procedures and techniques that would be helpful when working with permafrost samples. The current method most commonly used is DNA sequencing and identifying known pathogens. There are other approaches such as laboratory-based culturing, but there is a great deal of unknown diversity in the samples and these techniques likely could be improved. The group noted that there is a list of known pathogens, and it may be most efficient to identify sequences from that list. Proteomics could be used to confirm pathogenicity, though this is still quite challenging and could be an area for future improvement. Participants noted a distinction between environmental pathogens and pathogens from animal carcasses; in the case of animal carcasses, there will likely be visual indications of risk. Although indications of risk may not be quite as clear in the environment, there are "hot spots" of risk that could be identified. Therefore, a systematic approach for sampling in hot spot areas would be useful to understand the dispersal of those organisms for predictive purposes. Group members highlighted their discussion on a potential moral obligation to preserve both the environmental and clinical samples that are collected, though there is no clear method or resources to do this. Potential discord between the environmental microbiome versus the clinical (as well as the techniques that are used), indicates that it may be useful to culture the organisms and use information from genomes to try to predict substrate utilization.

Biocontainment, Engineering, and Safety Controls

A second breakout group covered topics related to biocontainment and engineering controls. They considered that people working or living in the Arctic might be unaware that samples may contain pathogens. There is also very limited biosafety in the North. Given that context, the group discussed how to regulate effectively without curtailing valid research, or if capacity building would be a better option rather than regulation. In addition, the potential for harmful or potentially hostile activities was noted, including the use of pathogens for nefarious purposes. There are opportunities for increased international data sharing and dissemination, especially with new technologies and citizen science approaches, though biosafety and biosecurity[2] concerns will still need to be taken into consideration. International frameworks, codes of ethics, or best practices may be used to ensure affected communities are kept informed and to ensure that sovereignty concerns are addressed.

Risk Assessment Approaches

During a discussion on approaches to risk assessment, participants noted that the isolates and samples themselves are not considered a risk, but risk emerges when the samples are combined with human activity and exposure. There is still a great deal of uncertainty about what the risks are and there are challenges to conducting foundational research and achieving higher levels of certainty. Therefore, questions

[2] "The analysis of ways and development of strategies to minimize the likelihood of the occurrence of biorisks (i.e. the probability or chance that a particular adverse event, including accidental infection or unauthorized access, loss, theft, misuse, diversion or intentional release, possibly leading to harm, will occur)." Source: https://www.cdc.gov/globalhealth/security/actionpackages/biosafety_and_biosecurity.htm.

remain about the probability of pathogen survival in permafrost, the probability of transmission, and the severity of outcome. There was some discussion about pathogens in human remains versus plant and animal matter, and the group noted that there are more plant and animal materials in the permafrost versus human remains; approximately 75 percent of emerging infectious diseases are zoonotic. Effective risk assessments begin with an understanding of whose risk is being assessed and for what purpose. It may be beneficial to start with occupational safety of researchers and capacity building for sustainability. Some participants raised additional questions for consideration: Is there a need to focus on evolutionary history studies versus present-day risk assessments? Should researchers start with a small number of current pathogens of concern that are hardy enough to survive in permafrost? Would it be most effective to focus efforts on highly exposed populations (e.g., miners, tusk miners) or certain sentinel species (e.g., Arctic fox or shellfish)? The group noted that starting with occupational risk and conducting this research in a safe way would be key.

Impacts of Potential Exposure on Indigenous and Local Communities

The final group shared thoughts on impacts for indigenous and local communities, and noted that impacts largely depend on the type of thawing permafrost and its contents. People will be exposed through pathogens in soil, as the ground is uncovered. For example, searching for for animal carcasses can be economically beneficial in some areas and the people revealing these materials may be sentinels in understanding exposure and associated impacts. An early indicator of concern may be living animals that are exposed and exhibit disease symptoms. The group noted that there are also spiritual factors that need to be taken into consideration; some communities may be wary of approaching permafrost for fear of mishandling human remains, and this can lead to stress and behavioral concerns within the communities. The State of Alaska has a fact sheet on best practices for handling human remains, even though the cause of death is not always clear. Eroding gravesites should be reported to appropriate authorities, however communities need to be involved with any decision making regarding these sites.

Another concern for local communities is food safety and the development of best practice materials as well as a common vocabulary to ensure understanding. Guidance from trusted authorities could be developed for both the public and officials. Participants pointed out that it is not practical for hunters and fishers to have personal protective equipment at all times. Local public health departments can be a helpful first contact, but coherence between police and public health entities is probably desirable.

Session 3: Research and Operational Paths Forward

During the final workshop session, participants and speakers reflected on some of the key opportunities to facilitate multidisciplinary, interagency, and international cooperation and collaboration. Building upon existing research and observational programs and platforms, participants discussed best practices as well as ethical dimensions to be considered for working with indigenous communities. Lessons learned from research in other regions (e.g., Antarctic research) were highlighted as well.

Local Environmental Observer Network

Mr. Michael Brubaker, Local Environmental Observer (LEO) Network,[1] shared information about this online platform to collect local observations of environmental change. This network is made specifically for people that are familiar with their local environments and are thus able to detect and report changes over time. He noted that some of the challenges faced by Arctic populations may include isolation and reduced access to resources. One benefit of this online resource is the ability to share information and knowledge regardless of location. Mr. Brubaker used examples from local communities to illustrate the intimate knowledge that community members possess about their environment and the related ability to perceive small changes. The goal is to collect and track “symptoms” of how the environment is changing, some of which can be identified through observations, and some of which require scientific research or remote sensing methods (i.e., structured monitoring). If local experts are able to provide information or “symptoms” of local change, this can be added to a database that can be tracked and compared over time and geographic range.

Using these methods, thousands of observations have been collected in Alaska revealing potential vulnerabilities to climate change (e.g., ice hazards, reduced food security, increased allergies, and others). The LEO Network was developed by the Alaska Tribal Health System beginning in 2012 as a strategy for gathering and sharing information about climate and other drivers of environmental change. Mr. Brubaker noted that the primary goal is to share knowledge with a secondary goal to help answer questions and connect local communities with resources. The content is observational (not structured monitoring) and takes holistic rather than topic specific approach. It is based on a social media (member owner) model and welcomes different knowledge systems, is multi-lingual (including indigenous languages), and is user driven and user friendly. Different groups of individuals use the network in different ways. For example, community members use the platform to share observations about significant environmental change, as witnessed through specific events, as a way to raise

[1] See https://www.leonetwork.org/.

awareness about pressing concerns and to connect with topic experts to receive technical support. Public health experts use it as a communication tool for engaging with communities, staying informed about emerging priorities, and providing environmental health consultations. Finally, researchers and agencies use this network as a surveillance system for receiving local updates on emerging issues, for identifying experts and research partners, for learning about local change and vulnerabilities, and for providing event specific consultations.

Mr. Brubaker outlined the network in detail, and noted that a future goal is to incorporate additional users and partners from Canada and Russia. The content of the network consists mostly of observations about specific events or articles about specific events from local newspapers. Observations primarily come from local residents, who can provide specifics on problem statements, background, hypotheses, photos, geographic information, and other crucial information. The system will ask users to identify aspects of the natural environment that are relevant to the observation, why it is unusual or unexpected, and how the human environment has been impacted. Observations are then forwarded to partner organizations or experts that can provide detailed topical consultations on the event and may be able to provide additional information or context. Previously added information is available for searches using specific filters such as date range, region, or type of observation.

An example of the effect of thawing permafrost on a mass burial site was outlined by Mr. Brubaker. Subsidence and erosion of the permafrost in the area of Brevig Mission caused gravesites to be disturbed (Figure 17). The issue was reported by local community members, and engagements with permafrost experts and relevant consultants may be able to provide ideas to preserve these sites. Using information collected by the network database, satellite and aerial images can be added along with weather data to indicate potential extreme events and historical data for context. As this issue becomes more prevalent with thawing permafrost, examples can be collected, categorized, and mapped within the LEO system.

Zoonotic Diseases of Importance to Subsistence Communities

Zoonoses and issues related to subsistence food handling and consumption was discussed by **Mr. Eduard Zdor, University of Alaska Fairbanks**. Indigenous peoples are facing and adapting, not only to social and cultural changes, but also to climatic changes. Food obtained from traditional subsistence hunting, fishing, and gathering is widespread in the remote villages of the Bering Strait region. For example, in 2012, 198.7 kilograms of meat, fish, birds, berries, and so on per capita were harvested on the Alaskan side of the Bering Strait (Fall, 2016). On the other side of the Bering Strait, in Chukotka, for part of 2012, 399 kilograms per family were stored, and a year earlier, 737 kilograms per family were consumed (Kochnev and Zdor, 2014). The amounts of food harvested, stored, and consumed are similar on both sides of the Bering Strait because the people living in these regions have similar lifestyles and food sources from the sea and tundra. Fishing, a crucial food source, provided 122 kilograms of food for Chukotkan households

