Pathogens and Permafrost Workshop
November 2-3, 2023

Workshop Report

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Problem Statement

Planetary scale environmental dynamics are resulting in both rapid and heterogenous arctic environmental alterations which include extensive thawing of permafrost soils. Permafrost, ground that has been consecutively frozen for at least two years (and in some cases, as many as hundreds of thousands of years) is a reservoir of largely uncharacterized microorganisms and viruses, several of which are known to carry the potential for pathogenesis through either direct or indirect pathways. Pathogenesis of a disease describes the mechanisms by which it develops, progresses, and either persists or is resolved. Our current knowledge of permafrost-resident microbes is limited, and we lack a foundational basis on which to assess risks to defense and security operations (Figure 1) in polar regions[1].

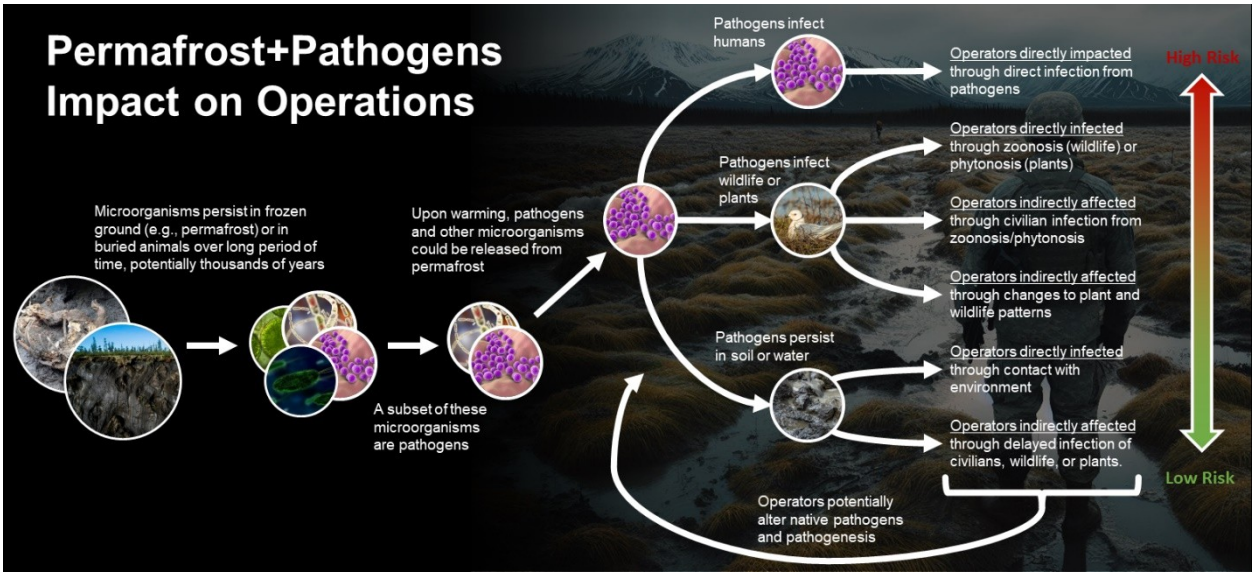

Figure 1: *Pathogens that exist in thawing permafrost may impact DOD operations and mission assurance. Source: Dr. Christopher McComb, Carnegie Mellon University, used with permission.*

The Earth's permafrost and Polar regions extend far beyond the Arctic operational environment. Though not specifically identified as a formal U.S. Department of Defense (DOD) Command Area of Responsibility (AOR) due to adherence to the Antarctic Treaty, we do have DOD personnel and equipment operating within Antarctic waters and on the Antarctic continent providing operational and logistical support to the United States Antarctic Program (USAP) operated by the US National Science Foundation (NSF). Some of the same, and perhaps additional – as yet unidentified – pathogens may well exist within the Antarctic domain. Our knowledge of these pathogens and their rapid transformation under exposure is limited (e.g., Figure 2). Given the recent shift toward renewed global strategic competition, and peer adversaries' grey zone. behaviors, there is a need for the study, inventory, surveillance, monitoring and detection of potential risks in the Antarctic domain as well as the Arctic.

[1] Some Arctic practitioners define three Arctic regions: North America, European/Scandinavian, and Russian/Asian. Others into four regions, based on continental shields (e.g., the Canadian Shield), or five based on oceanography.

On November 2 and 3, 2023 the Permafrost and Pathogens (P&P) working group brought together military operators, medical professionals, academic scientists, and cold regions scientists and engineers to establish a knowledge baseline from which the implications for human health and the sustainment of operations in an evolving Arctic environment can be assessed and developed. The meeting was hosted by Pacific Northwest National Laboratory (PNNL), the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), and the University of Idaho Center for Resilient Communities (CRC), in partnership with U.S. Northern Command (USNORTHCOM).

Figure 2: *Dormant cretaceous fungi exhibiting mycelial growth on remnant organic residues of leaf fossils within 20 seconds of exposure to air. Source: Dr. Lil Alessa, University of Idaho, used with permission.*

Methodology

The P&P workshop followed the Quadrant Enabled Delphi (QED) methodology as per Alessa et al. 2018. The QED operated under the Chatham House Rule. Initial group elicitation (brainstorming) identified the status quo and capability gaps in our body of knowledge relative to pathogens and permafrost. The Pareto/N3 Dot exercise then prioritized identified gaps for potential mitigation. Subsequent elicitation and Pareto/N3 exercise rounds identified specific operations that could be impacted or affected by pathogenic microbes potentially released from thawing permafrost along with proposed initial recommendations in order to better understand and alleviate risks.

Four Quadrants were established, each with a qualified Quadrant Manager:

- Microbial Distribution and Diversity.
- Data Repositories.
- Pathogenesis.
- Body of Knowledge Relevant to Department of Defense (DOD) Operations.

Pareto/N3 exercises included the following assessments:

- Severity as a measure of impact on operations, evaluated as “most severe,” “moderately severe,” and “least severe.”
- Urgency – for action, evaluated as “now,” “0-5 years,” “5-10 years,” and “10+ years.”
- Overall priority – the identification of the single highest priority issue to be addressed for each participant.

Data analysis was conducted using weighted linear regression of data acquired through the modified Pareto process. A total of 1,246 data points were collected over two days, and 138

narratives (Appendix B), including requirements, were collected in the comments box. Additionally, 16 potential sources of information were identified (Appendix C).

Demographics

Twenty-four individuals attended, 58% male, 42% female. Three individuals were between the ages of 18 and 35 years, nine between 35 and 50 years, and twelve were between 50 and 70 years old. Thirteen participants reported being or having been operational DOD personnel, seven identified as having First Responder backgrounds, and eight indicated roles as modelers, simulators, or wargamers. Five participants were permafrost experts, and ten had terminal degrees in fields relating to biological, microbial, molecular, or epidemiological sciences. Additionally, ten of the participants indicated roles in medical research, practice, or policy. Five contributors were active-duty military, two reserve military, and four retired military. Most of the participants currently live and/or have lived/worked extensively in Arctic regions and four had extensive field experience relating to small-group operations in remote and extreme environments.

Attendees represented ten U.S. Federal Government Departments or agencies, five U.S. and Canadian Universities, one private sector research Center, and one National Laboratory. Participating federal government organizations included: The U.S. DOD (11th Airborne Division, U.S. Army Engineer Research and Development Center/Cold Regions Research and Engineering Laboratory, Defense Threat Reduction Agency, Defense Health Agency (Global Emerging Infections Surveillance), North American Aerospace Defense Command (NORAD) and USNORTHCOM, Ted Stevens Center for Arctic Security Studies, U.S. Air Force Academy/ Department of Biology, Walter Reed Army Institute of Research), DOE (Pacific Northwest National Laboratory) and the U.S. Department of Homeland Security. Participating Universities included the Carnegie Mellon University/Department of Mechanical Engineering, the University of Alabama/Global Water Security Center, the University of Alaska Fairbanks/Permafrost Laboratory, Geophysical Institute, the University of Idaho/Center for Resilient Communities, and the University of Saskatchewan/Western College of Veterinary Medicine.

Results of Phase 1: What is the Status Quo?

The first phase of the workshop focused on delineating what is currently known (Body of Knowledge) regarding pathogens and permafrost, including issues of concern, what gaps the participants saw, and the priorities for closing those gaps. These data are shown in Table 1 and Figure 4.

While NORAD and USNORTHCOM together serve as the designated “Arctic Advocate,” there is no formal command and control (C^2) system to research, plan for, or respond to events specifically related to DOD. The role of various health-focused agencies, including the World Health Organization (WHO), the National Institutes of Health (NIH) and the Centers for Disease Control (CDC) were explored but none possess the authorities and/or mission scope to provide the necessary focus on defense planning for thawing of permafrost and potential pathogen-associated risks and/or opportunities. In addition, a civilian entity, the NSF, is the designated “Antarctic Advocate,” yet there are military personnel and equipment providing logistics and operational support to the USAP all around the continent and in its waters.

A significant finding that emerged during discussions was the lack of a central coordinating authority for issues around pathogen release from thawing permafrost that impact DOD operations.

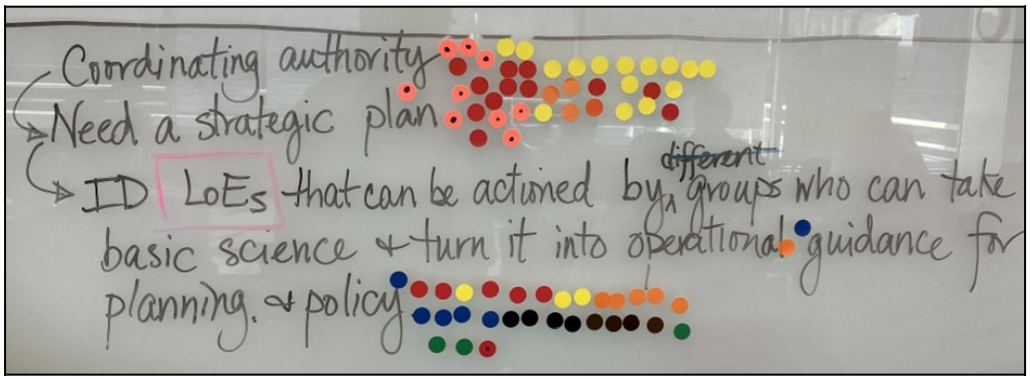

Figure 3: *Snapshot of white board with dots and "fish eyes" (highest priority and urgency) reflecting the broad view of a need for a coordinating authority.*

Participants articulated that there are significant knowledge gaps related to pathogens, specifically to pathogens from thawing permafrost, including: viability, pathogenesis, transmutability, transmissibility, key controlling variables in permafrost that factor into vectors for pathogen transmission, and the extent of geographic distribution. While anecdotal evidence exists, that pathogens are present and can emerge from thawing permafrost, and some case studies where this has occurred, the data are limited and poorly aggregated. Moreover, not all pathogens are fatal and non-fatal pathogenesis may be under-reported. However, less-than-fatal outcomes could impact the DOD's ability to perform missions as much as a large human mortality event. Finally, experts also noted that viruses, fungi, and microbes change over time. Just because something is not pathogenic now does not mean it cannot emerge as such later, including in cases of gene modifications resulting from interactions with humans, animals, and/or bioengineering. If they are zoonotic pathogens undergoing mutation in a non-human host then there are totally different selection pressures leading to wild cards for spilling back into humans.

Data were also articulated, assessed, ranked, and compiled with respect to knowledge about the impacts of DOD operations and infrastructure on the dynamics of permafrost thaw, and how that interaction could influence localized pathogen activation and spread. Understanding the bidirectional implications of human activity (e.g., generating heat and waste) and pathogen release is essential to assessing impacts related to DOD operations in the near-term such as exercises and long-term impacts such as fixed infrastructure. To advance this practical knowledge there was consensus that identifying ways to survey for pathogens in permafrost is critical and would be worthwhile to couple with improved mapping of the distribution of continuous, discontinuous, and sporadic (thaw/freeze) permafrost in locales that intersect DOD assets. The establishment of such practical knowledge is a critical first step for DOD planning and operations.

Within DOD, achieving this necessary foundational knowledge requires a Command and Control (C^2) structure with a central authority capable of issuing both requirements and providing resources. A central repository for data relevant to DOD planning and operations on both the physical environment and pathogens/outbreaks was also seen as important. One representative articulated that a portal/hub for health information is being developed for DOD but currently is not designed to address P&P, adding that this would be critical since permafrost underlies a large part of the Northern hemisphere. Challenges to such a portal/hub include ownership, input, data curation, maintenance, integration, and security which loops back to the need for a coordinating authority. Currently, our data and knowledge are a result of science-based activities focused on publication as opposed to supporting decision-making and development of policies, strategies, and strategic plans for national security and defense. For scientific purposes, working in decadal scales is appropriate while operational decision-making requires a minimal refresh rate at annual scales.

