Snow, frost, and anthrax: How climate change and permafrost thaw is leading to the re-emergence of deadly, infectious diseases

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In the warm summer months of 2016, over seventy nomadic Siberian hoarders were hospitalized after contracting a mysterious illness that caused breathing complications and blistering under the skin. Multiple microbial tests were performed on the bacterium causing this perturbing illness; the culprit was *Bacillus anthracis*, the etiological agent of anthrax. Anthrax cases have been extremely rare across the globe due to advancements in technology—in fact, this region had been completely void of anthrax cases since the early 1940s (Luhn, 2016). Then what, if anything, can explain such a widespread outbreak of a disease that is becoming increasingly more obsolete with the passage of time?

The answer lies within Earth's various permafrost layers. In the arctic region, subzero temperatures have encased the soil, and layers deep into the soil, in a thick coating of ice. These frozen layers, named permafrost, have the ability to preserve whatever has been trapped within the frost. Recent increases in global temperature have allowed some of this permafrost to thaw, thus liberating everything that had been originally frosted over. The Siberian permafrost had been preserving anthrax spores that were produced by mammalian anthrax victims over 70 years ago (Timofeev *et al.*, 2019).

Climate change and melting permafrost have enabled these preserved anthrax spores to emerge from the permafrost and reside within the soil, infecting the grazing reindeer who, in turn, infect humans. Global temperature projections indicate that the Siberian tundra will continue to warm and melt permafrost, consequently inviting more preserved microbes to awake from hibernation (Biskaborn *et al.*, 2019). The rise of these 'dead' microbes has led to the reemergence of diseases that had gone mostly dormant in recent decades. Outbreaks of already cured diseases and viruses (i.e. anthrax, smallpox) are becoming progressively more prevalent due to the melting permafrost. Researchers often focus their efforts on tropical regions when investigating reemerging diseases; such as mosquitoes serving as malicious vessels of malaria and dengue in warm, temperate regions. However, efforts to combat reemerging diseases should be focused more vehemently towards arctic regions since melting permafrost exposes preserved microbial communities.

Climate change as a driver of permafrost melt

As technological advancements have allowed society to evolve into a more robust state, the subsequent environmental impacts have been mostly disregarded as an afterthought. Big industry emissions, pesticide runoff, and deforestation are only a few, key examples of how nature has been altered for society's benefit regardless of environmental damage. Long-range air transportation has also been identified as a perpetrator of air pollution via atmospheric brown cloud production. These microscopic cloud particles have the ability to condense and absorb sunlight and further reflect solar radiation into the atmosphere. This absorption and reflection of radiation increases atmospheric temperatures and further enables greenhouse gases, like methane and carbon dioxide, to trap heat in the atmosphere (Ramanathan and Feng, 2009). Recent increases in global temperature caused by these greenhouse gases can account for the melting arctic permafrost.

Global temperatures have been prolifically increasing as a result of atmospheric warming. Within the decade between 2007 and 2016, global temperatures rose 0.3℃, with a 0.39℃ increase in the Arctic region alone. In fact, the southernmost border of permafrost has receded over 15 miles northbound as a result of such warming (Stella *et al.*, 2020). Melting of permafrost can be achieved when arctic temperatures fail to fall below freezing as a consequence of climate change. As seen in *Figure 1*, air temperature abnormalities are found to disproportionately target Arctic regions, thus catalyzing more permafrost thaw.

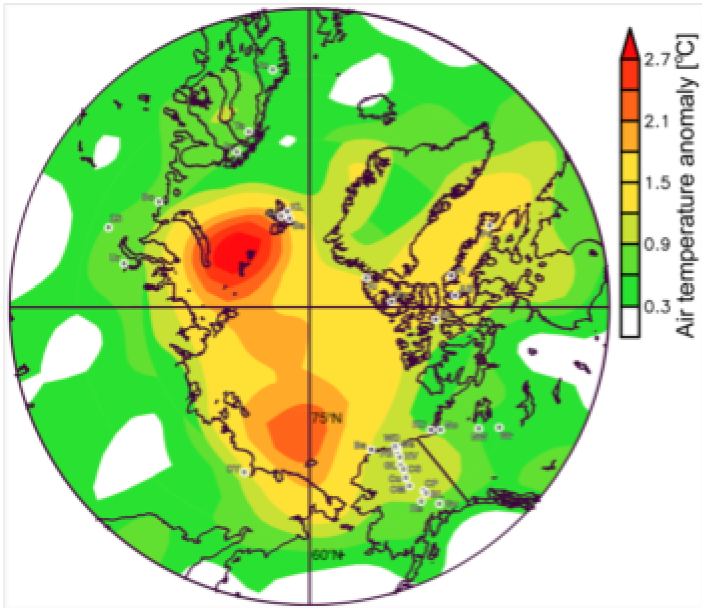

Figure 1: Areas of permafrost melt and surface air temperature anomalies during 2000-2016 (*National Oceanic and Atmospheric Administration*, 2017)