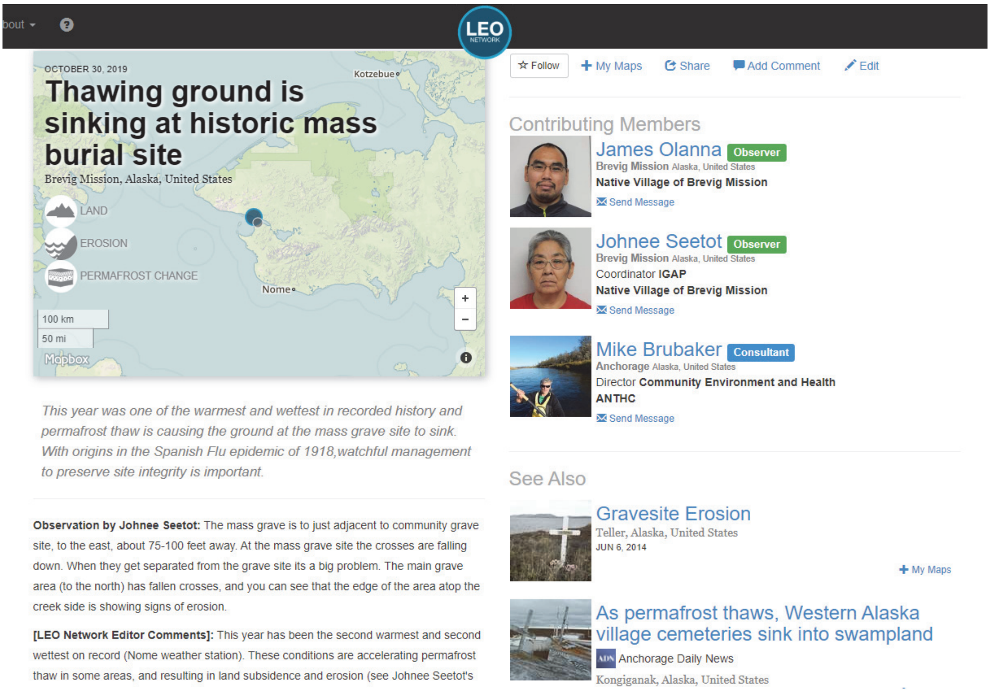

Figure 17 Screen shot of LEO Network website illustrating subsidence and erosion of the permafrost in the area of Brevig Mission causing disruption to gravesites. Source: Brubaker presentation.

in 2011, and 76 kilograms per capita in Alaskan rural communities in 2012 (Kochnev and Zdor, 2014). On the other hand, reindeer meat consumption is declining; in Chukotka in 2019, 23 kilograms of reindeer meat was consumed per capita, and 30.4 kilograms of caribou meat were harvested per capita in Alaskan rural communities in 2012 (Fall, 2016). Traditional processing and drying methods are still used for these foods, but salt is frequently used due to increasing temperatures above freezing.

Mr. Zdor noted that the efficiency of marine mammal hunters is high compared to 20-30 years ago due to the involvement of high-tech equipment and transportation. However, innovation is also contributing to a shift in traditional approaches to wildlife and thereby changing the sociocultural pattern of communities in the region. The Chukotkan annual average harvest includes 120 gray whales, 1 bowhead whale, 1,000 walruses and 3,000 seals of different species per year. In Alaska, on average, villages annually harvest several thousand seals, from 200 to 400 belugas (Hovelsrud et al. 2008), and 1,200 walrus. In 2017, 11 Alaskan villages landed 50 bowhead whales. In the past few decades, methods such as smoking, pickling, and salting have been increasingly used for processing and safe storage (versus more traditional methods such as ice cellars). Given ongoing changes to climate, subsistence consumers are forced to look for other ways to store traditional food. Villagers must limit meat consumption in the summer, postponing the hunt for autumn. Another example highlighted by Mr. Zdor was walrus meat, the most desirable traditional food on the Chukotka coastal settlements side; the cooking and preparation methods (boiling and fermentation) are of particular interest to epidemiologists. Initially, the decline in traditional processing and storage methods was attributed to sociocultural changes in the settlements. Over time, it emerged that the thawing of the permafrost also contributed to shifts in traditional food consumption.

Dr. Cheryl Rosa, US Arctic Research Commission, shared information on the "indigenous protocol" (as termed by co-presenter Mr. Zdor) when diseased or abnormal animals are discovered. Following indications of unusual animal behavior and organoleptic examination (i.e., assessment of flavor, odor, and appearance of a food product), appropriate processing measures are taken. For example, animals that appear abnormal or diseased are generally avoided or discarded. Animals are cut up and processed as quickly as possible, and only the processed meat is eaten. Low temperatures, and to some extent, dry weather, during processing and storage are crucial to ensure safety. As noted earlier, drying and fermentation are additional ways of processing products. Dr. Rosa mentioned that there are other ways to provide safe consumption, and examples of preventive measures may include sharing knowledge of these protocols amongst communities and generations as well as partitioning into small settlements along the coast. These measures may not always work, however, and entire communities have fallen ill with infectious diseases in the past.

A case study on "stinky whales" was discussed by Dr. Rosa. In 1998, Chukotka Native hunters began reporting an increase in the number of hunted eastern North Pacific gray whales that exhibited a strong medicinal odor. Tissues from these whales are deemed inedible (not palatable) by people and not consumed by sled dogs. People have tasted the blubber or meat and have noted numbness of the oral cavity and reported skin rashes or stomachaches. Samples were collected in the early 2000s, though it can be challenging to get marine mammal samples out of Russia into the US. Sample quality declined due to cycles of freezing and thawing. Additional samples were collected between 2008 and 2014, and the plan was to submit samples to several labs for analysis of the following: persistent organochlorines (OCs), polyaromatic hydrocarbons (PAHs), heavy metals (HM), stable isotopes (SI), and volatile organic compounds (VOCs) and HABs. Unfortunately, researchers still do not have access to these samples, highlighting the issues associated with policy and politics making this type of work more difficult.

At the end of her remarks, Dr. Rosa noted that it is critically important to take into consideration the benefits that come from eating a subsistence diet, and that culturally appropriate messaging is imperative when communicating risks. Mr. Zdor concluded by sharing that a high level of concern exists surrounding efforts to "ensure food safety"—specifically that these efforts could restrict subsistence hunting, handling, and consumption abilities. With changing environmental conditions (and recognizing the importance of food safety as a part of food security), the solution may be a compromise in the protocols that provide a safe way to process and store traditional foods while avoiding disruption to Indigenous lifestyles, which is a key factor in preserving cultural identity.

Using Indigenous Knowledge to Detect Emerging Pathogens

The use of community-based wildlife health surveillance for the detection of emerging pathogens in the Arctic was outlined by **Dr. Susan Kutz, University of Calgary**. If pathogens emerge from thawing permafrost, ice patches, glaciers, or graves, wildlife may be the first to be affected. Therefore, wildlife may be important sentinels and amplifying hosts as well as a food safety concern. Current wildlife health surveillance in the Arctic is often not adequately sensitive to detect emerging concerns, nor are current surveillance methods particularly effective. Population density is low in remote areas of the Canadian Arctic, and thus surveillance is hampered by the lack of local expertise as well as fear of diseases, costs and logistics, shipping of samples, time delays and sample quality, unknown existing pathogen diversity, and the lack of policies, reportable diseases, political will, and priorities. Dr. Kutz noted that there are many examples of unexplained wildlife mortalities and diseases across the Arctic region.

Dr. Kutz suggested that a possible solution is to bring knowledge systems together for wildlife health surveillance. The complexity of the Arctic forces researchers to draw on all sources of knowledge, including local and indigenous knowledge (Schoolmeester et al., 2019). Indigenous wildlife health knowledge is accumulated over generations. This knowledge is applicable in all seasons, across many species (Tomaselli et al., 2018), and includes information about what is normal and what is abnormal. A challenge is ensuring that knowledge and experience are respected, documented, and implemented. Dr. Kutz shared case studies on muskox and caribou health research. In 2008, a lungworm parasite (*Umingmakstrongylus pallikuukensis*) emerged further north into areas that it had not appeared before, indicating changing environmental conditions. Unusual muskox mortality events were reported between 2009 and 2013. In 2012, a sample was retrieved that showed septicemia caused by the bacteria *Erysipelothrix rhusiopathiae*. Whole genome sequencing revealed that there were no differences in the strain across multiple animals and across the entire area. A human infection was also recorded, but genome sequencing was unable to identify a source (Groeschel et al., 2019). Dr. Kutz and her colleagues began thinking about monitoring in a community-based wildlife health surveillance approach, including individual interviews, small group interviews, hunter-based sampling, and targeted sample collection. Fundamental to this program is building capacity within the local communities (including workshops, training, and science in the classroom).

Following the group interviews, areas of observation were highlighted from residents and pilots familiar with the territory. Dr. Kutz showed how estimated muskox population trends indicate a dramatic recent decline following a peak in population, and aerial surveys show similar results (Figure 18, Tomaselli et al., 2018). Understanding this decline involves comparing health indicators during peak and decline periods. This is

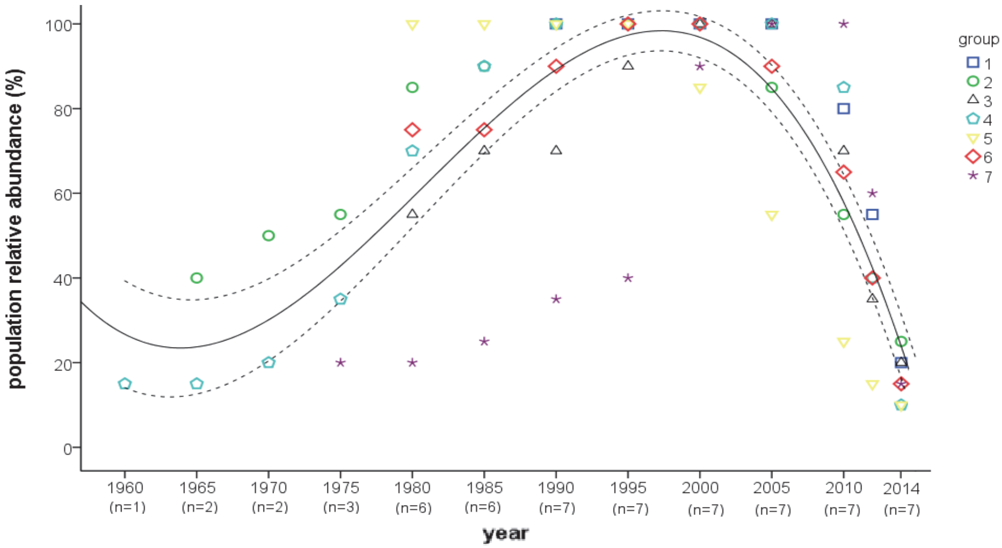

Figure 18 Estimates of population abundance over time, collected from group interviews. Source: Tomaselli et al., 2018. Reprinted with permission; copyright 2018, Elsevier.

accomplished through "proportional piling"[2] exercises used to quantify people's perceptions (i.e., participatory epidemiology). The exercise showed declines in the proportion of juveniles, body condition, and health status. The cause of death post-decline ranged from predation to acute death, and the exercise revealed that the number of cases between 2009 and 2014 was higher than anticipated. Dr. Kutz indicated that the epidemic was missed by standard scientific methods, and provides an example of the challenge of tracking emerging diseases in the Arctic when indigenous and local knowledge is not included (Tomaselli et al., 2018).