Finally, significant discussion in Phase 1 centered around a central challenge question: Is there really a problem? The consensus among participants was that proving or disproving this with solid data was critical. A case study demonstrating the framework by which we assess mechanisms of thaw, through various pathogenesis pathways, and connecting those to clinical symptoms would allow the DOD community to prioritize the research needed to assess the full mission risks. Given the magnitude and speed of a "doomsday scenario", sometimes referred to as a "midnight swan[2]" there was consensus among attendees that assessing this risk was a priority. A midnight swan refers to an extremely low probability but extremely high consequence event.

Following the collective brainstorming session, participants were asked to rate elicited topics in terms of severity, urgency for action, and overall priority. The highest ranked ten topics from each rating are displayed in table form in Tables 1 to 3, below, and graphically in Figures 4 to 6. Based on percentage rankings of the combination of both severity and urgency, priorities for action are displayed in Table 4 and Figure 7. A complete listing of topics and ratings for Phase 1 may be found in Appendix D.

[2] Unlike COVID 19 which derived from a modern coronavirus familiar to modern immune systems, it is unknown how competent existing mammalian immune systems would respond to ancient viruses, bacteria, and fungi.

Inputs	Quadrant	Severity
Coordinating authority, strategy development, and strategic planning	Quadrant 5: Other	43
Biosurveillance hub under development needs to include permafrost/pathogen data	Quadrant 2: Data Repositories	42
Science-based models/outputs don't directly support planning, policy, decision-making	Quadrant 2: Data Repositories	31
ID LOEs and teams who can take basic science and turn it into guidance for strategy development, planning, and policy	Quadrant 5: Other	30
Data pool continuity/upload/access	Quadrant 4: Body of Knowledge Relevance to DOD Operations	21
Permafrost active layer warrants specific consideration	Quadrant 3: Pathogenesis	20
Need better surveillance systems	Quadrant 4: Body of Knowledge Relevance to DOD Operations	19
Human environmental impact on pathogen release/introduction of existing/dormant organisms	Quadrant 3: Pathogenesis	17
Opportunistic pathogens change behavior in thaw not well known	Quadrant 4: Body of Knowledge Relevance to DOD Operations	17
First Nations Place Based Knowledge is Important	Quadrant 2: Data Repositories	16

Table 1: *Phase 1 top ten elicited topics of concern, ranked by severity of impact to DOD operations.*

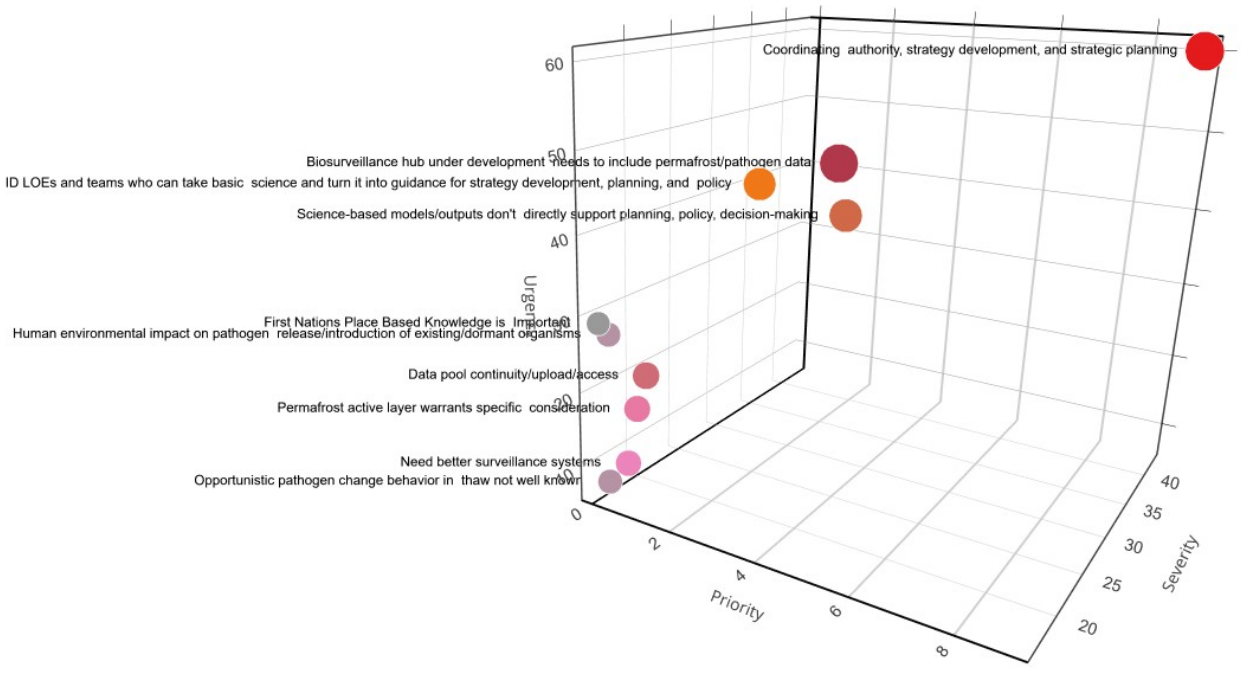

Figure 4: *Summary of top ten elicited Phase 1 topics. Distance from intersection of axis and size/color denote increasing severity. "Coordinating authority..." is most severe, "(f)irst Nations..." is least.*

Inputs	Quadrant	Urgency
Coordinating authority, strategy development, and strategic planning	Quadrant 5: Other	60
Understand relevance of permafrost types and pathogenicity	Quadrant 1: Microbial Distribution and Density	45
ID LOEs and teams who can take basic science and turn it into guidance for strategy development, planning, and policy	Quadrant 5: Other	42
Biosurveillance hub under development needs to include permafrost/pathogen data	Quadrant 2: Data Repositories	41
Science-based models/outputs don't directly support planning, policy, decision-making	Quadrant 2: Data Repositories	39
Place Based Knowledge is important	Quadrant 2: Data Repositories	29
Human environmental impact on pathogen release/introduction of existing/dormant organisms	Quadrant 3: Pathogenesis	27
Link between microbial genomic/ecology and clinical significance	Quadrant 3: Pathogenesis	27
NORAD and USNORTHCOM to identify a requirement, ID LOEs	Quadrant 4: Body of Knowledge Relevance to DOD Operations	25
Data pool continuity/upload/access	Quadrant 4: Body of Knowledge Relevance to DOD Operations	19

Table 2: *Phase 1 top ten elicited topics of concern, ranked by urgency for action.*

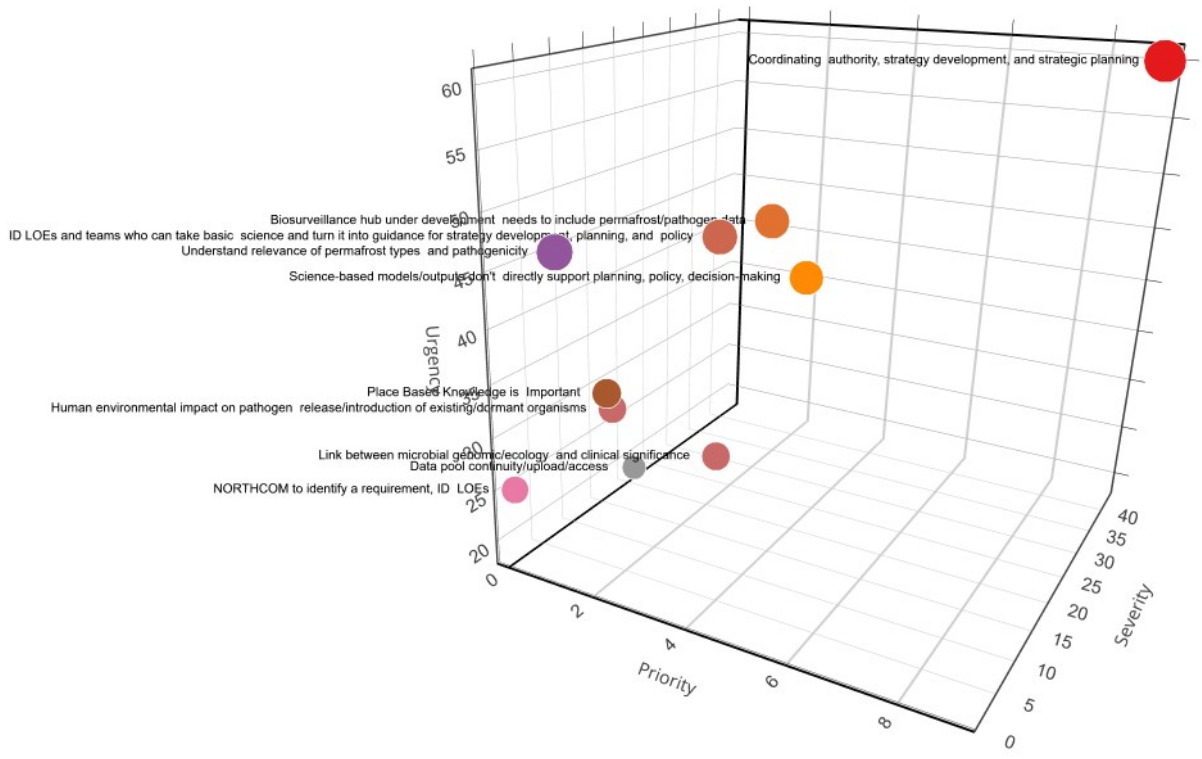

Figure 5: *Summary of top ten elicited Phase 1 topics. Distance from intersection of axis and size/color denote increasing urgency. "Coordinating authority..." is most urgent, "(d)ata pool continuity..." is least.*

Inputs	Quadrant	Priority
Coordinating authority, strategy development, and strategic planning	Quadrant 5: Other	9
Science-based models/outputs don't directly support planning, policy, decision-making	Quadrant 2: Data Repositories	3
Link between microbial genomic/ecology and clinical significance	Quadrant 3: Pathogenesis	3
Biosurveillance hub under development needs to include permafrost/pathogen data	Quadrant 2: Data Repositories	1
ID LOEs and teams who can take basic science and turn it into guidance for strategy development, planning, and policy	Quadrant 5: Other	1
Hub/portal on microbial diversity	Quadrant 1: Microbial Distribution and Density	1
Evaluate transmissibility with virulence and disease severity	Quadrant 3: Pathogenesis	1
New/novel microbes	Quadrant 1: Microbial Distribution and Density	1

Table 3: *Phase 1, nine elicited topics of concern prioritized by the participants.*

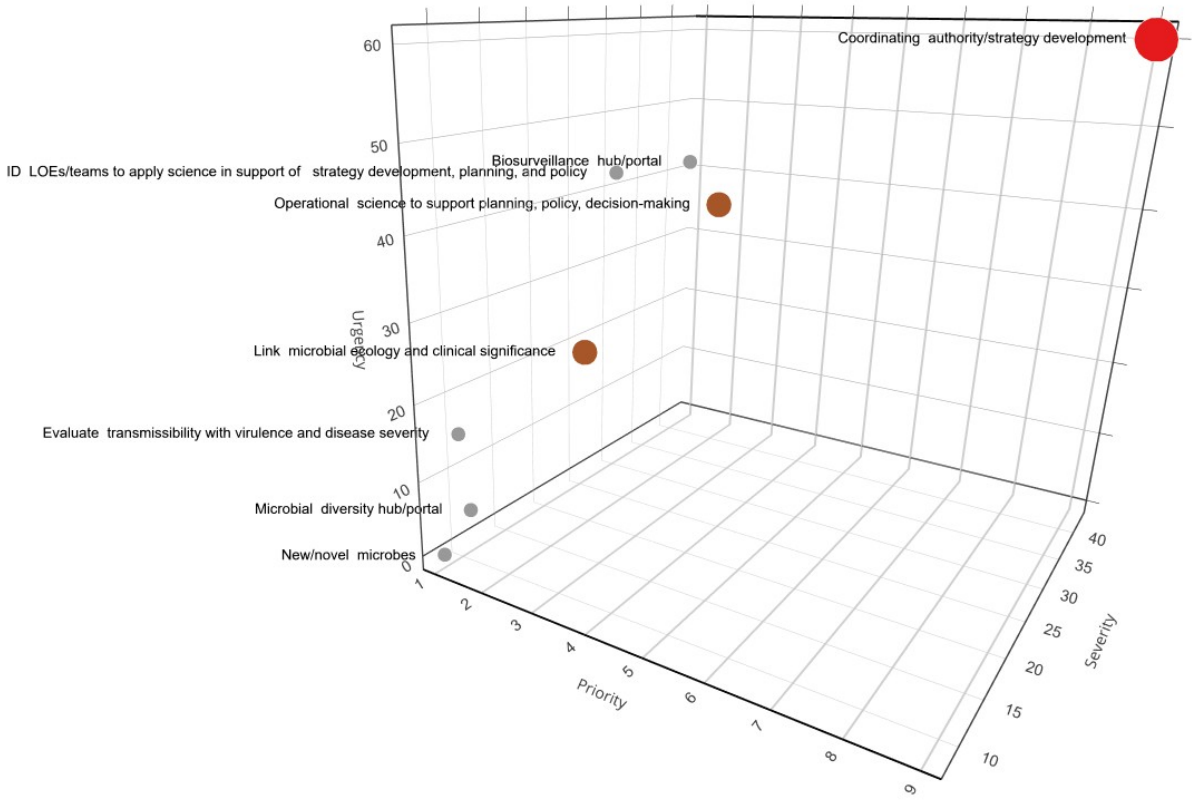

Figure 6: *Summary of nine priority elicited Phase 1 topics. Distance from intersection of axis and size/color denote increasing priority. "Coordinating authority..." is most urgent, "(b)iosurveillance..." and the remaining five are least.*

