**THE EFFECT OF CLIMATE CHANGE ON RISK OF ANTHRAX INFECTION IN THE KOBUK VALLEY, ALASKA**

by

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**ABSTRACT**

Because of rising global temperatures, erosion, and anthropogenic environmental degradation, permafrost in the Arctic is melting. *B. anthracis* spores preserved in the frozen ground can be rendered active upon thaw. This melt and release is responsible for an environmentally-mediated anthrax outbreak in northern Siberia in 2016, which resulted in the deaths of thousands of reindeer and the hospitalization of 90 people. Re-emergent anthrax has the potential to impact communities across the Arctic, especially indigenous peoples and those who practice subsistence hunting. An environmental anthrax outbreak poses a significant threat to public health, as it directly infects humans and depletes the resources they use for food, shelter, and income. Risk of an environmental anthrax outbreak was assessed for the Kobuk Valley, Alaska, which possesses multiple factors for such an event, including its geologic profile, agricultural history, wildlife dynamics, and vulnerability to climate change. These factors are examined in detail in order to assess the risk of an anthrax outbreak in the Kobuk Valley. The risk of an immediate outbreak is currently low. However, the progression of climate change will modify contributing factors and increase risk over time. Thus, preventative surveillance and outbreak response preparation are essential for the Kobuk Valley and similar Arctic regions.

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# INTRODUCTION

In the summer of 2016, over two thousand Siberian reindeer died and ninety people were hospitalized due to a bacterial threat long thought dormant. Anthrax infected reindeer and residents of the Yamal Peninsula, a remote subsistence-based village within the Arctic Circle. It is likely that dormant anthrax spores were activated through permafrost thaws, hallmarks of climate change in the Arctic region. Grazing reindeer likely contracted the bacteria through contaminated soil and humans were exposed when handling meat and pelts of the infected livestock (Doucleff, 2016a; Goudarzi, 2016).

Anthrax is a bacterial spore with the potential to infect humans and animals through multiple routes. It is extremely hardy and can survive in permafrost conditions for decades (Inglesby et al., 2002; Miller, 2011). Though it is commonly recognized as an agent in the 2001 US biological terror attacks, anthrax outbreaks typically occur in agricultural settings and appear sporadically throughout the histories of Northern regions (Epp, Waldner, & Argue, 2010; Hu et al., 2016; Inglesby et al., 2002).

The 2016 Siberian anthrax outbreak exemplifies an immediate impact of climate change in the Arctic region. Rising global temperatures thaw permafrost, decrease resource availability, and disrupt caribou migration and reindeer grazing patterns, which directly and indirectly influenced the anthrax outbreak in the Yamal Peninsula (Berkes & Jolly, 2002; Brouchkov et al., 2011; Iglovsky, 2014; Inglesby et al., 2002) .With intent to contribute to the understanding and prevention of environmentally-mediated anthrax outbreaks in North America, environmental and public health risk will be assessed within the framework of these factors, as well as historical context as they relate to Kobuk Valley, Alaska.

# Background

Anthrax poses a threat to public health due to its persistent and potent nature. Its takes between 2500 and 5500 spores to kill a human, but it only takes 1-3 spores to make someone sick. Anthrax was used in US bioterror attacks in 2001 infecting 22, killing five through inhalational exposure. Spores utilized in the attacks were not reflective of naturally-occurring anthrax because they were engineered for high density and uniform particle size (Inglesby et al., 2002). Because of these attacks, concern about environmental anthrax has been overshadowed by fear of its engineered counterpart.

Natural anthrax infects 20,000 people worldwide every year. Most of these infections occur in industrial settings where livestock and animal products are handled (Hu et al., 2016). Other outbreaks of anthrax have occurred through consumption of contaminated meat, contact with infected wildlife, and inhalation of volatilized spores (Brouchkov et al., 2011; Hu et al., 2016; Inglesby et al., 2002). Many anthrax outbreaks involve only animal populations, but the bacterium is easily spread both among and across species (Hicks, Sweeney, Cui, Li, & Eichacker, 2012; Hu et al., 2016).

Anthrax that caused the 2016 Siberian outbreak was traced to partially-decomposed reindeer carcasses in the top layer of permafrost (Doucleff, 2016a, 2016b; Goudarzi, 2016). It is likely that anthrax was preserved in the frozen ground and released when permafrost thawed (Brouchkov et al., 2011; Revich & Podolnaya, 2011). As climate change creates unseasonably warm temperatures in the typically-frozen Northern regions, permafrost thaws are likely to cause more dormant-spore outbreaks (Brouchkov et al., 2011; Iglovsky, 2014; Revich & Podolnaya, 2011).