A hunter-based sampling program provides hunters with kits to gather important indicators of health over time (e.g., blood samples, skin and hair, and bones). Dr. Kutz noted that interviews revealed observations about animals becoming thinner over time, developing scabs on their mouths, overgrown hooves, tooth abnormalities, fewer calves, and limping. Brucellosis was cultured from some of the hunter sampling kits and, combined with archive data, is shown to be increasing on Victoria Island (Tomaselli et al., 2019). This emerging condition was first identified through interviews with local residents and the research was improved using the hunter-based samples.

[2] "Proportional piling is a semi-quantitative method for determining community priorities. For example, circles can be drawn on the ground or pictures can be drawn on cards, which represent the problems mentioned. The respondents are then asked to pile pebbles or beans in proportion to the importance of the problem. A fixed number of beans can be used to make the technique more reproducible. The appraisal team then counts the number of beans placed on the symbol for each problem." Source: http://www.fao.org/3/X8833E/x8833e03.htm.

There is an intimate connection between Northern peoples and wildlife, and indigenous knowledge provides a contextual understanding and experiential knowledge on a temporal and spatial scale that cannot be accomplished through western science. In addition, Dr. Kutz highlighted the ability of indigenous knowledge and hunter-based sampling to inform science, generate research hypotheses, and serve as an early detection of change. At the conclusion of her remarks, Dr. Kutz suggested that effective wildlife health surveillance requires bridging knowledge systems. She highlighted the importance of communication with indigenous communities, understanding that sensitivities are crucial when researchers are interested in discussing food sources and traditional ways of life.

Panel on International and Multidisciplinary Research Examples

Dr. Kutz moderated a discussion to explore examples of international and multidisciplinary research projects from microbial discovery to surveillance and response. During the panel discussions, **Dr. Michael Bruce, US Centers for Disease Control and Prevention**, spoke about the International Circumpolar Surveillance (ICS) System for Invasive Bacterial Diseases and collaborative One Health research in the Arctic. Started in 1999, ICS is an infectious disease surveillance network of hospitals and public health laboratories across the Arctic. Current members include Alaska, Northern Canada, Greenland, Iceland, Norway, Northern Sweden, and Finland, and all members submit laboratory, clinical, and demographic data on invasive bacterial diseases to ICS. Testing and laboratory capabilities are not uniform across the Arctic, so the system conducts quality control. An example of data illustrated by Dr. Bruce includes rates of invasive disease in children under five, in a pre-vaccine period and post-vaccine period. With the introduction of pneumococcal vaccine, there was a dramatic decline of invasive pneumococcal disease in Native and non-Native children, though the rates of infection are still currently higher for Alaska Native children compared with non-Native children (Bruce et al., 2015). Additional data on *Haemophilus influenzae* serotype b also show significant decreases in the rates of infection in indigenous and non-indigenous children post-vaccine (Singleton et al., 2000). However, through this network, rates of *Haemophilus influenzae* serotype a have been identified and are highest in this region compared with the rest of the world. Approximately 11 percent of cases are fatal, 32 percent require hospital transfer, 78 percent require air transport, and 36 percent required intensive care or died before admission. Disease complications were identified in 14 percent of patients a year or more after the clinical episode (Bruce et al., 2013 and Plumb et al., 2018). Dr. Bruce also outlined how the network identified an outbreak in 2018, including four cases in one village (Nolen et al., 2020). A vaccine underway in Canada could avert considerable morbidity and mortality in affected populations (Barreto et al., 2017 and Cox et al., 2017).

Dr. Bruce outlined examples of collaborative One Health research projects in the Arctic. The Circumpolar Climate Change and Infectious Diseases Workgroup performed a survey of 11 climate-sensitive, reportable infectious diseases in the Arctic (arboviral

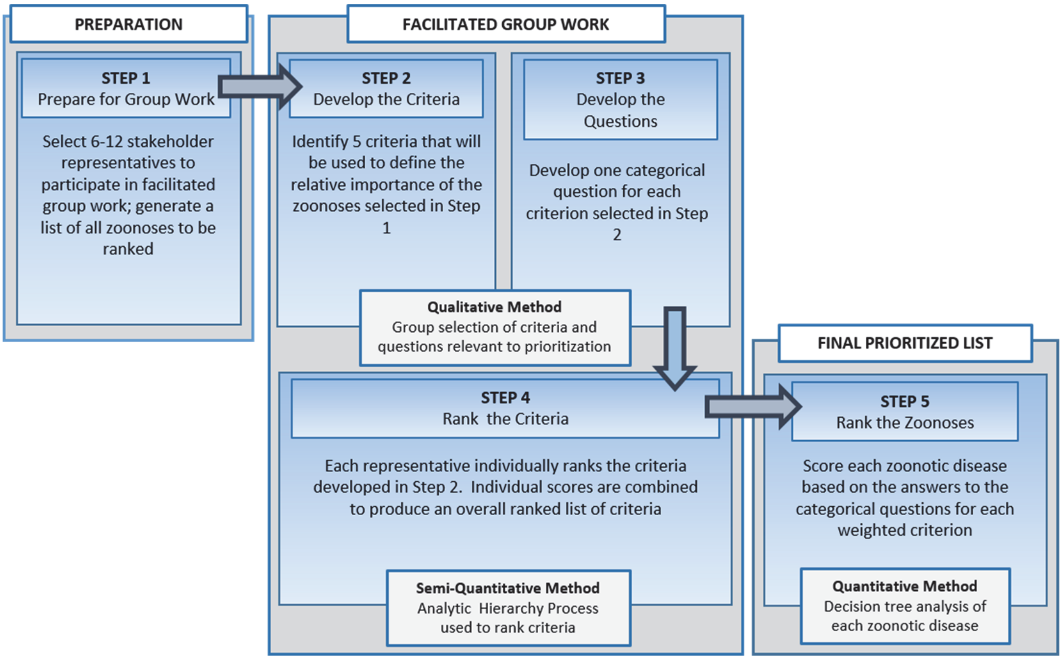

Figure 19 A five-step prioritization process was developed during a 2019 Alaska Zoonotic Prioritization Workshop. Information about the workshop and the priority diseases that were identified can be found at https://www.cdc.gov/onehealth/what-we-do/zoonotic-disease-prioritization/completed-workshops.html Source: Bruce Presentation.

disease, brucellosis, Q-fever (*Coxiella burnetti)*, cryptosporidiosis, echinococcus, giardiasis, hepatitis E, rabies, toxoplasmosis, trichinellosis, and tularemia). A serosurvey was completed in Alaska (Miernyk et al., 2019)and a serosurvey is planned in Greenland and Sweden. During a 2019 Alaska Zoonotic Prioritization Workshop, a five-step prioritization process was developed using quantitative and qualitative steps (Figure 19). The process starts with a list of zoonotic diseases for prioritization, specific criterion are applied to each (e.g., clinical outcome, prevalence and modes of transmission, social or economic effects, response capacity, and climate change), and after ranking numerically, a list of top priority diseases are developed. Dr. Bruce noted that the following diseases emerged as priorities for Alaska: amnesic shellfish poisoning, zoonotic influenza, rabies, cryptosporidiosis, toxoplasmosis, brucellosis, and Q fever. Landscape reviews are planned for the existing literature, surveillance, and testing to create a baseline level of knowledge in Alaska for each disease.

Sharing an Antarctic perspective, **Dr. Trista Vick-Majors, Michigan Technological University**, discussed subglacial lakes and tackling interdisciplinary problems of international interest. She noted that ice covers approximately 98 percent of the Antarctic continent. The ice sheets contain about 60 percent of Earth's freshwater. In addition to ice cover, water is widespread under Antarctic ice. Since the mid-1990s, nearly 400 lakes have been discovered, and many areas are thought to be underlain by water-saturated sediments and crossed by streams. Scientific interests in this area include microbial life, subglacial geology and sedimentology, and hydrology. In 1998, completion of the Vostok ice core (3623 m) provided climate records and information on microbiology of ice accreted from the lake. Between 2000 and 2009, multinational committees worked to determine the importance of subglacial work and ensure that the environments remain pristine after work commences. In 2011, the Scientific Committee on Antarctic Research developed a Code of Conduct for subglacial drilling presented at the Antarctic Treaty Consultative Meeting and following that, national programs pursued subglacial lake access plans.

Dr. Vick-Majors noted that the United States, United Kingdom, and Russia have been working in earnest to understand subglacial lakes, but the question of keeping the environment pristine remains. Clean access to subglacial lake environments (and controlling the potential for contamination) involves wearing protective clothing, pre-cleaning and bagging borehole instruments, and drilling with hot water. To provide an example, Dr. Vick-Majors discussed the steps associated with hot water drilling at Lake Whillans; the process involves melting snow from surrounding area, pumping high-pressure hot water to melt a hole, continually recirculating water through filters and UV light banks to destroy microbial cells, removing the drill at 700 m to sample borehole water, reducing borehole water level by 30 m before breakthrough, and at 801 m, the drill load cell is unloaded and borehole water level then increases by 30 m, indicating lake water movement into the borehole. The process prevents contamination associated with the drill water and produces a 7-log cumulative reduction in microbial cell numbers in drilling water and on surfaces using a combination of: filtration, UV radiation, pasteurization, and surface disinfection with H_2O_2 (Achberger et al., 2016; Christner et al., 2012; Priscu, et al., 2012).