Inputs	Severity	Urgency	Ranking for Action
Coordinating authority, strategy development, and strategic planning	43	60	1.00
Biosurveillance hub under development needs to include permafrost/pathogen data	42	41	0.83
ID LOEs and teams who can take basic science and turn it into guidance for strategy development, planning, and policy	30	42	0.78
Science-based models/outputs don't directly support planning, policy, decision-making	31	39	0.72
Data pool continuity/upload/access	21	19	0.44
Human environmental impact on pathogen release/introduction of existing/dormant organisms	17	27	0.33
Place Based Knowledge is Important	16	29	0.33
Need better surveillance systems	19	8	0.28
Permafrost active layer warrants specific consideration	2	15	0.11
Opportunistic pathogen change behavior in thaw not well known	17	7	0.11

***Table 4**: Phase 1 Relative rankings for action, based on ranked severity and urgency.*

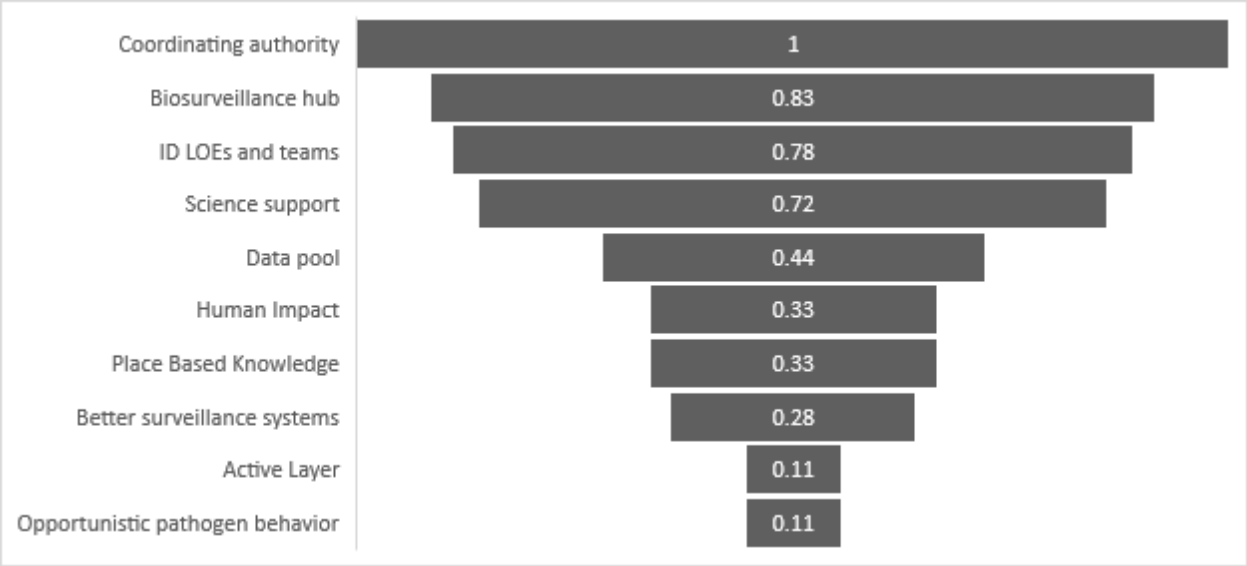

***Figure 7**:Waterfall display of Phase 1 rankings for action based on ranked severity and urgency.*

Results of Phase 2: Threats to Operations

The second phase of the Pathogens and Permafrost workshop focused on threats to DOD operations, specifically those that could be impacted or affected by pathogenic viruses, fungi, or microbes emerging from thawing permafrost. These discussions took place in the context of two of USNORTHCOM's primary missions: (1) protecting the United States and (2) supporting the Defense Support of Civil Authorities mission. The Commander of USNORTHCOM is also the commander of NORAD, a joint U.S.-Canada organization tasked with providing aerospace warning and control and maritime warning in defense of North America. A range of NORAD and USNORTHCOM operations were discussed with some participants articulating that ground-based interceptors, over-the-horizon radar, and assets involved in countering long-range aviation were a priority.

There was consensus among participants that there was a difference between short-term activities (e.g., training and exercises) and long-term, fixed infrastructure in potential risk profiles. Thirty-to-sixty-day deployments were seen as the threshold for permafrost change dynamics since that is known to create "warmth bubbles" that affect rates of thaw – warmth bubbles are localized areas where temporary or permanent structures increase heat exchange between surface and subsurface leading to potential permafrost thaw. Such deployments also create waste issues particularly if the same training area is used every year. Packing out waste was a challenge, and in the event of surge operations might not be realistic. Waste itself might be a source of pathogens to the soil - potentially allowing mingling of ancient and extant pathogens, and subsequent chances of gene transfer and mutation. Long-term activities were seen as significantly more impactful, with fixed infrastructure creating both long-term impacts and escalating shorter-term concerns through expanded operations. For example, a port attracts vessel traffic, potentially releasing black carbon which is implicated in ice/permafrost thaw. The pathways by which human activity alters thawing and subsequently impacts pathogenesis are not clear, but the working group agreed that research was needed to articulate the pathways and create a framework to address the risks to humans, animals, and plants in permafrost regions.

In discussing operations and operational impacts, understanding the rate of change was determined to be critical information needed to support decision making. Understanding the drivers, timing, and extent of permafrost thaw as it relates to potential release of microorganisms would allow risk maps to be developed that prioritize permafrost areas to avoid. Collectively understanding the key controlling variables that allow the release of pathogens and their survival to impact humans, animals, and plants will better inform operational decisions.

Permafrost characteristics as they relate to potential pathogen release were also discussed. The effects of the permafrost ice content or carbon content on the release of pathogen, as well as the effects of different permafrost thawing processes (e.g., continuous as opposed to discontinuous, deep as opposed to shallow) were identified as areas for further assessment and research. Further, the group identified that it is not clear whether there is a relationship between permafrost types and pathogen abundance.

The participants noted that there were known examples of permafrost thaw in and around burial grounds and accompanying disease outbreaks, with Anthrax, influenza, and smallpox being of

concern. It was suggested that mapping burial ground areas along with historically significant information about disease outbreaks (including oral histories) could be helpful. Emphasis was placed on attention to animal and avian vectors that might be buried in permafrost as well as humans.

Following the collective brainstorming session, participants were asked to rate elicited topics in terms of severity, urgency for action, and overall priority. The highest ranked ten from each rating category are displayed in table form in Tables 6 to 8, below, and graphically in Figures 8 to 10. Based on percentage rankings of the combination of both severity and urgency, priorities for action are displayed in Table 9 and Figure 11. A complete listing of topics and ratings for Phase 2 may be found in Appendix E.

Inputs	Quadrant	Severity
Permafrost thaw significance for dormant pathogens	Quadrant 3: Pathogenesis	44
Thaw rate related to pathogen release	Quadrant 3: Pathogenesis	38
Link surveillance to pathogenicity	Quadrant 4: Body of Knowledge Relevance to DOD Operations	31
Understand what is clinically significant	Quadrant 1: Microbial Distribution and Density	29
Tipping points/indicators not well known	Quadrant 4: Body of Knowledge Relevance to DOD Operations	29
Permafrost impacts from new infrastructure can influence future development	Quadrant 2: Data Repositories	23
Identify inflection points	Quadrant 1: Microbial Distribution and Density	20
Human presence promotes change through heat/waste	Quadrant 3: Pathogenesis	20
Need to conduct a meta search on Permafrost and Pathogens	Quadrant 2: Data Repositories	18
Must understand rate of change	Quadrant 5: Other	17

Table 5: *Phase 2 top ten elicited topics of concern, ranked by severity of impact to DOD operations.*

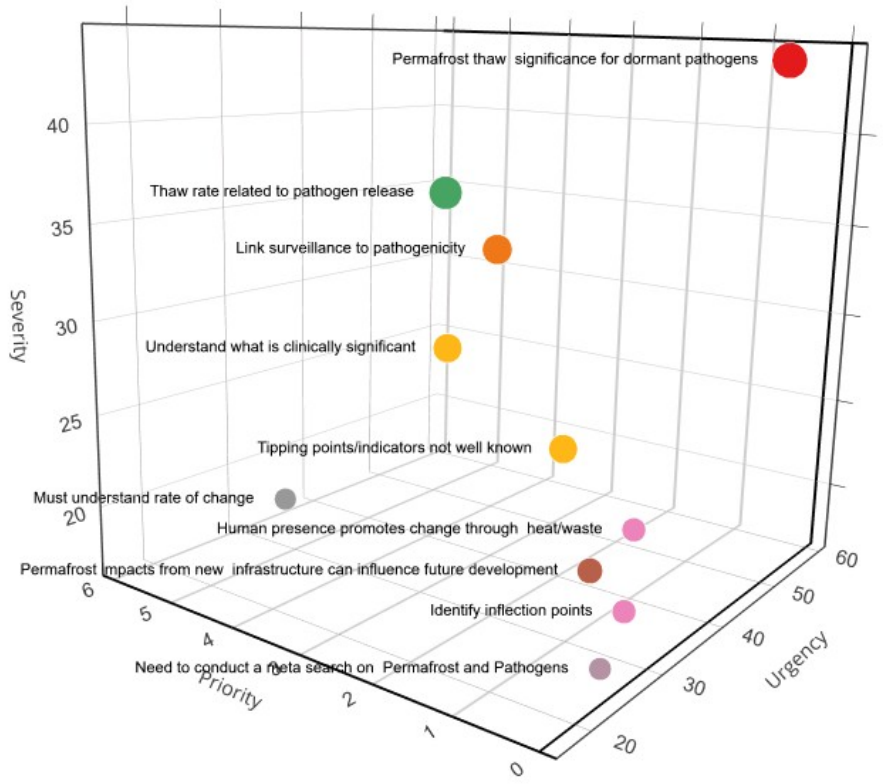

Figure 8: *Summary of top ten elicited Phase 2 topics. Distance from intersection of axis and size/color denote increasing severity. "Permafrost thaw..." is most severe, "(m)ust understand..." is least.*

Inputs	Quadrant	Urgency
Link surveillance to pathogenicity	Quadrant 4: Body of Knowledge Relevance to DOD Operations	60
Permafrost thaw significance for dormant pathogens	Quadrant 3: Pathogenesis	48
Human presence promotes change through heat/waste	Quadrant 3: Pathogenesis	40
Must understand rate of change	Quadrant 5: Other	36
Understand what is clinically significant	Quadrant 1: Microbial Distribution and Density	33
Identify inflection points	Quadrant 1: Microbial Distribution and Density	26
Need to conduct a meta search on Permafrost and Pathogens	Quadrant 2: Data Repositories	23
Thaw rate related to pathogen release	Quadrant 3: Pathogenesis	23
Permafrost impacts from new infrastructure can influence future development	Quadrant 2: Data Repositories	21
Need wastewater sampling	Quadrant 1: Microbial Distribution and Density	20

Table 6: *Phase 2 top ten elicited topics of concern, ranked by urgency for action.*