Permafrost is a blanket term that describes any type of ground layering bound together by ice that has been continuously frozen over for at least two years (Denchak, 2018). These layers can be soil, rock, sand, or any other layer of sediment deep into the Earth's crust. The thickness of each permafrost layer depends on the region it resides. Arctic territories, including Siberia, are correlated with having permafrost of increased thickness due to the frigid temperatures (National Geographic, 2011). Permafrost can be further classified into two different categories based on its thickness and distribution. Continuous permafrost, like Siberian permafrost, stays frozen throughout the duration of the year and does not waver in composition. Discontinuous permafrost, on the other hand, tends to thaw during the warmer months due to the sun's radiation. Continuous permafrost does not thaw as frequently as discontinuous permafrost since it naturally exists with a higher thickness and more uniform composition, however, more continuous permafrost has been thawing to form discontinuous permafrost, which is a blatantly clear indicator of climate change (Turetsky *et al.*, 2019).

Under ideal conditions, continuous permafrost will remain frozen. Increasing global temperatures have catalyzed some of this permafrost to undergo a phase change from solid to liquid, thus liberating the contents of the permafrost. *Figure 2* below illustrates the terrestrial effects of melting permafrost across a vast landscape. Melting permafrost has dire consequences for surrounding ecosystems, infrastructure, and landscapes because the structural integrity of the soil becomes compromised and loses rigidity (Denchak, 2018). Continuous permafrost thaw is especially dangerous because the ice can serve as a preservative for various organisms, microbes, and viruses. It takes years, or even decades and centuries, for areas of particularly thick continuous permafrost to accumulate, so when this permafrost thaws, years', decades', and centuries' worth of preserved material is released.

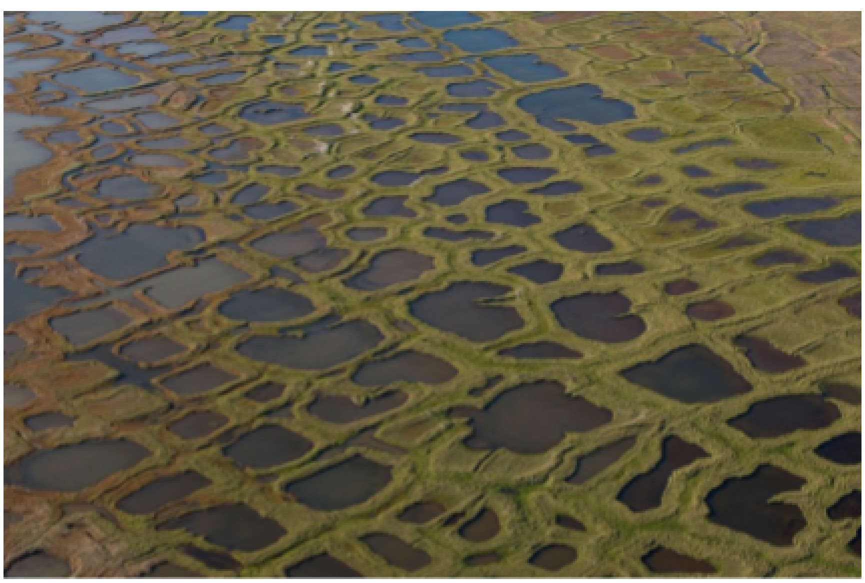

Figure 2: Small lakes form along the Arctic coast in Alaska as a result of melting permafrost and ice (Turetsky *et al.*, 2019).

Methanogenic microorganisms, methane, and permafrost: a feedback loop

The exact inhabitants of this permafrost will depend upon the region, as well as the region's history. Methanogenic microorganisms are commonly found in most permafrost because they have the ability to survive in extremely cold temperatures (Walter et al., 2006). Once unbound by ice, microorganisms will begin to break down organic matter in the soil. They will also continue to break down organic material from any dead organisms that were trapped in the permafrost as well. Decomposition of organic matter releases a myriad of greenhouse gases into the atmosphere, including methane and carbon dioxide (Turetsky et al., 2019). Once present in the atmosphere, methane is a very efficient greenhouse gas due to its innate ability to absorb heat in the form of radiation from the sun. This trapped heat leads to rising global temperatures, which then further catalyzes permafrost to melt.