Continuing the panel discussion, **Dr. Arja Rautio, University of Oulu**, highlighted the challenges associated with climate change, thawing permafrost, and related environmental and socioeconomic impacts, adaptation, and mitigation strategies. Progress depends on multiple disciplines working together. For example, physical science (e.g., terrestrial, subsea, and coastal permafrost and coastal waters), together with social science (e.g., health and pollution, coastal infrastructure, natural resources, and economy) and integration through modeling, adaptation, and mitigation, contributes to greater understanding of the issues in the region. Recently, discussions have centered on risk of contaminants and infectious diseases for local communities. Important considerations in these discussions include ethics, community-based participatory approaches, and involvement of the indigenous advisory boards. The foremost goal of the work discussed by Dr. Rautio is to determine the impacts of thawing permafrost on global climate and on humans in the Arctic and to develop targeted and co-designed adaptation and mitigation strategies. This includes assessing the vulnerability of coastal and subsea permafrost systems; determining the contribution of greenhouse gases released from organic matter along Arctic coasts; determining the impact of permafrost thaw on the health of Arctic coastal communities;

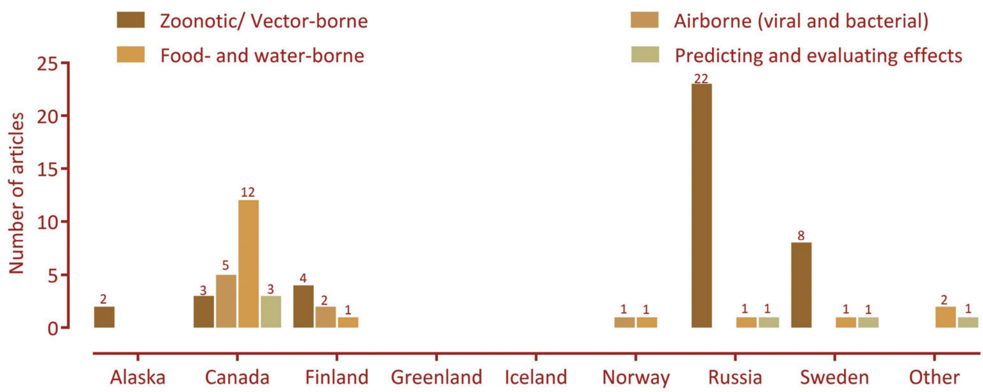

Figure 20 This graphic shows topical focus areas, gathered from a systematic review of 72 articles, illustrating the range of applicable health effects across the Arctic. Results are divided by country for articles published between 1970 and 2017.43 articles were reviewed in Waits et al. 2018 and 29 were reviewed in a previous study (Hedlund et al. 2014). "Other" represent articles that include more than 1 country. Source: Rautio presentation, Waits et al., 2018.

and assessing risks to local infrastructure, as well as the state of local societies, economies and cultures.

Focusing on the health and pollution aspects of the research, Dr. Rautio shared examples including mapping the state of human health in Arctic coastal communities (Abass et al., 2018; Waits et al., 2018), risk assessments of pollutants found in permafrost, modeling of anthrax, mental health aspects, and risks associated with permafrost thaw for human health (Rautio, 2009). She discussed a collection of papers from across the Arctic, illustrating examples of health effects (Figure 20), and highlighted a One Health approach to understanding risks.

Dr. Warwick Vincent, Université Laval, concluded the panel discussion with thoughts on multidisciplinarity and international perspectives to mobilize networks that are available for disease surveillance. The Arctic has seen many changes within the last decade. He discussed changes in lakes, in particular, which are the lowest points of the landscape and thus water and microbes often find their way into the lakes. Additional research could be undertaken to monitor for microbial threats in these waters. He also described recent research on airborne virome sampling associated with rapid glacier and permafrost change. Knowing that there are many research efforts occurring throughout the Arctic, Dr. Vincent noted that the Center for Northern Studies has developed the CEN Network[3] to understand how the environment is changing in a global perspective. The network includes 9 field stations and 110 climate stations, covering 30 degrees of latitude and 3500 kilometers. Aircraft must be used to travel from station to station, but automated instrumentation is increasingly used as well, especially in the winter months.

[3] See http://www.cen.ulaval.ca/en/.

The network of stations is included in a circumpolar network called INTERACT, funded through the European Union. Dr. Vincent noted that there are 86 northern field stations, and highlighted the work package on managing risks, which is intended to develop a rapid response approach by mobilizing the stations around the circumpolar north in case of an emerging microbial risk. Data can be obtained through these remote sites using the infrastructure already in place. An ongoing test case examines mosquito-borne diseases in the Arctic and asks station managers to provide samples that can be analyzed for viruses. Dr. Vincent noted the importance of working across disciplines and among nations, and specifically mentioned the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC)[4] project as an example of this type of collaborative research with partnerships across 20 countries. He noted that there are additional projects occurring in parallel, namely a terrestrial counterpart (T-MOSAiC)[5] that examines associated impacts on landscapes and ecosystems. Two action groups of particular interest include the Arctic microbiomes group and the northern community issues group.

Discussion on Harmonization of Surveillance Data

Workshop participants shared ideas on surveillance approaches, international standards, and microbiologic or diagnostic approaches in breakout group discussions.

Understanding the Need for Surveillance

One group discussed potential special surveillance approaches that could be taken in at-risk communities. They noted that subclinical and clinical symptoms could arise, and a good baseline (or background surveillance) may help illustrate best approaches. A One Health approach would be ideal and could be an opportunity to expand surveillance to humans and animals. Group members debated the ultimate goal, whether it is to increase local capacity or if it is primarily related to increased research. They noted that every community has a location-specific, individual risk profile that can help determine the distinct approaches that might be needed. In discussing syndromic surveillance systems, the group noted that this approach lends itself to working directly with communities and health care providers to ensure real-time surveillance in specific locations, with limited resources. The group also considered existing networks such as the LEO Network as a platform for this type of community engagement. Other large sources of data (e.g., from Google and Amazon) could be used as a resource in understanding flu trends, for example, and other epidemiological information. Use of military liaisons may be another method of connecting with local communities, though concerns about maintaining relationships and communication with indigenous people requires sensitivity. The group shared that co-production of research with local

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[4] See https://mosaic-expedition.org/.
[5] See https://www.t-mosaic.com/.

communities would ideally be planned from the beginning with robust community participation.

In thinking about a sentinel disease surveillance system, the group noted that a One Health approach is relevant for people and animals as well. The Arctic fox, for example, is circumpolar, crosses large distances, and scavenges for food sources and thus may be an interesting sentinel species to consider. Having case definitions for wildlife surveillance would be useful, and surveys could help establish baselines. A system may be needed to rapidly collect and analyze samples in local communities, for their health as well as the broader global health response network. If diagnostic testing is unavailable for individual diseases, whole genome sequencing, for example, could be used to identify outbreak clusters. Standardized approaches and informatics output around the purpose of surveillance will be key, but the groups emphasized the crucial need to build relationships and trust with communities.

Current Surveillance Approaches in the Arctic

Current surveillance approaches vary across Arctic countries, states, and territories. Most countries in the Arctic have state or countrywide surveillance programs looking for infectious diseases. In the US and some Canadian territories, states select their own reportable diseases. The breakout group noted that Finland has good system for coordination between both humans and wildlife; there are fewer transport issues and fewer issues related food quality surveillance. Most countries do not have wildlife surveillance networks. There are very isolated and closed networks, and veterinarians need to decide what tests to order and where to send information. The group emphasized that funding is a main concern. Currently, research projects are funded for a specific purpose, and wildlife surveillance programs might be able to utilize some of those resources, but there is no designated, funded, long-term, routine, and systematic program available. Different programs exist for different pathogens, and some must go through government labs for testing. Large geographic distances are problematic for sample transport. For example, in Canada, where there are concerns about brucellosis, the samples travel great distances, and the meat must be frozen until the lab tests are returned. However, this is unlikely to happen, and the meat is shared widely so may be hard to track. The group debated the ability of current systems to detect emergence of new human pathogens. They noted that research programs at universities may be able to test for emerging pathogens, but connections and partnerships with other laboratories would be useful. Improved animal/human interface surveillance programs may be able to detect new human pathogens, and unusual presentation in particular could be detected quickly in some areas. Despite progress in surveillance systems in some countries, cases of influenza-like illnesses and foodborne illnesses remain underdiagnosed and underreported in many Arctic areas.

Examining the Benefits of International Surveillance Standards

Small groups also discussed the need for international standards around surveillance. Existing procedures could be harmonized on an international level, together with harmonization of the types of diseases are reportable from labs. Diagnostic laboratories could be a good way to accomplish this. The group posed a number of questions such as: Why not report all diseases? How can standard methods for selecting reportable diseases be achieved? At issue are emerging infections that rely on surveillance systems, and the need to monitor geographically (including the Russian Arctic) and with wildlife to prepare for these events. This group also emphasized a One Health approach for looking at trends, especially given that the biggest driver for human health is global environmental change. The group underscored again that human data could be harmonized with wildlife surveillance and landscape surveillance.