In the case of the 2016 anthrax outbreak, the impacted human populations were nomadic peoples who relied on reindeer and caribou for food and material goods. In such a remote region, emergency health resources are difficult to access. Issues of access and resource loss contribute to health disparities in rural populations worldwide, and these disparities make treating a Northern anthrax outbreak difficult (Doucleff, 2016a, 2016b; Goudarzi, 2016). Thus, it is important to assess the risk of environmental anthrax outbreaks in other regions to prevent a devastating climate-mediated health effect.

# Review

## Anthrax

*Bacillus anthracis* is a rod-shaped bacterium responsible for anthrax’s virulence (Inglesby et al., 2002; Spencer, 2003). The bacterium is similar to three other members of the *B. cereus* group, but it is differentiated by is its ability to survive in nutrient-deficient environments and grow at human body temperature. There are several strains of *B. anthracis,* which are genetically distinct (Spencer, 2003; Van Ert et al., 2007). Strain identification is performed to assess strain distribution, migration, and emergence.

Anthrax is found on every continent excluding Antarctica, though strain distribution varies by location. *B. anthracis* evolution resulted in three distinct lineages: A, B, and C. Strains evolved from group A are considered the most successful; they are distributed worldwide and are adept to survival in diverse and harsh environments. Strains linked to groups B and C are found under more consistent conditions and are unlikely to spread across major distances. Evidence from genetic surveys and molecular dating suggests that the emergence and distribution of new strains occurred simultaneously to landmarks in human development, specifically the emergence of agriculture and global trade. When livestock was domesticated and began living in close-quarters, it is likely that anthrax spread and evolved. When infected livestock and animal products were traded along international and intercontinental routes, these new strains were distributed (Van Ert et al., 2007).

The most common genetic variant found in North America, A.Br.WNA, is derived from a dominant European sub-group, A.Br.008/009. Many A.Br.WNA bacteria were isolated in northern North America by Van Ert et al in 2007. It is hypothesized that transmission was the result of French and Spanish colonialism. North America now hosts an array of *B. anthracis* genotypes which reflect a high frequency of livestock-based trade (Van Ert et al., 2007).

Anthrax is an obligate pathogen, but it can survive in a dormant state for decades. Contact to anthrax spores occurs in humans and animals through ingestion, inhalational, and most frequently, cutaneous routes (Inglesby et al., 2002; Spencer, 2003; Van Ert et al., 2007). An emerging body of research also points to possible intravenous exposure in the case of infected IV drug users (Hicks et al., 2012; Parcell et al., 2010). While the skin typically acts as an effective protective barrier against anthrax, dermal exposure occurs through cuts or other injuries, and this exposure can occur up to twelve days after initial contact (Inglesby et al., 2002). The severity of infection depends upon exposure route and particle size, with inhalational exposure typically resulting in the highest mortality and morbidity. Only particles smaller than 5micrometers can impact in the lungs, so inhalational exposure is dependent on particle size. Large particles are less likely to penetrate the lungs. However, it is estimated that it only takes 1-3 small spores to cause infection through inhalation (Inglesby et al., 2002; Spencer, 2003).

Anthrax spores usually reach livestock directly through contact with contaminated soil or other infected animals. Subsequent human contact occurs through handling of contaminated animals or animal products, though human infection has occurred through contact with soil and inhalation of volatilized spores (Dragon, Elkin, Nishi, & Ellsworth, 1999; Hicks et al., 2012; Hu et al., 2016; Miller, 2011).

In the case of the Siberian anthrax outbreak, spores contaminated the permafrost through a preserved carcass (likely a reindeer) that harbored anthrax spores (Doucleff, 2016a). This cycle of contamination frequently occurs in arctic and sub-arctic regions because biological material rarely decomposes due to low temperatures. Instead, a carcass and its contaminants are preserved for decades (Brouchkov et al., 2011; Mackelprang et al., 2011; Revich & Podolnaya, 2011). With thawing of the frozen ground, spores reach an active temperature and can cause infection (Revich & Podolnaya, 2011; Spencer, 2003).