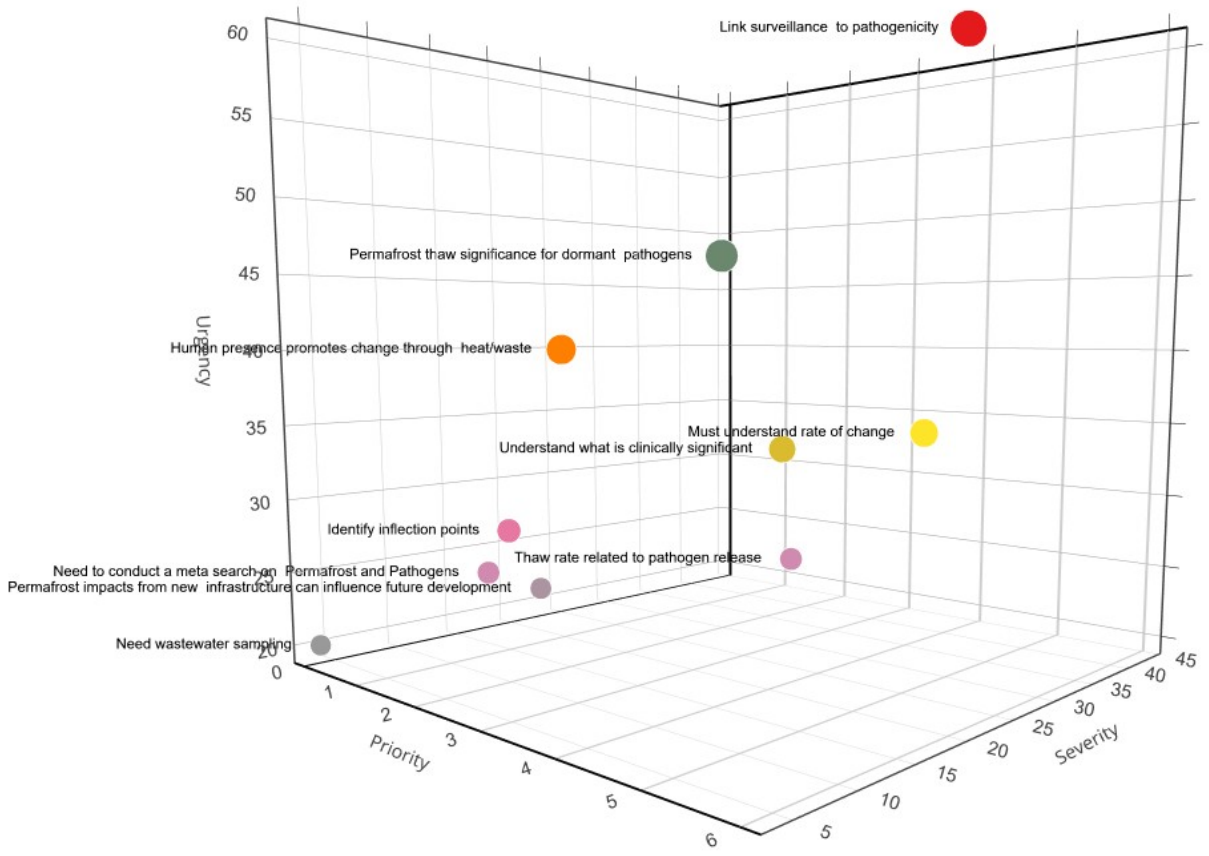

Figure 9: *Summary of top ten elicited Phase 2 topics. Distance from intersection of axis and size/color denote increasing urgency. "Link surveillance..." is most urgent, "(n)eed wastewater sampling" is least.*

Inputs	Quadrant	Priority
Must understand rate of change	Quadrant 5: Other	6
Link surveillance to pathogenicity	Quadrant 4: Body of Knowledge Relevance to DOD Operations	5
Understand what is clinically significant	Quadrant 1: Microbial Distribution and Density	3
Thaw rate related to pathogen release	Quadrant 3: Pathogenesis	2
Understand short- and long-term ground-based operations impacts	Quadrant 5: Other	1
Human presence promotes change through heat/waste	Quadrant 3: Pathogenesis	1
Human waste microenvironment impacts	Quadrant 4: Body of Knowledge Relevance to DOD Operations	1

Table 7: Phase 2, seven elicited topics of concern prioritized by the participants.

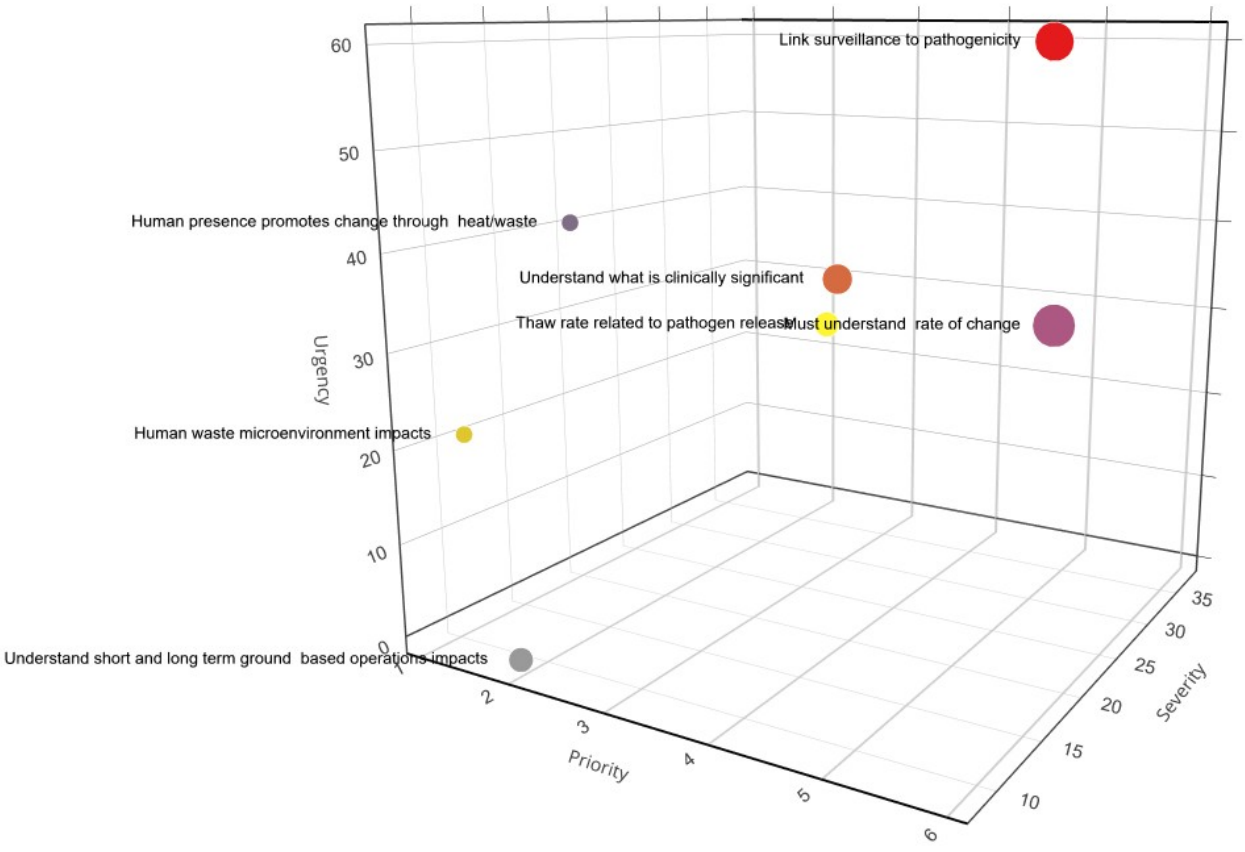

Figure 10: *Summary of seven priority elicited Phase 2 topics. Distance from intersection of axis and size/color denote increasing priority. "Must understand..." is most urgent, "(U)\ndertstand short- and long-term..." and the remaining 3 are least.*

Inputs	Severity	Urgency	Ranking for Action
Permafrost thaw significance for dormant pathogens	44	48	0.94
Link surveillance to pathogenicity	31	60	0.89
Thaw rate related to pathogen release	38	23	0.56
Understand what is clinically significant	29	33	0.56
Human presence promotes change through heat/waste	20	40	0.50
Identify inflection points	20	26	0.33
Must understand rate of change	17	36	0.33
Tipping points/indicators not well known	29	17	0.28
Permafrost impacts from new infrastructure can influence future development	23	21	0.28
Need to conduct a meta search on Permafrost and Pathogens	18	23	0.17

***Table 8**: Phase 2 Relative rankings for action, based on ranked severity and urgency.*

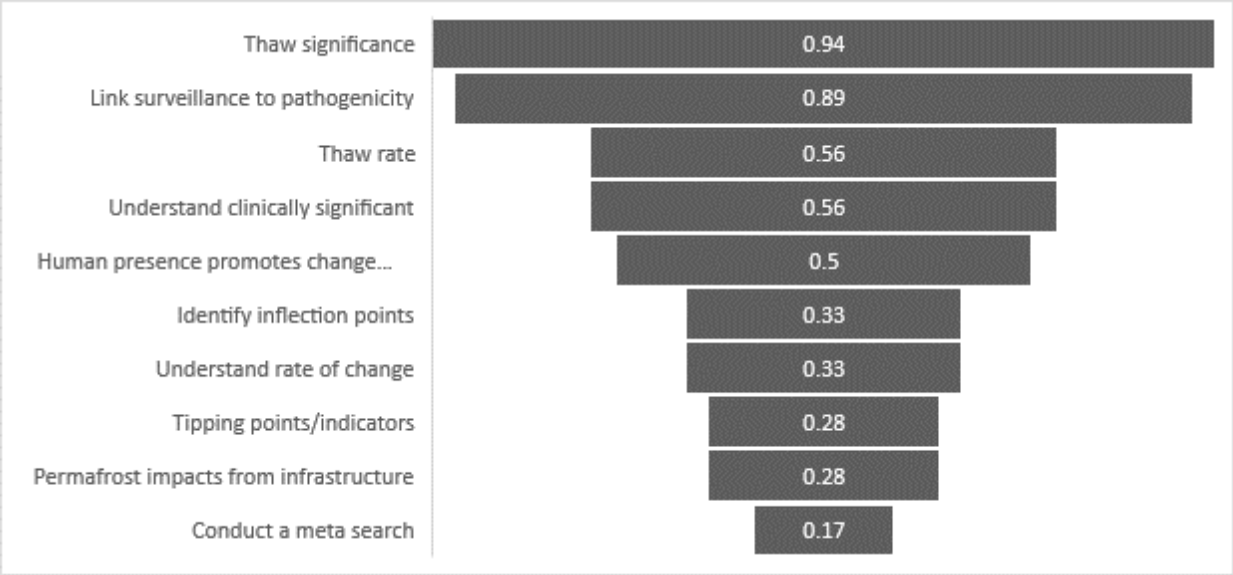

***Figure 11**:Waterfall display of Phase 2 rankings for action based on ranked severity and urgency.*

Results of Phase 3: Meeting the Challenges

After discussing the current body of knowledge and potential impacts to DOD operations, the third and final phase of the Pathogens and Permafrost workshop focused on possible requirements to address the identified issues.

A key issue from all three phases were reiterated by participants in Phase 3: That of being able to accurately determine the actual risk from pathogens potentially being released by the thawing permafrost, their level of threat/true biological risk, and their distribution in the thawing terrain to guide operational considerations. Here risk is the product of probability and severity. Participants believed that this should be achieved under the Extreme Cold Weather Operations Framework. This included a need to characterize extant microbial communities to understand potentially beneficial buffering capacities that could dampen the risk to operations. An understanding of actual risk could then be combined with geospatial information on permafrost types and distribution to generate a map identifying potential hotspots for decision maker consideration. The map could also include an aggregation of additional environmental risk factors to operations, such as frostbite exposure, mobility in thawing terrain, etc., to provide leadership with a comprehensive risk assessment during planning and war game scenario development.

Also of concern was the need to develop guidance for sampling, detection, and monitoring capabilities to bring a systematic approach that would allow aggregation of data across many different projects and sources. Improved or adapted sampling techniques, standardized methodologies, and support services were seen as critical, especially in-field testing capability with either an identified analysis site (e.g., a designated laboratory) with rapid sample transport, or field deployable rapid analysis. Expansion of exercise and testing to multiple laboratories was proposed as a possible means of method validation. Ideally a sampling mechanism would be developed for deployed troops to take and analyze samples and communicate results to a central repository for aggregation and analysis. The Special Operations community is currently developing a biological sequencing device for in-field usage that could potentially be tested in extreme cold weather, i.e., Fairbanks, AK, though currently it only analyzes isolates.

It was also clear that, while targeted field sampling and testing was the most probable current course of action to characterize the actual state of risk, success would require cooperation and coordination beyond the U.S. DOD. Multiple agencies that currently operate in the Arctic are potential partners. On the international side, Defense Research Development Canada would be a fruitful starting point.

Finally, participants reiterated that planning guidance with adequate resourcing was crucial to moving forward.

Specific requirements as identified by workshop participants may be found in Table 10, below.

Following discussions of possible requirements, attendees developed a suggested set of Lines of Effort (LOE) to implement the workshop results. These LOE were broadly categorized as requirements, conceptual models, establishing baselines, monitoring and surveillance indicators for early detection, and planning. The LOE are listed below, in Table 11.

Following the collective brainstorming session, participants were asked to rate elicited topics in terms of urgency for action and overall priority (severity was not evaluated). The highest ranked ten are displayed in table form in Tables 12 and 13, below, and graphically in Figures 12 and 13. A complete listing of topics and ratings for Phase 3 may be found in Appendix F.