Final Thoughts: Impacts of Microbial Threats on Stakeholder Organizations

During the final workshop discussion session, **Dr. Aðalheiður Inga Þorsteinsdóttir, Ministry for Foreign Affairs of Iceland**, shared information about the Arctic Council and the role it may play in considerations of Arctic microbial threats. The Arctic Council is the leading intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, indigenous communities and other Arctic inhabitants, on common Arctic issues. In particular, the Council focuses on issues of sustainable development and environmental protection in the Arctic. The Ottawa Declaration lists the following countries as Members of the Arctic Council: Canada, the Kingdom of Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden and the United States. In addition, six organizations representing Arctic indigenous peoples have status as Permanent Participants. The category of Permanent Participant was created to provide for active participation and full consultation with the Arctic indigenous peoples within the Council. Observer status in the Arctic Council is open to non-Arctic states, along with inter-governmental, inter-parliamentary, global, regional and non-governmental organizations that the Council determines can contribute to its work. Arctic Council Observers primarily contribute through their engagement at the level of the Council's Working Groups:

- The Arctic Contaminants Action Program acts as a strengthening and supporting mechanism to encourage national actions to reduce emissions and other releases of pollutants.
- The Arctic Monitoring and Assessment Programme monitors the Arctic environment, ecosystems and human populations, and provides scientific advice to support governments as they tackle pollution and adverse effects of climate change.
- The Conservation of Arctic Flora and Fauna Working Group addresses the conservation of Arctic biodiversity, working to ensure the sustainability of the Arctic's living resources.
- The Emergency Prevention, Preparedness and Response Working Group works to protect the Arctic environment from the threat or impact of an accidental release of pollutants.
- The Protection of the Arctic Marine Environment Working Group is the focal point of the Arctic Council's activities related to the protection and sustainable use of the Arctic marine environment.
- The Sustainable Development Working Group works to advance sustainable development in the Arctic and to improve the conditions of Arctic communities as a whole.

The Council may also establish Task Forces or Expert Groups to carry out specific work. Dr. Þorsteinsdóttir noted that at any given time, the Arctic Council is likely running close to a hundred projects. Arctic Council assessments and recommendations are the result of analysis and efforts undertaken by the Working Groups. Decisions of the Arctic Council are taken by consensus among the eight Arctic Council States, with consultation and involvement of the Permanent Participants. The Chairmanship of the Arctic Council rotates every two years among the Arctic States. Iceland assumed the Chairmanship from Finland in May 2019. The next Chair will be Russia in 2021. Icelandic Chairmanship priority areas include the Arctic marine environment, climate and green energy solutions, people and communities, and a stronger Arctic Council. It is important to note that the Arctic Council is a forum; it is not an international organization and it has no programming budget. All projects or initiatives are sponsored by one or more Arctic States. Some projects also receive support from other entities. The Arctic Council cannot implement or enforce its guidelines, assessments or recommendations. That responsibility belongs to each individual Arctic State. Last and not least, the Arctic Council's mandate, as articulated in the Ottawa Declaration, explicitly excludes military security.

In 2010, the Arctic Council's Sustainable Development Working Group (SDWG) created the Arctic Human Health Expert Group (AHHEG). Dr. Þorsteinsdóttir noted that it is responsible for framing the SDWG human health agenda, proposing priorities and projects, and assessing proposals for actions that will contribute to the advancement of a knowledge base on circumpolar human health. AHHEG is also a resource to the Council's Working Groups on broader crosscutting health research and activities. It may provide advice to the Council's Senior Arctic Officials, on current issues of relevance to the circumpolar human health community. The first phase of SDWG's *One Arctic, One Health* project was initiated under the US Chairmanship in 2015. The project has continued under the Chairmanship of Finland and now Iceland.

Mr. Joshua Glasser, US Department of State, reflected on workshop discussions and emphasized the value of circumpolar cooperation. Following Dr. Þorsteinsdóttir's remarks, Mr. Glasser noted that the activities of the *One Arctic, One Health* project include three pillars: information sharing, tabletop exercises, and collaborative investigations (which may be operational or research in nature). Two tabletop exercises have been held, one in Ottawa and one in Anchorage, that addressed gap analysis and partnership development after a simulated threat has been identified. The goal of the project is to establish points of contact throughout the Arctic to sustain networks of collaboration on One Health issues. Mr. Glasser noted the timeliness of these discussions, given the expectation that the trends driving emerging microbial risks will continue—due in part to rapid environmental and social change, but also due to increased travel and tourism to, from, and through the region.

The Arctic Council includes permanent participant organizations representing indigenous communities, and Mr. Glasser noted that many Working Group meetings take place above the Arctic Circle. It may be useful to conduct subsequent workshops in northern communities, to increase indigenous engagement. He also acknowledged the enterprise of sustainable development and the need to balance similarities and differences between public health perspective, a wildlife health perspective, and an environmental management perspective, as well as the need for both short-term emergency management and long-term research enterprises. In addition, he noted that it is critical to be aware of the region's bioinfrastructure context and to remain sensitized to biosafety and biosecurity concerns while this work progresses.

Additional reflections were shared by **Ms. Christina Chappell, US Agency for International Development** (USAID), who noted that the Office of Infectious Diseases collaborates with developing countries to increase their capacity to address infectious disease threats (particularly malaria and tuberculosis). Programming is done for global health security[1] with a One Health perspective to examine emerging pandemic threats as well as neglected tropical diseases and outbreaks of unusual nature. Most of the USAID current program is outside of the Arctic, but that work could potentially benefit from ongoing partnerships developed across disciplines. There are parallels to other USAID development work for health sector initiatives, particularly the focus on local capacity and best practices, which is vital to ensure interventions are targeted and effective. Ms. Chappell noted that collective systems are needed to ensure early alerts to proactively address emergent threats. There is also an interest in applying research for decision-making and action at state and community levels.

Ms. Chappell reiterated that a One Health lens is vital for programming at the confluence of human, animal, and ecosystem health. Cultural context is vital to ensure engagement of communities, tailored interventions to create behaviors that are effective in protecting communities and wildlife, cultivated and built in partnership. She asked if there is an implication of gender-based risk within communities, depending on who is placed at risk due to behaviors and expectations around burial practices, food preparation, and other activities. Innovative use of technologies, such as data platforms and data mining, communications for quick alerts, satellite technology, and micro-mapping can help accelerate accumulation of data sets and help to gather strategic expertise needed for a tailored response effort. She noted that partnership was a key theme of workshop discussions, and asked participants to also consider effective examples of collaborating with private sector enterprises. This may be an option for future exploration, especially with extractive industries and tourism. This is also related to global health security and potential interest in collectively building sustainable enterprises and capacity that can be retained long-term. Ms. Chappell concluded her remarks by noting that USAID seeks to help countries and communities assess risk, understand current and projected threats, and build resilience. Together with USAID's Office of Foreign Disaster Assistance, risk factors are identified that may be useful for international response efforts.

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[1] "Global health security is the existence of strong and resilient public health systems that can prevent, detect, and respond to infectious disease threats, wherever they occur in the world." Source: https://www.cdc.gov/globalhealth/security/index.htm.

Dr. Bert Rima, Wellcome-Wolfson Institute for Experimental Medicine, expressed his interest in risk assessments for genetically modified organisms and the relationship to gain of function experiments. Reflecting on workshop discussions, he pointed out that the Arctic research community is well connected in some ways, but research gaps remain. He felt that the workshop's emphasis on trying to improve health care for communities in the Arctic is an important element in assessing risk of emerging organisms. Tropical microorganisms have evolved to thrive in temperatures that are similar to human body temperatures, where as microorganisms in permafrost have evolved to live in very different temperatures. This difference may have an impact on the likelihood of emerging infections for humans. Animal carcasses are a potential source of pathogens, and people in the Arctic may interact with these for economic and also for personal reasons, especially where it concerns human remains. Scavengers are attracted to these and animal remains as well, and this can lead to a situation where it is likely that they will be exposed to pathogens and might become an amplifying host.

Surveillance for known pathogens may be difficult in Arctic regions due to complex geography, but the process is well known. Dr. Rima concluded from workshop discussions that the anthrax outbreak in Russia was an exceptional case, and it is not clear how long anthrax had been in the environment. It likely is a relatively recent re-introduction and this could not be considered to be a prior event to use as a baseline in Bayesian statistics. For known pathogens, there may not be much cause for concern, except for issues associated with challenging logistics of the Arctic environment. He emphasized that the likelihood of emergence of unknown or eradicated pathogens is extremely difficult to establish. Dr. Rima estimates that the likelihood of an RNA virus surviving in the Arctic environment for long periods of time is very low as RNA as a molecule is not very stable. Metagenomics do not always produce a useful result. He wondered what could be detected by sequencing DNA, what would be viable, what could be cultured, and what would be found to be pathogenic. Finding an unknown virus is likely a very difficult task due to the fact that much of the so-called "dark sequence material" in metagenomic studies is probably derived from viruses of animal, plant, and bacterial organisms. It would require much more research before that technology could be used to find viable organisms as most of the nucleic acids are degraded. Using relatively simple, structured experiments of spiking microbes into permafrost (that goes through freeze and thaw cycles) could be helpful research to understand survivability and stability of the organisms and their nucleic acids.

Closing Remarks

Reflecting on workshop discussions and presentations, participants engaged in an open discussion session to share thoughts on what is known about microbial risks, what is unknown, and potential paths forward. **Mr. Bob Reiss, an author and journalist**, started the discussion by noting the importance of the intersection of science, policy, and language especially in communicating about difficult issues. One participant proposed a thought exercise: if Arctic countries agreed to initiate a new global health security initiative and committed significant new funding sources, how should the funding be spent? For example, it could be spent on early warning for global health security threats, capabilities for human and animal surveillance, gathering additional data, and a number of other priorities. Participants considered what mechanisms would help to improve understanding of global health security threats around the Arctic, and noting that it ultimately depends on the source of funding, made several suggestions including:

- Capacity building in communities, including education;
- Improved access to remote regions;
- Harmonization of data;
- Mechanisms to encourage international global collaboration;
- Introduction of the One Health concept into reporting systems;
- Training for One Health in every rural community;
- Support for basic research to identify environmental triggers and improve mechanistic understanding;
- Mechanisms for networks to inform each other effectively and tools to facilitate communication;
- Sentinel health systems to pick up severe health disturbances in people and animals in the Arctic;
- Definitive rapid diagnoses when there are unusual disturbances; and
- Systems that are of routine value for people in local communities.