This relationship forms a positive feedback loop because methane is promoting the permafrost to melt and release methanogenic microorganisms. In turn, methanogenic microorganisms continue to produce methane, a perpetuator of climate change. Once added to atmospheric oxygen, methane will react to form another greenhouse gas, carbon dioxide. Both methane and carbon dioxide play an instrumental role in trapping and retaining heat within the atmosphere, thus increasing global temperatures. The total concentration of atmospheric methane has increased as a result of this positive feedback loop (Saunois et al., 2016).

Another source of methane emission via permafrost melt is thaw lake bubbling. In Northern Siberia, small lakes reside where the permafrost has melted, creating a similar scene as in *Figure 2*. These lakes also have the ability to emit methane as a result of an ebullition process, thus increasing atmospheric methane concentrations. In fact, North Siberian thaw lakes release

3.8 teragrams of methane per year, which raises the current methane emission projections by up to 63% (Walter *et al.*, 2006). However, methane emissions and methanogenic microorganisms are not the only resulting factors of permafrost thaw. Preserved microbial communities, including bacteria and viruses, are also released by this thaw.

***Bacillus anthracis* and other reemerging microbes**

Bacillus anthracis is a rod-shaped, gram-positive bacterium that causes the rare, yet infectious disease anthrax. This bacterium is very resilient because it has the ability to produce spores, which can go dormant for extensive periods of time and still be infectious (Sweeney *et al.*, 2011). Contraction of anthrax occurs most commonly in either a cutaneous, gastrointestinal, or inhalational manner. Once inhabiting a body, *Bacillus anthracis* spores become active, thus allowing the bacteria to multiply and produce toxins (CDC, 2010). Effects of anthrax on humans depend on how the bacterium has entered the body, but these complications can include anything from shortness of breath and chest or abdominal pain, to blistering, dark scabs on the skin as shown in *Figure 3*. Anthrax, however, is very treatable with antibiotics if they are used in a

Figure 3: a skin ulcer produced as a symptom of cutaneous anthrax (CDC, 2011)

timely manner. If anthrax remains untreated, *Bacillus anthracis* will continue to spread throughout the body, eventually leading to death in two to three days (CDC, 2011).

Anthrax is classified as a zoonotic and epizootic disease, indicating that it predominantly impacts animal populations, but it can also spread to humans via infected animals. *Figure 4* shows how anthrax spores are transported from the soil to grazing animals, which can, in turn, infect humans through close contact with the animal or spores produced by the animal. In the 2016 case of anthrax transmission among the 70 Siberian hoarders, anthrax spores from a dead, infected reindeer remained dormant in the permafrost for decades until thawing released these anthrax spores into the soil, water, and food supply. Over 2,000 reindeer became infected with anthrax through these spores, which subsequently led to the infection of nomadic humans due to the sheer volume of anthrax spores present in the area (Timofeev *et al.*, 2019). There is growing fear that this case is only a microcosm of what awaits in the future if global temperatures