Key Findings (Table 9)

Category and Action	Partners	Outcomes
Monitoring and Surveillance: a. Medical surveillance. Define SOPs for identifying new/unusual outbreaks in plants/animals/people beyond "flu like symptoms". b. Adapt existing CBRN sampling strategies for Arctic extreme environments. c. Inventory and assess CRREL's repository of permafrost/ice cores and determine a sampling strategy near/around DOD facilities. d. Leverage existing arctic infrastructure for wastewater sampling.	CRREL, DTRA, USACE, USSOCOM, MIC, GEISS, PNNL	Early Warning System that aggregates data on unusual health events to help ID clusters. That information should then be sent to providers to encourage identification and reporting of similar cases. Should not be limited to DOD. Should encompass civilians and animals. Continued and expanded exploration of in-situ permafrost for rate of change to estimate when the greatest plethora of new (and potentially) dangerous pathogens could be released. Could identify the possible need for different decontamination procedures for personnel and equipment (mostly equipment).
Research & Analysis a. Form collaborations across teams currently engaged in research for DOD relevant data.	DOD/DOE, FFRDCs, Academia, NIH, CDC, NSF	Establishes baselines: knowledge of what is in permafrost now and what is or could become dangerous, when and where for planning guidance. Establish human/population exposure and immune susceptibility. Rapidly advances our understanding of mechanism of evolution of extremophiles in changing environments, such as rapid warming vs slow warming and pathogenicity. When combined with monitoring and surveillance, it reveals hot spots for higher vs lower risk.

Key Findings		
Category and Action	Partners	Outcomes
		Data and analysis of links from potential to probable pathogenicity in permafrost. Geospatially, data-driven model of hotspots of pathogenicity in thawing permafrost with probability of risk of potential exposure.
Strategies and Plans	DOD Enterprise	Time and space-specific quantification of threats and/or opportunities within the NORAD and NORTHCOM Area of Responsibility in terms of probability of detrimental consequences to inform Arctic planning efforts. Develop a better understanding of planned or contingency operations in the Arctic where forces may be exposed at a greater rate to pathogens. Integration of knowledge/science to inform operations/actions. Establish targeted collaborations between permafrost data/expertise and pathogen/biology data/expertise. Identify a coordinated authority to set other LOEs that can be incorporated into decision cycles for planning and to designate funding.

Table 9: *Potential requirements identified by participants to be disseminated through the coordinating DOD agency, with gaps provided to science agencies.*

Suggested Lines of Effort (Table 10)	
LOE 1 Requirements – Disseminated through coordinating DOD agency/gaps provided to science agencies	
	Strategic communications package: Education and Awareness (maps to Arctic Implementation Plan)
	Coordination to establish a comprehensive baseline
	Protective measures such as minimizing thermal footprint, waste handling, etc.
LOE 2 Working Model (harness lessons learned and leverage underutilized programs/translators)	
	Scenarios of future conditions we should plan toward
	Assess microbial reservoirs in permafrost and identify controlling variables for pathogenesis
	Human impacts broadly – (DOD impacts on permafrost and potential to probability)
	Permafrost impact on mission in all domains
LOE 3 Establishing baselines	
	Sharing data – International and national guidelines
	Permafrost and pathogen level baseline maps (used to assess changes relative to)
	Clinical indicators and existing information from diverse resident communities working and living in permafrost: residential communities, mining operations, DOD operations, etc.
LOE 4 Monitoring and surveillance indicators for early detection	
	Applies to both permafrost and clinical surveillance (which is a public health approach)
	Canada and U.S. Surgeon Generals' Offices: best practices
	Physical conditions (rate of thaw, ice content, carbon content, water quality)
	Data sharing and Guidelines – International and national
	Wildlife monitoring through partnerships with other agencies such as USFWS, USDA etc.
Beyond the List (Identifying tools for identification of pathogens not on our lists)	
Solutions	
	Identify beneficial microbes in the permafrost, inherent buffering capacity[3]
	Identify technologies need to assess microbial function rather than just expressions

Table 10: *Suggested Lines of Effort to implement Pathogens and Permafrost workshop outcomes.*

[3] Not all microbes are detrimental. Many are beneficial and keep harmful ones at bay. Understanding the ratios and dynamics of this can be achieved using advanced modeling techniques in partnership with e.g., academia.

Inputs	Quadrant	Urgency
Demonstrate true risk/threat to human health under Extreme Weather Operations Framework	Quadrant 3: Pathogenesis	104
ID operationally relevant high-risk regions we already operate in	Quadrant 1: Microbial Distribution and Density	73
Scope for early identification and probability assignments	Quadrant 4: Body of Knowledge Relevance to DOD Operations	42
Need proof of concept data	Quadrant 4: Body of Knowledge Relevance to DOD Operations	37
Data/sample sharing for method development and validation	Quadrant 2: Data Repositories	36
Focus on how/where we are vulnerable	Quadrant 3: Pathogenesis	26
Research previous wars for lesson learned vis a vis environmental interaction	Quadrant 4: Body of Knowledge Relevance to DOD Operations	24
Need data-driven strategic communications package to educate leadership	Quadrant 5: Other	24
Outline probability & severity of consequences to force health/mission assurance for planning	Quadrant 3: Pathogenesis	22
Characterize beneficial microbial communities - Buffering capacity	Quadrant 1: Microbial Distribution and Density	19

Table 11: *Phase 3 top ten elicited topics of concern, ranked by urgency for action.*

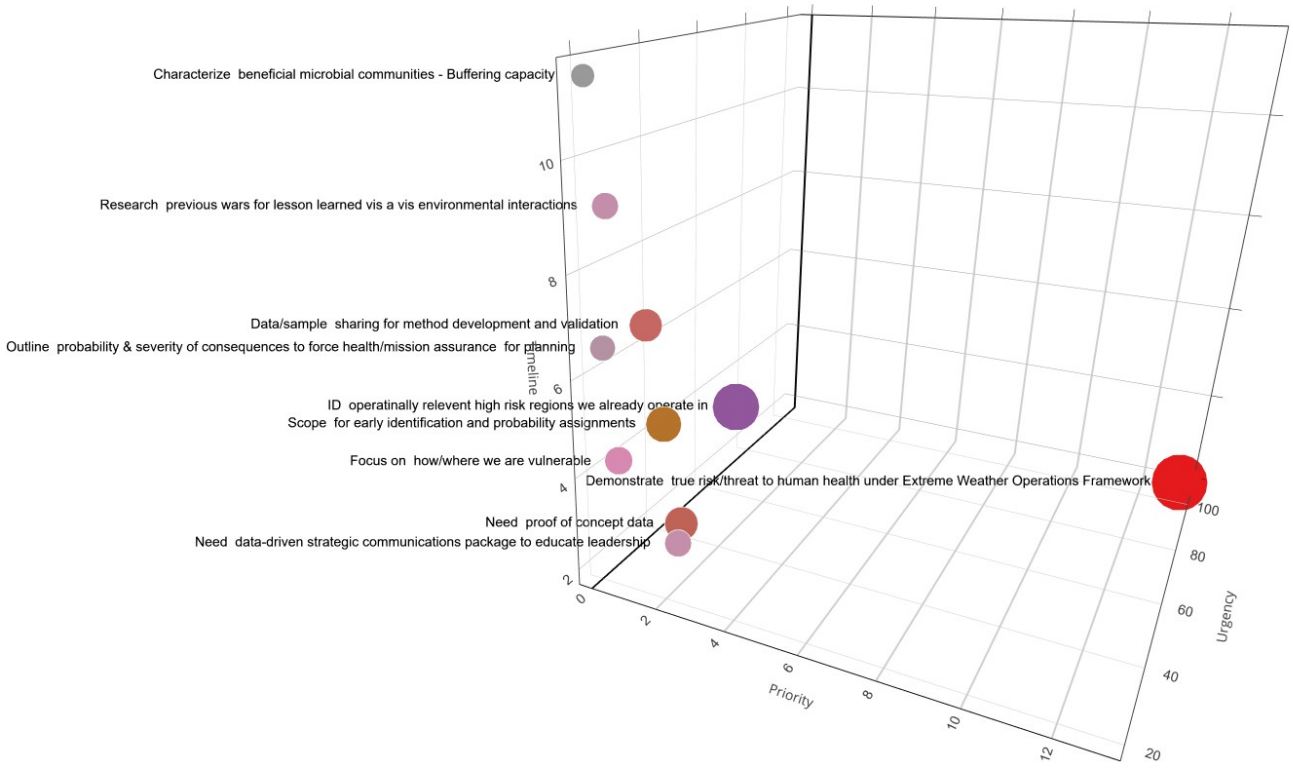

Figure 12: *Summary of top ten elicited Phase 3 topics. Distance from intersection of axis and size/color denote increasing urgency. "Demonstrate true risk/threat..." is most urgent, "(c)haracterize beneficial" is least.*

Inputs	Quadrant	Priority
Demonstrate true risk/threat to human health under Extreme Weather Operations Framework	Quadrant 3: Pathogenesis	13
Need data-driven strategic communications package to educate leadership	Quadrant 5: Other	2
Need proof of concept data	Quadrant 4: Body of Knowledge Relevance to DOD Operations	1

Table 12: *Phase 3, three elicited topics of concern prioritized by the participants.*

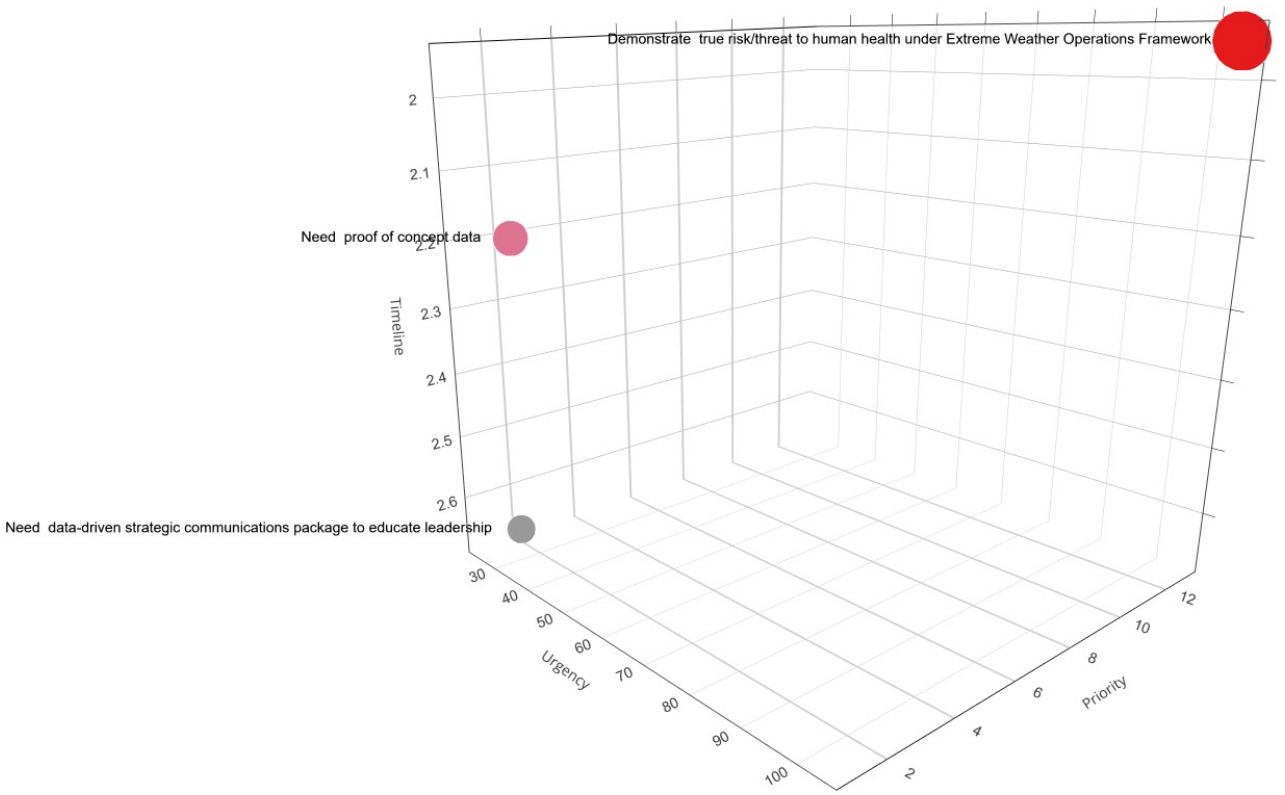

Figure 13: *Summary of top ten elicited Phase 3 topics. Distance from intersection of axis and size/color denote increasing urgency. "Demonstrate true risk/threat..." is most urgent, "(n)eed proof of concept data" is least.*

Conclusion

The Permafrost and Pathogens workshop was the first coordinated effort to develop an understanding of the current state of knowledge and frame critical follow-on actions specific to defense operations. We used the simple rubric of "is there a problem?" "how do we know?" "what is the nature of the problem?" and "how does the Department of Defense plan for it to ensure personnel and readiness are not affected?". It was emphasized that partnering across rigorous disciplinary skill sets that include medical personnel, epidemiologists, biologists, microbiologists, soil scientists, physical scientists (especially permafrost experts), systems scientists, and operational practitioners is critical to developing a full understanding of the true threat from pathogens being released from thawing permafrost.