Participants noted that it would be helpful to understand relative risks specifically in the Arctic compared to health security across the globe. What is the potential reduction in the global disease burden associated with research investments in the Arctic and where could that spending be maximized? Are there opportunities for bioprospecting or exploration of potentially beneficial biochemical or genetic materials in the permafrost? Given the uncertainties and gaps in research to date, it is challenging to understand the potential benefits and real risks posed by the Arctic regions in this context. A participant noted that continued research and resources are warranted, especially considering the sheer pace of environmental and social change in the Arctic as well as commonalities between Arctic and non-Arctic communities. Given that there is the potential to achieve relatively high impact with comparatively straightforward interventions built on robust health systems, there are important benefits to continuing engagement in the Arctic region. There may also be broad benefits associated with scientific information acquired about the permafrost microbiome. Significant changes in the Arctic associated with increased tourism and increased travel may indicate the need and value of understanding the potential for harmful microorganisms in the region. However, it is not clear that the Arctic should be considered a "hot spot" for disease emergence, especially compared to areas that are known to be high risk.

Importantly, global health security threats do exist in regions of the Arctic. Participants noted that there are areas of the Arctic in which a large disparity exists between the health of northern people and non-Arctic people. Hot spot maps may have detection bias, and population density in the Arctic is much smaller than other places under study. However, the potential impacts on those small communities could be catastrophic and there are different ways of weighing the risks. The Arctic is changing and could become a bigger risk as it thaws. In this context, participants considered the value of stopping an outbreak before it starts versus waiting until it is out of control. In terms of biodiversity, plants and animals are more diverse around the equator, but that does not apply for microorganisms, where diversity is perhaps uniform (albeit different) throughout the globe. New diseases are appearing in the Arctic and certain species of wildlife are disappearing. That may imply that the Arctic is a hot spot for bioconservation efforts, and a One Health approach could be utilized to ensure well-being of humans and animals in the region. Technology being developed for emerging diseases elsewhere in the world could be leveraged and tailored specifically for Arctic needs (i.e., education and sampling). Participants noted that, in much of the world, indigenous people are land stewards and they face activities (industrial and otherwise) that may be damaging to local and downstream health effects.

Discussion turned to the types of data that could be collected to counteract skepticism about the Arctic as a potential hot spot for emerging infectious disease. Beyond risks associated with permafrost thaw and ice melt, other risks were not explored in this workshop. In many Arctic countries, “hidden” populations may not be represented in research on risk. The associated health differences and disparities are important factors to consider. Many people live in lower socio-economic conditions and may have reduced access to care, contributing to higher disease rates. It is estimated that 70 percent of Canadian Inuit youth are food insecure. Because the Arctic is rich in resources, it is also under a large amount of pressure from outside sources (e.g., shipping, climate change, etc.). Given the extent of change occurring in the Arctic system, there may be valuable lessons learned that could be applied throughout the rest of the world. A participant noted that although the discussions have been focused on pathogenic microbes, cryosphere change might lead to the loss of entire microbial ecosystems, with uncertain implications for the rest of the biosphere. Most of the microbiology of the north remains unknown, and it can be difficult to communicate the crucial need for local capacity building and augmentation to those unfamiliar with the region. Many participants stressed the importance of a common vocabulary and communication within a One Health framework.

Concluding the workshop, **Dr. Volker Ter Meulen, InterAcademy Partnership and Planning Committee Vice Chair**, noted that increased engagement with Arctic research colleagues across disciplines will be useful for continued exploration of this topic. Arctic countries have a responsibility to understand what is needed to care for Arctic people and environments. He encouraged participants to consider continued exploration of these topics, collaborations with social scientists, and ensuring broader societal engagement. Although there may currently be more questions than answers, researching the risks associated with pathogen emergence is a crucial way forward.

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Appendix A
Statement of Task

This workshop will bring together an international, interdisciplinary group of experts to explore what is known, and what critical knowledge gaps remain, regarding existing and possible future risks of harmful infectious agents emerging from thawing Arctic environments. Discussions will encompass topics such as:

- known risks such as anthrax, and other unknown human and animal microbial health risks that could conceivably be harbored in ice and permafrost;
- key research needs and critical tools for improving observations and surveillance, to advance our understanding of these risks, and to develop effective early warning systems;
- relevant lessons learned from efforts to address emerging/re-emerging microbial threats elsewhere in the world; and
- opportunities to facilitate interagency and international cooperation on such efforts, and to build upon existing programs and platforms for cooperation.

Appendix B
Planning Committee Biosketches

Diana Wall, Ph.D., *(Chair),* is an elected member of the National Academy of Sciences and the American Academy of Arts and Sciences and is the 2013 Laureate of the Tyler Prize for Environmental Achievement. She is currently Science Chair, Global Soil Biodiversity Initiative. To understand the importance of soil biodiversity, she works at the physical limits to life in the Antarctic dry valleys where climate change effects are amplified and species diversity is much reduced compared to other soil ecosystems. Dr. Wall's more than 25 years of research in the Antarctic continues to clarify the critical links between climate change and soil biodiversity. Her interdisciplinary research has uncovered dramatic impacts to invertebrate communities in response to climate change, the key role nematode species play in soil carbon turnover, and how they survive such extreme environments. Dr. Wall has combined her polar research with global scale field studies demonstrating that soil animals increase decomposition rates more in temperate and moist tropical climates than in cold and dry conditions, indicating a latitudinal gradient in their roles in ecosystems. Dr. Wall served as President of the Ecological Society of America, the American Institute of Biological Sciences, and the Society of Nematologists. Dr. Wall received the 2017 Eminent Ecologist Award from the Ecological Society of America, the 2016 Honorary Member award from the British Ecological Society, the 2015 Ulysses Medal from University College Dublin, the 2012 SCAR President's Medal for Excellence in Antarctic Research and the 2013 Soil Science Society of America Presidential Award. Wall Valley, Antarctica was named in 2004 to recognize her research. She is a Fellow of the Ecological Society of America and the Society of Nematologists and holds an Honorary Doctorate from Utrecht University, The Netherlands. She is the Inaugural Director of the School of Global Environmental Sustainability at Colorado State University. She received a B.A. in biology and Ph.D. in plant pathology at the University of Kentucky, Lexington.

Volker ter Meulen, M.D., *(Vice Chair),* qualified as an M.D. in 1960. He received his post-doctoral training in virology in the United States at the Children's Hospital of Philadelphia. On returning to Germany in 1966, he specialised in paediatrics and was subsequently Visiting Scientist at the Wistar Institute for Anatomy and Biology in Philadelphia and at the Viral and Rickettsial Disease Laboratory in Berkeley from 1969 to 1970. In 1975 he became a full professor and Chairman of the Institute of Virology and Immunobiology at the University of Würzburg. He retired in 2002, having twice been elected Dean of the Faculty of Medicine of Würzburg University. During his research career, Dr. ter Meulen worked on molecular and pathogenic aspects of viral infections in man and animals, in particular on infections of the central nervous system. Due to the recognition of his research achievements and his experience in heading a Medical Faculty, Dr. ter Meulen has on numerous occasions been invited to give policy advice on research matters to German research organizations and to state and federal ministries of science in Germany. Internationally, Dr. ter Meulen has served on a number of committees of organizations and scientific societies/unions in the area of virology and infectious diseases, covering a broad spectrum of important issues connected to human and animal pathogens. From 2003 to 2010, Dr. ter Meulen was President of the German Academy of Sciences Leopoldina. Under his leadership, the Leopoldina strengthened its international commitments in different inter-academic councils and was appointed to the National Academy of Sciences in 2008. From 2007 to 2010, he was President of the European Academies Science Advisory Council (EASAC), the association of the National Science Academies of the European Union, which is the Interacademy Panel (IAP) associated regional network for Europe. He was elected IAP Co-Chair in February 2013.

Robyn A. Barbato, M.Sc., Ph.D., has, since October, 2013, served as a Research Microbiologist at the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, one of seven laboratories that comprise the U.S. Army Engineer Research and Development Center (ERDC). Dr. Barbato leads the Cold Regions Microbiology Team and conducts research on extremophiles in the environment. Dr. Barbato began her career with the Army in 2011 as a postdoctoral fellow with CRREL. After a year and a half of service, she became a federal employee at the laboratory. In 2016, Dr. Barbato was awarded the Department of the Army Achievement Medal for Civilian Service. She has completed the Leadership Development Program and in 2018 was competitively selected for the Emerging Leaders Group. As an extremophile microbiologist, Dr. Barbato leads a team of researchers to answer challenging questions relating to life in the cold regions of the planet. She has extensive experience leading field campaigns in the sub-Arctic and Arctic Alaska to study the permafrost microbiome and how it changes during thaw, as well as the efficacy of bioremediation treatment technologies in cold regions. She and her team write competitive grants to explore the intricate relationships among microorganisms and their surrounding environment, including their ecosystem impacts to address Department of Defense problems on range sustainability, forensics, and detection. Dr. Barbato takes a holistic systems-based approach by combining empirical laboratory and field measurements with stand-off sensing techniques like terrestrial laser scanning and modeling efforts. In doing so, she answers ecosystem-level research questions such as shifts in microbial communities and processes as a result of extreme weather. By generating high resolution microbial sequencing and metagenomics data, she and her collaborators attempt to statistically describe the natural environment and how it changes with perturbations, particularly in extreme environments such as the cold. Dr. Barbato graduated with a Bachelor of Science degree at Cook College, Rutgers University in New Brunswick, New Jersey in 2005. In 2008, Dr. Barbato earned her Master of Science degree at the Graduate School of New Brunswick at Rutgers University. Four years later, Dr. Barbato earned her Ph.D. at Rutgers University studying the response of the soil microbiome to wildfire.