The clinical manifestations of anthrax exposure in humans depend on exposure route but include the development of black sores and local edema, flu-like symptoms, sepsis, and hemorrhagic meningitis. Clinical onset of infection can occur up to 60 days after exposure (Inglesby et al., 2002). Clinical symptoms of *B. anthracis* infection are reflective of the actions of virulence plasmid pX01, which causes cellular edema, necrosis, and hemorrhage. This plasmid also contains a protective agent which allows entry to host cells. pX01 is one in a two-part virulence pair that also contains pX02, which limits phagocytosis by a host immune system. Without both plasmids, *B. anthracis* is considered avirulent (Pezard, Berche, & Mock, 1991; Spencer, 2003).

Prophylaxis for humans and animals at risk of anthrax consists mainly of vaccination. An attenuated version of *B. anthracis*, with only one functional virulence plasmid, can be administered to vulnerable populations or livestock herds (Inglesby et al., 2002; Pezard et al., 1991). In occupational settings, personal protective equipment (PPE) is recommended for workers in contact with contaminated animal material (Hu et al., 2016; Inglesby et al., 2002). The most effective treatments for anthrax exposure are antibacterial drugs (Inglesby et al., 2002; Miller, 2011; Spencer, 2003). The antibacterial course can last for months due to *B. anthracis’s* potential latency period (Spencer, 2003).

### Epidemiological History

Of the 20,000 annual human anthrax infections, a majority occur in occupational settings (Inglesby et al., 2002; Meselson, 1994). These cases are closely related to animal outbreaks, but the strength of this relationship varies between outbreak setting. For example, it is estimated that in Africa and Central Asia, there are ten human anthrax cases for every livestock case, while in Europe, the ratio is reversed with one human case per ten livestock cases (Inglesby et al., 2002). The difference between outbreaks depends upon industrial characteristics such as PPE use and ventilation, and on climate and seasonality; workers may be less likely to wear long sleeves, pants, or gloves during summer months or in warm climates (Hu et al., 2016; Inglesby et al., 2002).

Environmental and occupational anthrax outbreaks have been documented throughout history and around the world. The largest environmental anthrax outbreak occurred in Zimbabwe with 10,000 human cutaneous infections between 1979-1985 (Inglesby et al., 2002). Other notable environmental anthrax outbreaks have occurred in Russia, Iran, the United States, and Canada (Dragon et al., 1999; Dragon, Rennie, & Elkin, 2001; Hu et al., 2016; Inglesby et al., 2002; Meselson, 1994; Petersen, 1976). An examination of Canada’s anthrax outbreaks shows that until the 1960s, outbreaks occurred almost exclusively in southern provinces downstream from textile factories and livestock farms. This study suggests that the outbreaks had an occupational source. After 1960, however, outbreaks have occurred in northern regions with a weaker industrial link. These outbreaks appear to stem from the same source, however, as only one strain of *B. anthracis* has been detected in infected mammals. Many recent Canadian anthrax outbreaks have been sourced from contaminated animal feces (Van Ert et al., 2007).

Workers with regular contact to livestock hides, furs, meats, and waste are at heightened risk of anthrax exposure; they account for the majority of human cases (Hu et al., 2016; Inglesby et al., 2002). However, in 1979, residents in Sverdlovsk in the USSR were exposed to volatilized anthrax spores from an accident at a military facility located upwind from where they lived. While there were multiple versions of the official report (some by the US, others by Soviet sources), later study determined that the occupational accident led to the infection of multiple humans and animals (Meselson, 1994).

Immediate response to an anthrax outbreak includes vaccination for unexposed but at risk individuals, antibiotic distribution, and in some cases, euthanasia of exposed animals (Hu et al., 2016; Inglesby et al., 2002; Miller, 2011). Because of spore longevity, anthrax outbreaks are unique in that they require long-term remediation after an exposure is identified. In the case of the 2001 US bioterror attacks, cleanup of attack sites took years (Day, 2003; Inglesby et al., 2002; Schmitt & Zacchia, 2012). It took 280 tons of formaldehyde to remediate spores 36 years after anthrax was tested as a bioweapon on Gruinard Island, Scotland (Manchee, Broster, Melling, Henstridge, & Stagg, 1981).