The P&P workshop successfully identified gaps in current knowledge, including geospatial distribution of different types of permafrost, the implications of different compositions of permafrost on pathogens, and the need to harness science in service of risk-based decision-making. An important part of this last point was the need to communicate risks that are driven by data and analysis to DOD leadership. The workshop was also successful in developing a set of potential requirements and lines of effort for future activities. These include developing field sampling systems, developing monitoring and surveillance systems, and distributing operationally relevant information on potential high-risk geographic areas, including both current areas of operation and areas anticipated for a variety of scenarios. Specific conclusions are as follows and reflect analysis of the 1267 data points collected, discussions among participants over the two days and natural language processing of written comments provided by attendees.

CONCLUSION 1

A Coordinating Authority is Needed: Permafrost-associated pathogens are largely unmapped. However, those collected and analyzed carry the potential for pathogenesis. Excellent work exists in isolated pockets across US federal government agencies, academia, and National Labs. Such an authority would allow us to establish a comprehensive baseline of what we know now, who is doing what, and what information is needed for defense planning now and into the future.

CONCLUSION 2

Planning Needs to Start Now: While we estimate that 2-5% of permafrost in the Northern Hemisphere has currently thawed, in some regions we may be approaching a threshold where abrupt thaw, an accelerated and compounding process, has the potential to release a significant pulse of viruses, bacteria, parasites, fungi, and/or prions into the environment. Mitigation strategies such as minimizing thermal footprints, decontamination procedures and biosurveillance can be readily accomplished but require coordinated planning both within DOD and across partners.

CONCLUSION 3

We have a Blueprint for Ways Forward: The Permafrost and Pathogens Working Group articulated a set of steps that would allow us to conduct rapid assessment of a baseline which can be used in comparison to on-going monitoring and surveillance. The first steps involve an aggregation and meta-analysis of existing data, analysis of archived samples, and a set of standards for

determining risk, geospatially, which can guide routine sampling. The outputs of these activities will guide military planning.

We know that harmful pathogens exist in permafrost (i.e., smallpox, yellow fever, and Anthrax, among others), we know that some of these are viable upon thaw, and we know that permafrost degradation is already occurring. Given the potential impact from the combination of these factors on DOD missions and personnel, as well as the public, developing understanding and methods to monitor, detect, and act on outbreaks is an important DOD responsibility in the Arctic domain. As demonstrated by the recent COVID-19 pandemic, not planning for a black swan, particularly one involving microbial agents that are unknown to modern ecosystems, could result in catastrophic and undesirable outcomes.

Appendix A: Selected References

Alessa, L., Moon, S., Griffith, D., Kliskey, A. (2018). Operator driven policy: Deriving action from data using the quadrant-enabled Delphi (QED) method. Homeland Security Affairs Journal 14, Article 6. https://www.hsaj.org/articles/14586.

Alessa, L., Valentine, J., Moon, S., Kliskey, A. (2021). Asymmetric competition in the Arctic: Implications for North American defense and security. Journal of Indo-Pacific Affairs, Winter 2021, 1 – 28.

Alessa, L., Valentine, J., Moon, S., McComb, C., Hicks, S., Romanovsky, V., Xiao, M., Kliskey, A. (2023). Toward a permafrost vulnerability index for critical infrastructure, community resilience and national security. Geographies 3, 522-542.DOI: https://doi.org/10.3390/geographies3030027

Anderson, J.E., Douglas, T.A., Barbato, R.A., Saari, S., Edwards, J.D. and Jones, R.M. (2019). Linking vegetation cover and seasonal thaw depths in interior Alaska permafrost terrains using remote sensing. Remote Sensing of Environment, 233, p.111363. https://www.sciencedirect.com/science/article/abs/pii/S0034425719303827

Baker, C.C., Barker, A.J., Douglas, T.A., Doherty, S.J. and Barbato, R.A. (2023). Seasonal variation in near-surface seasonally thawed active layer and permafrost soil microbial communities. Environmental Research Letters, 18(5), p.055001. https://iopscience.iop.org/article/10.1088/1748-9326/acc542

Barbato, R.A., Jones, R.M., Douglas, T.A., Doherty, S.J., Messan, K., Foley, K.L., Perkins, E.J., Thurston, A.K. and Garcia-Reyero, N. (2022). Not all permafrost microbiomes are created equal: Influence of permafrost thaw on the soil microbiome in a laboratory incubation study. Soil Biology and Biochemistry, 167, p.108605. https://www.sciencedirect.com/science/article/pii/S0038071722000621

Barbato, R.A., Garcia-Reyero, N., Foley, K., Jones, R., Courville, Z., Douglas, T., Perkins, E. and Reynolds, C.M. (2016). Removal of exogenous materials from the outer portion of frozen cores to investigate the ancient biological communities harbored inside. JoVE (Journal of Visualized Experiments), (113), p.e54091. https://www.jove.com/v/54091/removal-exogenous-materials-from-outer-portion-frozen-cores-to

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., … Lantuit, H. (2019). Permafrost is warming at a global scale. Nature Communications, 10(1), 264. https://doi.org/10.1038/s41467-018-08240-4

Buhler, K., Dibernardo, A., Pilfold, N.W., Harms, NJ., Fenton, H., Carriere, S., Kelly, A., Schwantje, H., Fernandez Aguilar, X., Leclerc, L-M., Gouin, G-G, Lunn, N.J., Richardson, N.S., McGeachy, D., Bouchard, É. Hernández Ortiz, A., Samelius, G., Lindsay, L.R., Drebot, M.A., Gaffney, P., Leighton, P., Alisauskas, R., Jenkins, E. (2023). Widespread exposure to mosquito-borne California Serogroup Viruses in caribou, arctic fox, red fox, and polar bears, Canada. Emerging Infectious Diseases 29(1):54-63. https://wwwnc.cdc.gov/eid/article/29/1/22-0154_article

Buhler, K., Bouchard, É., Elmore, S., Samelius, G., Jackson, J., Tomaselli, M., Fenton, H., Alisauskas, F., Jenkins, E. (2022). Tularemia above the treeline: climate and rodent abundance influences exposure of a sentinel species, the arctic fox (Vulpes lagopus), to Francisella tularensis. Pathogens 12(1):28. https://www.mdpi.com/2076-0817/12/1/28

Douglas, T.A., Hiemstra, C.A., Anderson, J.E., Barbato, R.A., Bjella, K.L., Deeb, E.J., Gelvin, A.B., Nelsen, P.E., Newman, S.D., Saari, S.P. and Wagner, A.M. (2021). Recent degradation of interior Alaska permafrost mapped with ground surveys, geophysics, deep drilling, and repeat airborne lidar. The Cryosphere, 15(8), pp.3555-3575. https://tc.copernicus.org/articles/15/3555/2021/

Doherty, S.J., Barbato, R.A., Grandy, A.S., Thomas, W.K., Monteux, S., Dorrepaal, E., Johansson, M. and Ernakovich, J.G. (2020). The transition from stochastic to deterministic bacterial community assembly during permafrost thaw succession. Frontiers in Microbiology, 11, p.596589. https://pubmed.ncbi.nlm.nih.gov/33281795/

Ernakovich, J.G., Barbato, R.A., Rich, V.I., Schädel, C., Hewitt, R.E., Doherty, S.J., Whalen, E.D., Abbott, B.W., Barta, J., Biasi, C. and Chabot, C.L. (2022). Microbiome assembly in thawing permafrost and its feedbacks to climate. Global Change Biology, 28(17), pp.5007-5026. https://onlinelibrary.wiley.com/doi/10.1111/gcb.16231?af=R

Farquharson, L. M., V. E. Romanovsky, D. J. Nicolsky, and A. L. Kholodov, 2022. Novel sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska, Nature Geoscienses, https://doi.org/10.1038/s41561-022-00952-z

Golan, Y., Campos, J. A. S., Woolson, R., Cilla, D., Hanabergh, R., Gonzales-Rojas, Y., Lopez, R., Finberg, R., & Balboni, A. (2023). Favipiravir in Patients With Early Mild-to-moderate Coronavirus Disease 2019 (COVID-19): A Randomized Controlled Trial. Clinical infectious diseases: an official publication of the Infectious Diseases Society of America, 76(3), e10–e17. https://doi.org/10.1093/cid/ciac712

Goodwin, J. M., Golder, P. M., LeClair, A. R., Jun, S. C., Huckstep, O. J., Steel, J. J., & Balboni, A. L. (2023). Designing a Wastewater-Based Epidemiology Study at the U.S. Air Force Academy: Using Severe Acute Respiratory Syndrome Coronavirus 2 to Test a Sentinel System for Early Disease Outbreak Detection. Military medicine, 188(11-12), e3675–e3679. https://doi.org/10.1093/milmed/usad239

Hicks, S., McComb, C., Alessa, L. (2021). Agents and the Arctic: The case for increased use of agent-based modeling to study permafrost. The Arctic Institute Permafrost Series 2021. https://www.thearcticinstitute.org/agents-arctic-case-increased-use-agent-based-modeling-study-permafrost/

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., Etzelmüller, B., & Luoto, M. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. Nature Communications, 9(1), 5147. https://doi.org/10.1038/s41467-018-07557-4

Hueffer, K., D. Drown, V. Romanovsky, and T. Hennessy. (2020). Anthrax in the Circumpolar North: Thawing Permafrost and other factors contributing to outbreak on Siberia's Yamal Peninsula., EcoHealth, 17:174–180 https://doi.org/10.1007/s10393-020-01474-z.

Jensen, A. (2019). Critical information for the study of ecodynamics and socio-natural systems: Rescuing endangered heritage and data from Arctic Alaskan Coastal Sites. Quaternary International 549:227-238. DOI:10.1016/j.quaint.2019.05.001. https://www.sciencedirect.com/science/article/abs/pii/S1040618218304002

Kliskey, A., Williams, P., Abatzoglou, J. T., Alessa, L., & Lammers, R. B. (2019). Enhancing a community-based water resource tool for assessing environmental change: The arctic water resources vulnerability index revisited. Environment Systems and Decisions, 39(2), 183–197. https://doi.org/10.1007/s10669-018-9712-7

Mann, P. J., Strauss, J., Palmtag, J., Dowdy, K., Ogneva, O., Fuchs, M., Bedington, M., Torres, R., Polimene, L., Overduin, P., Mollenhauer, G., Grosse, G., Rachold, V., Sobczak, W. V., Spencer, R. G. M., & Juhls, B. (2022). Degrading permafrost river catchments and their impact on Arctic Ocean nearshore processes. Ambio, 51(2), 439–455. https://doi.org/10.1007/s13280-021-01666-z

McComb, C., Jablokow, K. (2022). A conceptual framework for multidisciplinary design research with example application to agent-based modeling. Design Studies, 78, 101074. https://doi.org/10.1016/j.destud.2021.101074

McKenzie, J. M., Kurylyk, B. L., Walvoord, M. A., Bense, V. F., Fortier, D., Spence, C., & Grenier, C. (2021). Invited perspective: What lies beneath a changing Arctic? The Cryosphere, 15(1), 479–484. https://doi.org/10.5194/tc-15-479-2021

Messan, K.S., Jones, R.M., Doherty, S.J., Foley, K., Douglas, T.A. and Barbato, R.A. (2020). The role of changing temperature in microbial metabolic processes during permafrost thaw. PloS one, 15(4), p.e0232169. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0232169

Nicolsky, D. J., V. E. Romanovsky, S. K. Panda, S. S. Marchenko, and R. R. Muskett (2017), Applicability of the ecosystem type approach to model permafrost dynamics across the Alaska North Slope, J. Geophys. Res. Earth Surf., 122: 50-75, doi:10.1002/2016JF003852

Office of the White House. 2022. National Strategy for the Arctic Region. Federal Government of the United States. https://www.whitehouse.gov/wp-content/uploads/2023/10/NSAR-Implementation-Plan.pdf.

Pilfold, N.W., Richardson E.S., Ellis J, Jenkins E, Scandrett B, Hernandez A, Buhler K, McGeachy D, Al-Adhami B, Lobanov V, Owen MA, Rideout B, Lunn NJ. (2021). Long-term increases in pathogen seroprevalence in polar bears (Ursus maritimus) influenced by climate change. Global Change Biology 27 (19): 4481-4497. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15537

Romanovsky, Vladimir, Ketil Isaksen, Dmitry Drozdov, Oleg Anisimov, Arne Instanes, Marina Leibman, A. David McGuire, Nikolay Shiklomanov, Sharon Smith, and Donald Walker, 2017. [Changing permafrost and its impacts]. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, pp. 65-102. Arctic, Monitoring and Assessment Programme (AMAP), Oslo, Norway, Narayana Press, Gylling, DK-8300 Odder, Denmark

Steel, J., Goodwin, J. M., Golder, P. M., LeClair, A. R., Metchikoff, M., Macmillan, D., Peterson, A., Balboni, A. L. (2024). Viral Metagenomics in Wastewater at the United States Air Force Academy: Unlocking Insights into Microbial Communities that Impact Force Health and Readiness. Proceedings of the Tri-Service Microbiome Conference, Washington, D.C.