Birgitta Evengård, M.D., Ph.D., is a professor of infectious diseases in the Department of Clinical Microbiology at Umeå University, Sweden and is a senior consultant for Clinic Infectious diseases at Umeå University hospital. From 2008 to 2015, she was a member of the Arctic Human Health Expert group, and between 2011 and 2013 she was chair. Dr. Evengård was chair of ARCUM, the Arctic Research Center at Umeå University, between 2012 and 2016. Since 2016, she has been a member National Committee for Global Environmental Change at the Swedish Royal Swedish Academy of Sciences. She is Principal Investigator for the Nordic Center of Excellence funded by Nordforsk: Responsible Development in the North, 2016-2021. Dr. Evengård has over 135 publications in peer-reviewed journals, and she is the author and editor of 11 books. The focus of her research has been infectious diseases in diagnostics, epidemiology and clinical findings with a focus since 2007 on Arctic issues, including health in a changing climate in the North.

Robin Fears, Ph.D., D.Sc., has 29 years experience in the pharmaceutical industry in the UK in research and development (R&D). The first 20 years were focused on cardiovascular disease and neurosciences, from discovery through to marketed product. The final nine years of this industry experience was occupied in setting up and leading a policy group for R&D in Europe. While in industry, he served on committees advising UK and EU trade associations, UK government, Research Councils, university groups and the European Commission and he was Honorary Senior Fellow at the School of Public Policy at the University College London. Since leaving the UK pharmaceutical sector, he has worked as an advisor to various bodies including academies, universities, businesses and parliamentary groups on issues relating to biomedical science and innovation within the European policy environment. He has provided biosciences support to EASAC since 2002.

Charles N. Haas, Ph.D., M.S., is the L.D. Betz Professor of Environmental Engineering and head of the Department of Civil, Architectural and Environmental Engineering, at Drexel University, where he has been since 1991. He also has courtesy appointments in the Department of Emergency Medicine of the Drexel University College of Medicine and in the School of Public Health. He received his B.S. (Biology) and M.S. (Environmental Engineering) from the Illinois Institute of Technology and his Ph.D. in Environmental Engineering from the University of Illinois at Urbana-Champaign. He has served on the faculties of Rensselaer Polytechnic Institute and the Illinois Institute of Technology prior to joining Drexel. He co-directed the USEPA/DHS University Cooperative Center of Excellence – Center for Advancing Microbial Risk Assessment (CAMRA). He is a fellow of the International Water Association, American Academy for the Advancement of Science, the Society for Risk Analysis, the American Society of Civil

Engineers the American Academy of Microbiology and the Association of Environmental Engineering and Science Professors. He is a Board Certified Environmental Engineering Member by eminence of the American Academy of Environmental Engineers. He has received the Dr. John Leal Award and the AP Black Award of the American Water Works Association and the Clarke Water Prize. Over his career, Professor Haas has specialized in the assessment of risk from and control of human exposure to pathogenic microorganisms, and in particular the treatment of water and wastewater to minimize microbial risk to human health. Professor Haas has served on numerous panels of the National Academies of Sciences, Engineering and Medicine. He is a past member of the Water Science and Technology Board of the National Academies, and the US EPA Board of Scientific Counselors.

Thomas Inglesby, M.D., is the Director of the Center for Health Security of the Johns Hopkins Bloomberg School of Public Health. Dr. Inglesby is also a Professor in the Department of Environmental Health and Engineering in the Johns Hopkins Bloomberg School of Public Health, with a Joint Appointment in the Johns Hopkins School of Medicine. Dr. Inglesby's work is internationally recognized in the fields of public health preparedness, pandemic and emerging infectious disease, and prevention of and response to biological threats. He is Chair of the Board of Scientific Counselors, Office of Public Health Preparedness and Response, US Centers for Disease Control and Prevention (CDC). He previously served as Chair of the National Advisory Council of the Robert Wood Johnson Foundation's National Health Security Preparedness Index. He was a member of the CDC Director's External Laboratory Safety Workgroup, which examined biosafety practices of the CDC, the National Institutes of Health (NIH), and the Food and Drug Administration (FDA) following high-profile laboratory incidents in federal agencies. He was on the 2016 Working Group assessing US biosecurity on behalf of the President's Council of Advisors on Science and Technology (PCAST). He has served on committees of the Defense Science Board, the National Academies of Sciences, and the Institute of Medicine, and in an advisory capacity to NIH, BARDA, DHS, and DARPA. Dr. Inglesby has authored or co-authored more than 130 publications, including peer-reviewed research, reports, and commentaries on issues related to health security, preparedness for epidemics, biological threats, and disasters. He is Editor-in-Chief of the peer-reviewed journal *Health Security*, which he helped establish in 2003. He was a principal editor of the JAMA book *Bioterrorism: Guidelines for Medical and Public Health Management*. He has been invited to brief White House officials from the past four presidential administrations on national biosecurity challenges and priorities, and he has delivered Congressional testimony on a number of issues related to public health preparedness and biosecurity. He is regularly consulted by major news outlets for his expertise. He is a member of the Board of Directors of PurThread, a company dedicated to developing antimicrobial textiles. Dr. Inglesby completed his internal medicine and infectious diseases training at Johns Hopkins University School of Medicine, where he also served as Assistant Chief of Service in 1996-97. Dr. Inglesby received his M.D. from

Columbia University College of Physicians and Surgeons and his B.A. from Georgetown University. He sees patients in a weekly infectious disease clinic.

Rebecca Katz, Ph.D., M.P.H., is a Professor and Director of the Center for Global Health Science and Security at Georgetown University. Prior to coming to Georgetown, she spent ten years at The George Washington University as faculty in the Milken Institute School of Public Health. Her research is focused on global health security, public health preparedness and health diplomacy. Since 2007, much of her work has been on the domestic and global implementation of the International Health Regulations. Since 2004, Dr. Katz has been a consultant to the Department of State, working on issues related to the Biological Weapons Convention, pandemic influenza and disease surveillance. She was the co-convener of the Global Health Security 2019 conference in Sydney, Australia. Dr. Katz received her undergraduate degree from Swarthmore College, an M.P.H. from Yale University, and a Ph.D. from Princeton University.

Susan Kutz, DVM, Ph.D., is a Professor in the Department of Ecosystem and Public Health at the University of Calgary Faculty of Veterinary Medicine, Calgary, Alberta. She completed her Doctor of Veterinary Medicine at the Western College of Veterinary Medicine, University of Saskatchewan in 1992. After working as a veterinarian in the Canadian Arctic for a few years she returned to do a Ph.D. in wildlife parasitology at the University of Saskatchewan. Following that she was a post-doctoral fellow at the University of Alaska, Fairbanks, where she studied host-parasite associations in Beringia. She was a founding member of the Faculty of Veterinary Medicine at the University of Calgary, is Co-Editor in Chief for the journal International Journal of Parasitology - Parasites and Wildlife, is on the Board of Directors for the Arctic Institute of North America, is past Director of the Alberta Centre of the Canadian Cooperative Wildlife Health Centre and past member of the Terrestrial Mammals Committee on COSEWIC (Committee on the Status of Endangered Wildlife in Canada).Dr. Kutz's research interests include understanding the impacts of climate and landscape change on host-parasite interactions in the Arctic. She has research programs investigating parasite biodiversity, invasion processes, and the impacts of parasites on host populations, food safety and food security and has published widely in this field (over 125 publications). She brings local, traditional and scientific knowledge together to generate a better understanding of wildlife health and ecology and for early detection and response to emerging health issues. She has extensive collaborations around the Arctic, led a major circumarctic caribou and reindeer health assessment program during International Polar Year, and sits on the Muskox Expert Network for CAFF. In the Arctic, Dr. Kutz works closely with aboriginal subsistence hunters to monitor wildlife health and has maintained a popular NSERC PromoScience funded outreach program in the Canadian North since 2004. Her research interests in parasitology extend beyond the Arctic, where she also collaborates on studies in behavioral ecology and parasitism in non-human primates, wild ungulates, and carnivores.

Appendix C
Workshop Agenda

Understanding and Responding to Global Health Security Risks from Microbial Threats in the Arctic

6 – 7 November 2019
Herrenhausen Palace
Herrenhäuser Straße 5, 30419 Hanover, Germany

Workshop Goals

- Bring together an interdisciplinary, international group of researchers and public health officials to explore what is known and what critical knowledge gaps remain regarding existing and possible future risks of harmful infectious agents emerging from thawing permafrost and ice in polar climates.
- Provide a helpful state-of-the-science overview and information to help frame new actions that advance research, surveillance, and response capacity.

Wednesday, 6 November 2019

8:30 AM **Welcome and Plans for the Workshop**
- Henrike Hartmann, Executive Management, Volkswagen Foundation
- Diana Wall and Volker ter Meulen, Planning Committee Chair and Vice Chair

8:45 AM **Vladimir Romanovsky, University of Alaska Fairbanks**
The driving forces: Arctic and Antarctic warming and permafrost thaw (observed and projected changes)

9:05 AM **Albert Osterhaus, University of Veterinary Medicine Hannover**
Emerging infectious and zoonotic diseases and environmental change; One Health

9:25 AM **Keith Chaulk, Stantec**
Broader global context, sustainable development goals, human dimensions

9:45 AM **Discussion**

SESSION 1: WHAT DO WE KNOW?