## Permafrost

Approximately 25% of Earth’s land area is covered by permafrost (Anisimov & Nelson, 1996). Found in arctic and sub-arctic regions, the temperature of this frozen ground falls between -2 and -8°C (Anisimov & Nelson, 1996; Jorgenson & Osterkamp, 2005; Revich & Podolnaya, 2011; Schuur et al., 2008). Temperature does vary with seasonality, but major shifts are considered abnormal. Global permafrost temperatures rose steadily through the 20th century, and this trend is expected to continue exponentially through the current century. Rising global temperatures will cause permafrost loss (Anisimov & Nelson, 1996; Brouchkov et al., 2011; Iglovsky, 2014; Jorgenson & Osterkamp, 2005; Karlsson, Jaramillo, & Destouni, 2015; Mackelprang et al., 2011; Revich & Podolnaya, 2011; Schuur et al., 2008). It is estimated that between 25 and 44% of permafrost cover would be lost for a 2°C increase in global temperatures (Anisimov & Nelson, 1996; Iglovsky, 2014; Jorgenson & Osterkamp, 2005). In 2016, the average global temperature was 0.99°C higher than average, making it the warmest year ever recorded. ("Global Land-Ocean Temperature Index," 2017).

Permafrost melts and other forms of degradation are typically anthropogenic in origin. The direct damage that contributes to permafrost thawing is the result of resource use (*e.g.* farming, grazing), processes of urbanization (*e.g.* vehicle use, land movement), and pollution (Iglovsky, 2014). Anthropogenic activities that contribute to a more general rise in global temperatures include heavy industry, deforestation, industrial agriculture, and burning of fossil fuels for heat, electricity, and transportation (Rosenzweig et al., 2008). These release mass quantities of insulating gasses such as carbon dioxide and methane along with ozone-depleting gasses like chlorofluorocarbons (CFCs) and nitrous oxide (Ravishankara, Daniel, & Portmann, 2009; Rosenzweig et al., 2008). Melting permafrost can result in surface erosion and subsurface degradation, which leads to decreased land stability and changes in groundwater activity (Jorgenson & Osterkamp, 2005; Karlsson et al., 2015). Recent data from northern Europe suggests that anthropogenic activities have significantly contributed to the segmentation and thaw of historically continuous tracts of permafrost (Iglovsky, 2014). Permafrost degradation causes significant habitat loss for organisms that depend on it, and increases the risk of the release of dormant bacteria like *B. anthracis* (Anisimov & Nelson, 1996; Revich & Podolnaya, 2011).

Because of low temperatures, bacterial activity is inhibited in permafrost. Organic material does not decay and dormant organisms are preserved (Brouchkov et al., 2011; Mackelprang et al., 2011). This creates a twofold risk for anthrax outbreaks if infected organisms remain frozen after death. *B. anthracis*can remain in a host and is preserved due to cold temperatures. As permafrost melts, the spores are released from the host material and can volatilize or be transported through the soil (Brouchkov et al., 2011; Dragon et al., 1999; Revich & Podolnaya, 2011).

While all permafrost is susceptible to melting, thickness and moisture are factors that determine an area’s ability to tolerate change (Jorgenson & Osterkamp, 2005; Schuur et al., 2008). Factors that contribute to increased risk of a thaw-related anthrax outbreak include tolerance to change, depth of burial, proximity to a source, and soil profile (Brouchkov et al., 2011; Revich & Podolnaya, 2011). Despite these factors, increased temperatures are the most significant influence on risk (Revich & Podolnaya, 2011). Rising temperatures lead to thawed runoff, which speeds melting (Jorgenson & Osterkamp, 2005; Karlsson et al., 2015). Higher temperature also increases survivability for hosts, bacteria, and soil enzymes that contribute to a bacterial release (Dragon, Bader, Mitchell, & Woollen, 2005; Mackelprang et al., 2011; Panikov, Flanagan, Oechel, Mastepanov, & Christensen, 2006; Spencer, 2003).

Enzymatic soil analysis can provide a profile of permafrost’s metabolic potential. Invertase is frequently found in tandem with organic material and may provide resources for bound proteins; it is used as an indicator for the presence of other microorganisms in soil (Brouchkov et al., 2011; Mackelprang et al., 2011). This analysis technique may prove valuable in predicting the reemergence of bacteria during permafrost thawing.

Northern Russia has experienced multiple permafrost-mediated anthrax outbreaks. Outbreaks in 1897 and 1925 affected deer populations and the 2016 anthrax outbreak impacted reindeer, caribou, and humans. Infections occurred nearby to preserved livestock burial grounds that likely released the bacteria (Doucleff, 2016a; Revich & Podolnaya, 2011). Permafrost in these regions had experienced only a few degrees of temperature change (Revich & Podolnaya, 2011).