Steel, J., Metchikoff, M., Macmillan, D., Peterson, Wickiser, JK., A., Balboni, A. L. (2024). High Altitude Sampling and Metagenomic Characterization of Potentially Pathogenic Vertebrate Viruses: Towards Early Detection of Diseases in Deployed Service Members. American Journal of Tropical Medicine and Hygiene (ASTMH), In-Press.

Williams, P., Kliskey, A., McCarthy, M., Lammers, R., Alessa, L., & Abatzoglou, J. (2019). Using the Arctic water resources vulnerability index in assessing and responding to environmental change in Alaskan communities. Climate Risk Management, 23, 19–31. https://doi.org/10.1016/j.crm.2018.09.00

Wang, Z., Xiao, M., Liew, M., Jensen, A.M., Farquharson, L., Romanovsky, V., Nicolsky, D., McComb, C., Jones. B.M., Zhang, X., and Alessa, L. (2023). Arctic Geohazard mapping tools for civil

infrastructure planning: A systematic review. *Cold Regions Science and Technology* 24 DOI: 10.1016/j.coldregions.2023.103969. https://www.sciencedirect.com/science/article/abs/pii/S0165232X23001994

Wu, R., Trubl, G, Tas, N. and Jansson, J. 2022. Permafrost as a potential pathogen reservoir. One Earth Volume 5, Issue 4, pp. 351-360. https://www.cell.com/one-earth/fulltext/S2590-3322(22)00143-9?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2590332222001439%3Fshowall%3Dtrue.

Appendix B: Permafrost and Pathogens Workshop Comment Box Narratives (Less requirements identified during Phase 3)

Day 1:

- Require prototype to design and test the "practical problem" to get at "different ways of knowing" the emerging topics (concerns). Technologies: Permafrost and pathogens current and future threats.
- Best workshop I've ever been to! Usually go away with a few business cards but my head hurt after this one in a good way. Need more of these with same group and leaders.
- Looking at the time horizons for arms control and non-proliferation, has thought ever been given to an "Arctic Bio-Weapon Convention?"
- Do current Bio-Weapon Convention parameters address the potential misuse of permafrost/novel pathogens in the Arctic? Would RUS or/and CHI ever accede to a new treaty?
- Geographic distribution needs to be increased – e.g., add Tibet which has permafrost.
- Better temperature data/weather data is needed for modelling.
- Permafrost degradation is non-linear. It starts and stops.
- Need data archives, including samples.
- Where are all the samples and who has access to them?
- Pathogenesis is the principle of development of diseases. In permafrost, it is changing behavior.
- Microbes change – non-pathogenic could become pathogenic and vice versa.
- Permafrost region:
    - More than circum-Arctic.
    - What is the absolute range?
    - What about altitude vs just latitude?
- To better marry microbial genomics/shot gun sequencing of permafrost ecosystem, consider surveillance of acute febrile illness, acute respiratory illness, etc., in patients in Arctic environments, especially if diagnostic tests are negative for standard pathogen panels.
- DOD is working on building a Bio-surveillance Hub & Portal for capturing information on all hazard health threats. NORAD and USNORTHCOM could include requirements for including data sources relevant to the Arctic and permafrost.
- Need ability to predict depth of permafrost thaw seasonally.
- Need biosurveillance for emerging pathogens with thaw – what is there?
- Need human/animal interface with permafrost thaw.
- Need – use information to inform operations.
- The worry is where the nexus of changing permafrost, pathogenesis, and transmissibility, meets DOD areas of concerns (geolocations) of defense critical infrastructure or anticipated operating areas. Note: "Defense Critical Infrastructure" is the latest NORAD and USNORTHCOM focus area of concern. The bad corollary is NORAD and USNORTHCOM segregated staff into Cheyenne Mountain (social distancing during COVID).

- Need a strategy before a strategic plan. Two different functions – well established in peer reviewed literature (even different cognitive processes).
- Use the databases we have now rather than create new ones. Will help with funding and data preservation.
- Great dynamic group – some humor.
- What does this mean for operational troops in the Arctic right now? Should we not use tents that might warm the ground? Not only snow caves? Do we know if any of this matters?
- Defining what we mean when we say "permafrost" or "Arctic" in this operational context has to consider cascade impacts in nearby locations. Similarly, this will eventually boil down to laws from the operations perspective. What we define as permafrost/Arctic will define our decision sets.
- What changes in permafrost are relevant to DOD operations. DOD articulates where and when they operate. That's where we start looking.
- Permafrost data should not be connected to biosurveillance. It should be independent with different classification levels. NGA is the right place for this task.
- ChatGPT identified permafrost datasets down to 1km resolution and can model it on maps for us. It even found studies confirming spatial data with borehole ground temperature analysis. Maybe more raw data can be used to extrapolate additional Arctic relevant information inexpensively with open-source AI.
- DOD has housed years of serum in its DOD Serum Repository. This could be queried to understand if there are any indicators unique to service members exposed to Arctic environments.
- Operationally, the weather/climate community does not work with the health community.
- No strategic foresight to provide actionable intelligence (operationally).
- The thousands of soldiers training in the same locations every year in the Arctic provide a perfect opportunity to measure human impacts on permafrost. How do human/mil inputs and impacts affect permafrost and microbial populations? The data collected could be very predictive of what's encountered in an operation.

Day 2:

- Development or implementation of pilot program to sample permafrost soil for nucleic acid extraction and sequencing as well as microbial isolation/culturing from samples.
- Need a way to sample and analyze samples in situ, on demand.
- Need an operational science; includes methods/framework/cycle/decision outputs.
- We need a detailed conceptual model that describes the permafrost and pathogen and operations system.
- Need more of these QEDs. This has been a great way to get at knowledge as a group. Wish I paid more attention in biology.
- Development of methods to identify unknown microbes that have pathogenic potential.
- Require a solvable practical (operator focused problem) that can provide insight into possible risk to the environment, conditions, and actors. Variables: Composition of

permafrost, properties (material, geometry, etc.), permafrost, pathogen, extreme cold-weather conditions.

- Establish lines of communication between experts and DOD – people with clearances and who are experienced with military operations and/or civil response.
- Define command/control/communications structure and methods.
- Research – build robust SOPs that work in the environment.
    - What is the path/SOP for sample collection and analysis?
    - Is the testing done in the field or prepared for transport – if transport, what lab? How to preserve samples? What tests? Soil, water, clinical?
- We need a clear link between permafrost data/expertise and pathogen/biology data/expertise.
- Variables/Key words:
    - Skilled decision making
    - Risk
    - Permafrost
    - Pathogens
    - Extreme cold weather conditions
    - Transmissibility
    - Data
    - Emerging Technologies (monitor characteristics and dynamics)

DOD	Project PMP	Proposal Science
LOE1: LL	Initiate	Literature Review
LOE2:	Plan	
LOE3:	Execute	Experiment, Proof of Concept
LOE4:	Maintain/Sustain	
LOE5: J7	Assess	Method
LOE6: Innovate	Close	Areas for Future Research

- Need means for field testing in field. Ideally includes non-bio threats.
- Need clear message to engage lead agency.
- Consolidated data guidance across permafrost, DOD operations, communities at risk, clinical end points, microbial screening, time horizon.
- Interagency working group – Science, DOD, DTRA, NIH
- Obtain more information/data on presence of potentially pathogenic microorganisms in the permafrost environment.
- Collect data to be able to relate known permafrost properties/characteristics to increased probability of long-term survival of these microorganisms.
- Collect data to relate changes in permafrost (present and future) to potential release or re-mobilization of these organisms.

- Need to understand/predict surface permafrost thaw geographically, and animal/insect/human interactions/activities in those areas. Areas of higher risk to pathogen emergence to monitor.
- Environment – Early detection. Need biosurveillance of permafrost regions, humans, animals, environment. Need integration of as much of this data as possible.
- Appointing an "Arctic Authority." Without proper authority in place to coordinate all "Arctic" initiatives, there is no common operational picture possible.
- Baseline of potential permafrost microbial population that cause wound infections. Are the pathogens there?
- Baselines:
    - Physical baselines should include up to date extent of permafrost.
    - Ideally identify likely organisms based on physical conditions on ground.
    - Need baseline disease data in permafrost areas to identify deviations of norms and likely diseases.
- Modeling expansion of permafrost and pathogenesis – i.e., what could possibly kill you first and foremost, even if remotely possible if a bacterium found in permafrost. Or – to a lesser extent, degrade your ability to conduct security operations.
- Better understanding of zoonosis in the Arctic of new/novel pathogens.
- Consider if/how the topic of pathogens and permafrost can be communicated at the OSD/DASD level in the context of the recent Biodefense Posture Review.
- Develop field training exercise with AML, Biological Defense Research Directorate (BDRD) and others to test field deployable lab diagnostic tools in Arctic environments.
- Initiate active, lab surveillance service members with fever or respiratory illness of unknown origin. Feed samples into GEIS genomic sequencing pipeline. Ensure genomes are posted to public databases for sharing (e.g., GENBANK).
- NORAD and USNORTHCOM may need to consider a JUON/JEON with requirements to ensure combat support agencies prioritize this work and invest resources.
- Blanket interagency agreement to be able to share data and samples between groups.
- Need to be able to identify symptom clusters in all permafrost affected areas and be able to create case definitions to drive further identification of cases. Follow up would be able to assign lab assets to make definitive diagnoses.
- Mining of DAN/RNA sequence data for both potential pathogens and mitigating factors (biotech!).
- Scrutiny for recovery of pathogens from animal and human remains.
- Coordinated animal (wildlife) and human surveillance for emerging pathogens in the Arctic.
- Research into evolutionary mismatch between paleo-pathogens and modern species.
- Guidelines for generic biohazard protection when working with permafrost.
- Guidelines for ethical "de-extinction" of pathogens.
- Joint Canada/U.S. calls for targeted research on pathogens in permafrost.
- Identify coordinating authority. Provide small list of potential coordinating authority candidates. Example: Joint Staff, Ted Stevens Center, DTRA, NORAD and USNORTHCOM.

- Provide framework to allow quick transfer of information to allow for rapid response.
- Need the authoritative agency to have the capability to:
    - Define needs.
    - Collect/analyze data.
    - Disseminate findings.
    - Update needs.
- We need case studies that clearly demonstrate pathogen presence in the permafrost in operationally relevant areas.
- Funding mechanism.
- There's a problem with previously "eradicated" diseases coming back because we don't recognize them.
- Privacy law differences between the EU, the US, and Canada can keep us from sharing detections.
- Sharing is challenged by concerns of reporting operational readiness.
- Subsistence communities actively monitor wildlife. They rely on it. This is a possible indicator without extensive privacy protections.
- Clinicians in Operation Planning reduce risk and increase resilience.
- DOD has a surveillance system, but Disease and Non-Battle Injury trackers are narrow. Need to broaden aperture and expand systems to civilian.

Appendix C: Potential Data Repositories (Non-exhaustive)

Panarctic permafrost microbial community and edaphic data collected from 2010-2020 – ScienceBase - Catalog (https://www.sciencebase.gov/catalog/item/625dd640d34e85fa62b7a7ab)

National Oceanic and Atmospheric Administration (raw data source)

National Aeronautics and Space Administration (raw data source)

Global Water Security Center

Defense Centers for Public Health

Defense Medical Surveillance System

DOD Disease and Non-Battle Injury Data Sets

DOD Serum Repository

Department of Energy Office of Science (Models)

U.S. Geological Survey (freshwater data, permafrost data)

U.S. Fish and Wildlife (river data)

U.S. Department of the Interior (river data)

National Park Service (river data)

Alaska Resources Library and Information Services (Library Service)

Global Terrestrial Network for Permafrost (permafrost data)

Geophysical Institute (permafrost data)

Appendix D: Participant Inputs Sorted by Priority, from Phase 1, Permafrost and Pathogens Workshop – "What is the Status Quo?"