Guiding questions for the session:

- *How quickly is the permafrost thawing and where (including mountain glaciers and high altitudes)?*
- *What do we expect to find (animals? corpses? ancient pathogens in frozen animals? pathogens in permafrost?) and where? How old are the animals, corpses, ancient pathogens that will be uncovered in the next 5-10 years?*
- *What are the existing research efforts in permafrost now to determine if the DNA parts can be sequenced?*
- *What do we know about the microbial ecology of permafrost and ice environments and their sensitivity to climatic changes (including how fast frozen microbes can evolve)?*
- *What do we know about the viability of microorganisms in these environments?*
- *What do we know about our ability to detect changes/emergence in arctic peoples and animals?*

10:00 AM **Jean Michel Claverie, Aix-Marseille University**
Viruses in permafrost

10:30 AM *Break*

10:50 AM **Alexander Volkovitskiy, Russian Academy of Sciences and Yamal Expedition**
2016 Anthrax Outbreak

11:10 AM **Panel: Ecosystem Changes: What are the microbial threats we know are in the environment?**
Moderated by: Birgitta Evengård, Umeå University, Planning Committee Member

- **Tom Douglas, CRREL:** ecosystem-permafrost relationships, seasonal thaw, and thermokarst
- **Emily Jenkins, University of Saskatchewan:** diseases at the human / animal / environment interface
- **Aleksandr Sokolov, Russian Academy of Sciences:** terrestrial ecosystems of Yamal

11:50 AM **Jan Semenza, European Centre for Disease Prevention and Control**
Environmental and climatic determinants of infectious disease

12:10 PM **Panel: Exploring the Potential Risk of Human and Animal Exposure to Threats**
Moderated by: Charles Haas, Drexel University, Planning Committee Member

- **Natalia Pshenichnaya, National Medical Research Center of Phthisiopulmonology and Infectious Diseases:** infectious pathology
- **Anne Jensen, Ukpeavik Inupiaq Corporation (UIC) Science LLC:** human adaptation in arctic and subarctic environments; traditional knowledge of Inupiaq peoples
- **Dmitry Orlov, University of Moscow:** infectious diseases
- **Jay Butler, US Centers for Disease Control and Prevention:** clear and present dangers from infectious diseases in Alaska related to climate change
- **William Bower, US Centers for Disease Control and Prevention**

1:10 PM *Lunch*

SESSION 2: WHAT DO WE NEED TO KNOW?

Guiding questions for the session:

- *Given the kinds of permafrost research on living organisms and disease organisms that will go on, which of these areas of research will expose scientists or the local communities to microbial risk? Will other activities such as oil extraction expose populations?*
- *What are best scientific judgments regarding what kinds of pathogens might be uncovered in the permafrost?*
- *Which of these might be still viable?*
- *What scientific approaches should be used?*
- *What kind of facilities/institutions should do the work?*
- *What are the different pathways through which people could be exposed to harmful infectious agents?*
- *What are the critical gaps in our scientific understanding and surveillance/observational capabilities?*

2:20 PM **Craig Stephen, Canadian Wildlife Health Cooperative**
Wildlife health surveillance

2:40 PM **Luise Müller, Statens Serum Institut**
Human health surveillance

3:00 PM **Panel: Priority Research Needs: What are the critical gaps in our scientific understanding and surveillance capabilities?**
Moderated by: Robyn Barbato, Cold Regions Research and Engineering Lab, Planning Committee Member

- **Lise Øvreås, University of Bergen:** Arctic ecology and micro-organisms
- **Sanne Eline Wennerberg, Veterinary & Food Authority of Greenland:** human/animal exposure
- **Jessica Ernakovich, University of New Hampshire:** permafrost microbiome and Arctic biogeochemistry
- **Tatiana Vishnivetskaya, University of Tennessee:** microbial community structure and biodiversity of extreme environments
- **David Stanton, Swedish Museum of Natural History**

3:45 PM **Instructions for the Breakout Groups**

3:55 PM *Break*

4:15 PM **Breakout Group Discussions on Biosafety and Biosecurity Risks**

- *Group 1: Assessing lab procedures / techniques likely to be used*
- *Group 2: Appropriate biocontainment and engineering controls*
- *Group 3: Approach to risk assessment for this work*
- *Group 4: Impacts of organisms in thawing permafrost and exposed carcasses on indigenous and local communities*

5:15 PM **Breakout Groups Report Back in Plenary**

5:45 PM **Wrap-Up and Goals for Day 2**
Diana Wall and Volker ter Meulen, Planning Committee Chair and Vice Chair

6:00 PM *Adjourn Day 1*

Thursday, 7 November 2019

8:30 AM **Reflections on Day 1 and Plans for Day 2**
Diana Wall and Volker ter Meulen, Planning Committee Chair and Vice Chair

SESSION 3: RESEARCH AND OPERATIONAL PATHS FORWARD

Guiding questions for the session:

- *What are some key opportunities to facilitate multidisciplinary, interagency, and international cooperation and collaboration?*
- *How can we build upon existing research and observational programs and platforms?*
- *What sorts of ethical dimensions must be considered for working with indigenous communities, and for monitoring and recovering samples from human remains?*
- *What can we learn from research in other regions (e.g., Antarctic research)?*

8:45 AM **Michael Brubaker, Local Environmental Observer (LEO) Network**

9:05 AM **Eduard Zdor, University of Alaska Fairbanks & Cheryl Rosa, US Arctic Research Commission**
Zoonotic diseases of importance to subsistence communities

9:25 AM **Susan Kutz, University of Calgary**
Using indigenous knowledge and community-based surveillance to detect emerging pathogens

9:45 AM **Panel: Examples of International and Multidisciplinary Research Projects (From microbial discovery to surveillance to response)**
Moderated by: Susan Kutz, University of Calgary, Planning Committee Member

- **Michael Bruce, US Centers for Disease Control and Prevention:** International Circumpolar Surveillance and collaborative One Health research in the Arctic
- **Trista Vick-Majors, Michigan Tech:** examples from Antarctic microbiology
- **Arja Rautio, University of Oulu**
- **Warwick Vincent, Université Laval**

10:45 AM **Instructions for the Breakout Groups**

10:55 AM *Break*

11:15 AM **Breakout Group Discussions on Harmonization of Surveillance Data**

- *Group 1: Need for special surveillance approaches*
- *Group 2: Current surveillance approaches in the Arctic*
- *Group 3: Need for international standards around surveillance*
- *Group 4: Microbiologic / diagnostic approaches for surveillance in the Arctic to have the earliest possible warning of diseases that emerge from the permafrost*

12:15 AM **Breakout Groups Report Back in Plenary**

1:00 PM *Lunch*

2:20 PM **Comments from Participating Stakeholders**
Which aspects of microbial threats in the Arctic may influence decisions at your agency or organization? What are near-term concerns vs. far-term concerns?

- **Aðalheiður Inga Þorsteinsdóttir, Ministry for Foreign Affairs of Iceland**
- **Joshua Glasser, US Department of State**
- **Christina Chappell, US Agency for International Development**
- **Bert Rima, Wellcome-Wolfson Institute for Experimental Medicine**

3:10 PM **Guided Discussion Session**
Facilitated by: **Bob Reiss, author and journalist**

3:50 PM **Final Thoughts and Wrap-Up**
Planning Committee Members

4:00 PM *Adjourn Workshop*

Appendix D
Workshop Participants

Robyn Barbato, U.S. Army CRREL,* United States of America
Andrew Bartlow, Los Alamos National Laboratory, United States of America
William Bower, US Centers for Disease Control and Prevention, United States of America
Michael Brubaker, Local Environmental Observer (LEO) Network, United States of America
Michael Bruce, US Centers for Disease Control and Prevention, United States of America
Jay Butler, US Centers for Disease Control and Prevention, United States of America
Christina Chappell, US Agency for International Development, United States of America
Keith Chaulk, Stantec, Canada
Jean Michel Claverie, Aix-Marseille University, France
Tom Douglas, U.S. Army CRREL, United States of America
Jessica Ernakovich, University of New Hampshire, United States of America
Julio Escarce, United States of America
Birgitta Evengård, Umeå University,* Sweden
Lauren Everett, National Academies of Sciences, Engineering, and Medicine, United States of America
Robin Fears, European Academies Science Advisory Council,* United Kingdom
Beat Frey, Federal Research Institute for Forest, Landscape and Snow Research, Switzerland
Joshua Glasser, US Department of State, United States of America
Charles Haas, Drexel University,* United States of America
Henrike Hartmann, Volkswagen Foundation, Germany
Thomas Inglesby, Johns Hopkins Bloomberg School of Public Health,* United States of America
Emily Jenkins, University of Saskatchewan, Canada
Anne Jensen, University of Alaska Fairbanks, United States of America
Kai Kupferschmidt, Science Correspondent, Germany
Susan Kutz, University of Calgary,* Canada
Anne-Sophie Lequarre, European Commission Joint Research Center, Belgium
Teresa Lettieri, European Commission Joint Research Center, Italy
Brett Makens, US Department of State, Denmark
Volker ter Meulen, InterAcademy Partnership,* Germany
Henry Mix, Altay Film, Germany
Luise Müller, Statens Serum Institut, Denmark
Dmitry Orlov, Lomonosov Moscow State University, Russia

Albert Osterhaus, University of Veterinary Medicine Hannover, Germany
Lise Øvreås, University of Bergen, Norway
Julie Pavlin, National Academies, United States of America
Katie Perez, National Academies, United States of America
Natalia Pshenichnaya, Central Research Institute of Epidemiology, Russia
Arja Rautio, University of Oulu, Finland
Bob Reiss, author and journalist, United States of America
Bert Rima, Centre of Experimental Medicine, Queen's University, United Kingdom
Vladimir Romanovsky, University of Alaska, Fairbanks, United States of America
Cheryl Rosa, US Arctic Research Commission, United States of America
Richard Schoske, US Defense Threat Reduction Agency, United States of America
Boas Schwarz, Altay Film, Germany
Jan Semenza, European Centre for Disease Prevention and Control, Sweden
Mark Smolinski, Ending Pandemics, United States of America
Aleksandr Sokolov, Russian Academy of Sciences, Russia
David Stanton, Swedish Museum of Natural History, Sweden
Craig Stephen, Canadian Wildlife Health Cooperative, Canada
Aðalheiður Inga Þorsteinsdóttir, Ministry of Foreign Affairs, Iceland
Trista Vick-Majors, Michigan Technological University, United States of America
Warwick Vincent, Université Laval, Canada
Tatiana Vishnivetskaya, University of Tennessee Knoxville, United States of America
Alexander Volkovitskiy, Russian Academy of Sciences and Yamal Expedition, Russia
Diana Wall, Colorado State University,* United States of America
Sanne Eline Wennerberg, Veterinary and Food Authority, Greenland
Eduard Zdor, University of Alaska Fairbanks, United States of America

* *indicates Planning Committee Member*