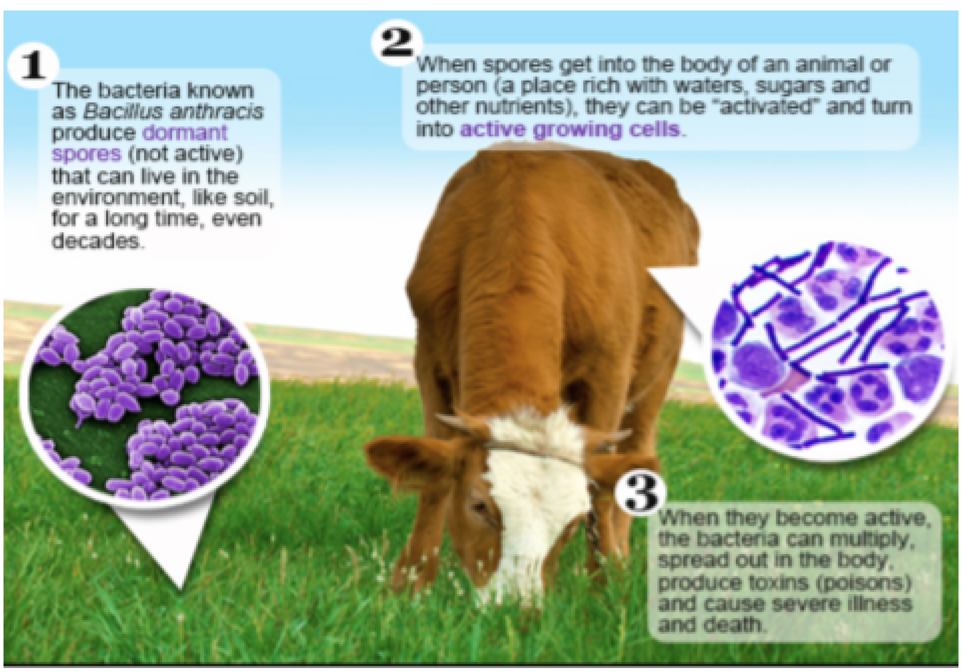

Figure 4 shows how anthrax is mostly commonly traced from soil to mammal (CDC, 2011).

continue to rise and thaw permafrost in a rapid manner, thus releasing more microbes and paving the way for more diseases to reemerge from the ice.

Circa 1890, Siberia was a hotspot for a smallpox epidemic, resulting in fatalities for over 40% of the local population (Théves, Biagini, and Crubézy, 2014). Mass graves and burial sites of these smallpox victims lie under the permafrost near the Kolyma River where recent thawing has expedited erosion. In the early 1990s, researchers entered these mass graves to analyze the mummified bodies of the smallpox victims in fear that more thawing and erosion would naturally unearth the graves (Stone, 2002). Samples from the corpses were tested and surveyed; bodies with sores and lesions from smallpox were identified, indicating that smallpox victims were, in fact, present within the graves. However, the virus itself was not identified within the grave, and only small DNA fragments of smallpox were discovered (Reardon, 2014). Fortunately, not all permafrost microorganisms are well-suited to survive the frigid temperatures for extended periods of time. Spore-producing bacteria, like *Bacillus anthracis*, thrive under these conditions due to the resiliency of the spores. This alludes to the fact that other spore-forming microbes, like the etiological agent of botulism, *Clostridium botulinum*, could also emerge from the permafrost thaw, but no traces of these microorganisms have been identified—yet.

The permafrost harbors carcasses of diseased humans and animals that lived centuries prior, therefore the infectious agents that once killed those organisms can remerge as the permafrost thaws and infect humanity once more. In a mass burial grave within the Alaskan tundra, RNA fragments from the 1918 Spanish flu virus have been discovered (Taubenburger, Hultin, and Morens, 2007). This prolific, deadly influenza virus was active over a century ago, and now its remnants have been unearthed with permafrost thaw. To further exemplify the longevity of permafrost microorganisms, NASA scientists have extracted *Carnobacterium pleistocenium* microbes from an Alaskan pond that had been frozen for roughly 32,000 years. For context, the microbes sheathed within this pond existed during a time synchronous to wooly mammoths (Pikuta *et al.*, 2005). Researchers are excavating microbes from permafrost that existed well before any human timeline, which further reiterates the foreboding nature of these microbes. There is still much uncertainty about the potential impacts of such ancient microbes, which further drives the urgency to halt permafrost thaw.

Conclusion

Amid a society where technological advancements have accelerated the dire effects of climate change, global temperatures are gradually increasing. The Arctic regions become disproportionately targeted by this increase in atmospheric temperature, as evidenced by rapid permafrost thaw shown previously in *Figure 1*. The consequences of permafrost thaw have been identified through positive feedback mechanisms and reemerging microbes. It is only a matter of time before harmful microbes within the permafrost rise and incite infections across humanity.

This fate, however, is not certain for humanity since there is a possibility to mitigate human-driven global warming to delay permafrost thaw. Mitigation tactics for methane and carbon dioxide, two notoriously powerful greenhouse gases, include reducing carbon emissions via fuel switching and energy conservation. Additionally, methane management strategies in industrial and agricultural sectors can be further implemented to reduce greenhouse gas abundance in the atmosphere (EPA, 2021). The same elation must be felt among society when discovering ways to reduce carbon emissions as the way emotions were when developing the next technological breakthrough. Urgency upon mitigation fronts is of the utmost importance, because the sake of humanity truly relies upon it.

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