		Pareto/N3 Tallies							
		Priority			Urgency for Action				
ELICITED INPUTS	*Quadrant*	Most	Moderate	Least	Now	0-5 Years	5-10 Years	10+ Years	Highest Priority
Coordinating authority, strategy development, and strategic planning	*Other*	12	3	1	15				9
Biosurveillance hub under development needs to include permafrost/pathogen data	*Data Repositories*	10	6		9	1	1		1
Science-based models/outputs don't directly support planning, policy, decision-making	*Data Repositories*	6	6	1	7	3	1		3
ID LOEs and teams who can take basic science and turn it into guidance for strategy development, planning, and policy	*Other*	5	6	3	3	6	4	4	1
Data pool continuity/upload/access	*Body of Knowledge Relevance to DOD Operations*	5	3		4	1			
Permafrost active layer warrants specific consideration	*Pathogenesis*	4	4		3	1			
Need better surveillance systems	*Body of Knowledge Relevance to DOD Operations*	5	2		2				
Human environmental impact on pathogen release/introduction of existing/dormant organisms	*Pathogenesis*	4		5	2	1	7	2	
Opportunistic pathogen change behavior in thaw not well known	*Body of Knowledge Relevance to DOD Operations*	5	1		1	1			
Place Based Knowledge is important	*Data Repositories*	3	3	1	2	5	3		
Data maintenance is critical	*Data Repositories*	4	1		1		3	5	

		Pareto/N3 Tallies							
Link between microbial genomic/ecology and clinical significance	*Pathogenesis*	3	2		3	5			3
Ownership/stewardship of the Arctic data mission	*Other*	3	2		1				
Understand impact of people/equipment on environment re: pathogen release	*Other*	2	1	5	1	4	1		
Hub/portal on microbial diversity	*Microbial Distribution and Density*	3	1		1				1
Unknown vectors/vector competence	*Pathogenesis*	2	2	1	1	1			
Evaluate transmissibility with virulence and disease severity	*Pathogenesis*	2	2		1	3	1		1
New/novel microbes	*Microbial Distribution and Density*	2	1						1
Understand relevance of permafrost types and pathogenicity	*Microbial Distribution and Density*		4		6	7			
Clinical/operational relevance/significance must be determined	*Pathogenesis*	1	1	3	2		2	1	
Environment decontamination	*Microbial Distribution and Density*		2	3	2		3	1	
Unrecognized microbial diversity	*Microbial Distribution and Density*	1	2		1				
Data security is an active concern	*Data Repositories*		3						
Geographic information is compartmentalized/lacking	*Body of Knowledge Relevance to DOD Operations*		1	4		3		6	
Human pathogen/microbe introduction	*Microbial Distribution and Density*		1	3	3	2			
Microbe stability over time - freeze/thaw	*Microbial Distribution and Density*	1	1					1	
Lack of translatability	*Data Repositories*	1	1						
Arctic connectivity through sea ice in	*Body of Knowledge*			5		1	2	3	

		Pareto/N3 Tallies							
disease context	*Relevance to DOD Operations*								
Data standardization lacking	*Body of Knowledge Relevance to DOD Operations*	1	1					1	
Operational considerations for known threats & prophylaxis	*Body of Knowledge Relevance to DOD Operations*	1	1		1	1	2		
ID who is accountable for US, Canada, Russia	*Microbial Distribution and Density*	1		1					
Data quality is huge issue	*Data Repositories*		2			3			
Host susceptibility/genetic variations impact pathogenic potential	*Pathogenesis*		2			1	1		
How permafrost changes effect pathogenic microbe behavior	*Pathogenesis*		2		2	3			
Different microbes in active/frozen layers	*Microbial Distribution and Density*	1			1				
Microbe phenotype changes	*Microbial Distribution and Density*		1	1					
Microbes adapt to host	*Microbial Distribution and Density*			3		1	2	1	
Sea ice as microbe carrier - foot traffic warms ice	*Microbial Distribution and Density*			3				2	
Data pooling/clearing/usability/discoverability needed	*Data Repositories*		1	1	1				
Global Water Center - No existing freshwater data	*Data Repositories*	1			1	2			
Similar sources in Canada/Russia/Etc./China	*Data Repositories*		1	1		1			
Complexity and environmental changes impact pathogenesis	*Pathogenesis*			3		1	1		
Virulence factors in frozen/thawed state already known for certain microbes	*Pathogenesis*		1	1	1	1			
Diffuse and disaggregated data	*Body of Knowledge Relevance to DOD Operations*	1			1				

		Pareto/N3 Tallies							
How does permafrost thaw timeline affect operations?	*Body of Knowledge Relevance to DOD Operations*		1	1	1		3	2	
Need permafrost ice content data	*Body of Knowledge Relevance to DOD Operations*		1	1					
Data ownership is critical	*Data Repositories*			2					
Permafrost extent is changing - Need decadal refresh for science, summer thaw for ops	*Data Repositories*		1		1			1	
Assess NORAD and NORTHCOM interest in enhanced syndromic surveillance	*Pathogenesis*		1			1		2	
Challenges with samples/specimens	*Pathogenesis*		1						
Disease and Non-Battle Injury	*Pathogenesis*		1						
Drivers of microbial/viral evolution	*Pathogenesis*		1				2	2	
Knowledge gap of genetic variation of pathogens and vectors	*Pathogenesis*		1						
More data on temperature (permafrost)	*Body of Knowledge Relevance to DOD Operations*			2	1				
Need data curation	*Body of Knowledge Relevance to DOD Operations*		1			2			
Economic impacts	*Other*			2	2		1	5	
Bird migration patterns	*Microbial Distribution and Density*			1					
Gene introduction	*Microbial Distribution and Density*			1				2	
Refresh data every year (operations), every decade (science)	*Microbial Distribution and Density*			1			1		
Spectrum of pathogenesis (fatal vs incapacitation) must be considered	*Pathogenesis*			1			4	1	
Transmission as important as pathogenic impact	*Pathogenesis*			1					
NORAD and NORTHCOM to identify a	*Body of Knowledge*			1	1	7			

		Pareto/N3 Tallies							
requirement, ID LOEs	*Relevance to DOD Operations*								
Permafrost distribution known, but not continuous, discontinuous, sporadic	*Body of Knowledge Relevance to DOD Operations*			1				1	
Animal link cryoprotects microbes	*Microbial Distribution and Density*				1				
Bacteria, virus', fungi are of concern	*Microbial Distribution and Density*							1	
Diversity characterization technology	*Microbial Distribution and Density*								
Global information gaps - microbes across geography	*Microbial Distribution and Density*					1		1	
Vector diversity not well understood	*Microbial Distribution and Density*							2	
Lack of alignment in acquisition	*Data Repositories*								
Point-based permafrost data (historical log)	*Data Repositories*					1			
Raw data exists; interpretation takes effort	*Data Repositories*						2		
Wastewater & COVID databases starting to disappear.	*Data Repositories*				1				
Geographic dispersion - multi-national/global impacts	*Pathogenesis*					2	1		
Need to consider implications for intermediate hosts.	*Pathogenesis*								
Public Health Emerging Infections of Concern	*Pathogenesis*						1		
2010, UN brought cholera to Haiti	*Body of Knowledge Relevance to DOD Operations*								
Funding driving database sustainment	*Body of Knowledge Relevance to DOD Operations*				1		1		
How good is upload of data to International Polar Year	*Body of Knowledge Relevance to DOD Operations*								
Pathogen specificity, but horizontal gene transfer	*Body of Knowledge Relevance to DOD*								

		Pareto/N3 Tallies							
	Operations								

Appendix E: Participant Inputs Sorted by Priority, from Phase 2, Permafrost and Pathogens Workshop – "Prioritization for Mitigating Operational Impacts"

		Pareto/N3 Tallies							
		Priority			Urgency for Action				
ELICITED INPUTS	Quadrant	Most	Moderate	Least	Now	0-5 Years	5-10 Years	10+ Years	Highest Priority
Must understand rate of change	*Other*	2	5	1	6	2	2	2	6
Link surveillance to pathogenicity	*Body of Knowledge Relevance to DOD Operations*	6	6	1	12	4			5
Understand what is clinically significant	*Microbial Distribution and Density*	6	4	3	3	7			3
Thaw rate related to pathogen release	*Pathogenesis*	6	10		5	1			2
Understand short- and long-term ground-based operations impacts	*Other*	2	1						2
Human presence promotes change through heat/waste	*Pathogenesis*	6	1		10				1
Human waste microenvironment impacts	*Body of Knowledge Relevance to DOD Operations*	2		5		5	2	1	1
Need wastewater sampling	*Microbial Distribution and Density*		1	2	2	3	1	1	
Human waste introduces microbes & virulence genes	*Microbial Distribution and Density*			3	1	1	1		
Warmth bubbles increase thaw & microbe release	*Microbial Distribution and Density*	1	2			1			
Fuel release impacts unknown	*Microbial Distribution and Density*		1	4		1		1	
Identify inflection points	*Microbial Distribution and Density*	4	3	2	5		3		
Study microbial diversity in permafrost/ice rich layers	*Microbial Distribution and Density*	2	2	1					

		Pareto/N3 Tallies							
Understand ice content and microbe resistance	*Microbial Distribution and Density*		2						
Infrastructure changes microbe distribution	*Microbial Distribution and Density*		2				2	3	
Limited data WRT Defense Support for Civil Authorities impacts	*Data Repositories*					1	1		
Waste streams during ops/training are unknown	*Data Repositories*	4	1			3			
Defense Occupational and Environmental Health Readiness System is a wealth of information	*Data Repositories*								
Individual Longitudinal Exposure Record - Individual Level data	*Data Repositories*		1	1		1	1	1	
PubMed English translations on Russia waste handling studies	*Data Repositories*							1	
Permafrost impacts from new infrastructure can influence future development	*Data Repositories*	6	1	3		6	1	1	
Need data on maritime activity impacts on permafrost	*Data Repositories*			2					
Need to conduct a meta search on Permafrost and Pathogens	*Data Repositories*		8	2	5	1			
Permafrost thaw significance for dormant pathogens	*Pathogenesis*	14	1		8	3	3	1	
Force/mission risk from tipping points	*Pathogenesis*			1		1			
Focus on higher ice content permafrost	*Pathogenesis*				1				
Risk from increased infrastructure to support maritime activity	*Pathogenesis*			5			5	3	
Different national policies r.e. waste cleanup	*Body of Knowledge Relevance to DOD Operations*				1				
Define long/near term environmental impacts for operators	*Body of Knowledge Relevance to DOD Operations*								
Tipping points/indicators not well known	*Body of Knowledge*	6	5	1	3	1	1		

		Pareto/N3 Tallies							
	Relevance to DOD Operations								
Need to analyze pathogenicity in permafrost drivers	*Body of Knowledge* *Relevance to DOD Operations*	1	6	1			2	2	
Study permafrost as ecosystem to understand fixed site infrastructure impacts	*Body of Knowledge* *Relevance to DOD Operations*							3	
Need to understand exercise impacts	*Other*		1	1					
Shore infrastructure impacts need to be understood	*Other*			3			1	3	

Appendix F: Participant Inputs Sorted by Priority, from Phase 3, Permafrost and Pathogens Workshop – "Prioritization of developing and closing requirement gaps"

		Pareto/N3 Tallies				
		Urgency for Action				
ELICITED INPUTS	*Quadrant*	Now	0-5 Years	5-10 Years	10+ Years	Highest Priority
Need proof of concept data	*Body of Knowledge Relevance to DOD Operations*	9			1	1
Need data-driven strategic communications package to educate leadership	*Other*	4	2	1		2
Demonstrate true risk/threat to human health under Extreme Weather Operations Framework	*Pathogenesis*	22	3	3	1	13
Characterize beneficial microbial communities - Buffering capacity	*Microbial Distribution and Density*		1	6	4	
Catch microbes early that may carry risk	*Microbial Distribution and Density*		1	3	2	
ID operationally relevant high-risk regions we already operate in	*Microbial Distribution and Density*	11	9	1		
Data/sample sharing for method development and validation	*Data Repositories*	4	4	3	2	
Synchronize data requirements across federal/science agencies	*Data Repositories*		1	3	2	
Engage I.C.A.R.	*Data Repositories*	2				
Develop guidance to inform commands on where to operate (e.g., risk heatmap)	*Data Repositories*		1	3	1	
Symptomology across all Arctic regions and species	*Data Repositories*	1	1	3		
Ensure relevant data source integrity	*Data Repositories*			2		
ID responsible party and aggregate diverse data from	*Data Repositories*		5			

		Pareto/N3 Tallies				
RFI or DCL	Quadrant	Now	0-5	5-10	10+	High
Improve/adapt/train data collections procedures	*Data Repositories*		1	3	3	
Focus on how/where we are vulnerable	*Pathogenesis*	2	6			
Outline probability & severity of consequences to force health/mission assurance for planning	*Pathogenesis*	2	3	2	1	
Threat reduction requirement to maintain/establish strategic advantage in known/current areas to start	*Pathogenesis*	2	2	1	2	
Strategy to align pathogens in permafrost with other emerging threats	*Body of Knowledge Relevance to DOD Operations*	2				
Scope for early identification and probability assignments	*Body of Knowledge Relevance to DOD Operations*	3	10			
Focus on risk mitigation	*Body of Knowledge Relevance to DOD Operations*	1				
Relevant bio testing of threats (e.g., MINION)	*Body of Knowledge Relevance to DOD Operations*			1		
Expand exercise testing to multiple labs to validate methods	*Body of Knowledge Relevance to DOD Operations*					
Research previous wars for lesson learned vis a vis environmental interaction	*Body of Knowledge Relevance to DOD Operations*		5	3	3	
Short term: Planning guidance	*Other*					
Short to mid-term: Resolve data for authority to operate/risk	*Other*					
Short to mid to long term: Policies for mitigation	*Other*					
Intel bucket	*Other*					