Permafrost in the Kobuk Valley, AK, is at high risk of anthropogenic degradation; it is bordered by an eroding coast and changes in seasonality have caused permafrost temperatures to rise ("Climate Impacts in Alaska," 2017; "What Climate Change Means for Alaska," 2016). Because of these factors, the Kobuk Valley is at high risk for permafrost-mediated bacterial outbreaks.

## The Kobuk Valley

The Kobuk Valley lies in northwestern Alaska within the Arctic circle (Figure 1). Its nearest shore borders the Bering Strait. It is transected by the Kobuk River, and its land area is mainly composed of Kobuk Valley National Park ("History and Culture"). The nearest city to this remote area is Kotzebue, which lies on the shore of the Kotzebue Sound. The Kobuk Valley’s history includes early human migration, a culture of subsistence farming, and gold rush activity ("History and Culture" ; "Kobuk River Stampede" ; Schock, 2016; "Subsistence Practices in the Kobuk Valley").

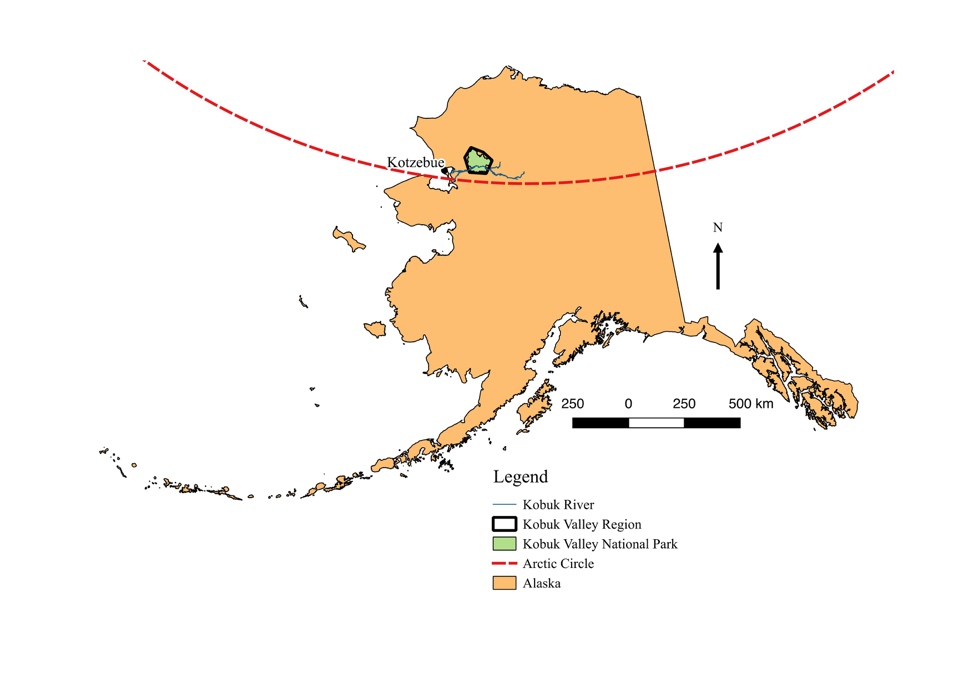


Figure 1. The Kobuk Valley Region in relation to Kobuk River and Arctic Circle

(Alaska Major Rivers, 1998; Cartographic Boundary Shapefiles - States, 2015; "Incorporated City Boundaries of Alaska," 2003; National Park Boundaries, 2014; Swanson, 2001).

The land falls within the migration route of the Western Arctic Caribou Heard (WACH), which has crossed the Kobuk River biannually for approximately 9,000 years (Parrett, 2016). Because of the availability of caribou, along with river access, the area has supported human groups for 10,000 years. Though many indigenous groups have prospered from the land’s vibrancy, the dominant group is currently the Inupiaq ("History and Culture" ; "Subsistence Practices in the Kobuk Valley"). While Kotzebue boasts many amenities, most Kobuk Valley residents practice reindeer farming or subsistence hunting (Schock, 2016; "Subsistence Practices in the Kobuk Valley").

Caribou and reindeer are the second most consumed animal in the Kobuk Valley, falling just behind fish ("Subsistence Practices in the Kobuk Valley"). While caribou migrate throughout the tundra without the restrictions of farmers, reindeer, a smaller, domesticated version, are raised as livestock (Finstad, Bader, & Prichard, 2002). Both ungulates have large appetites for lichens (Joly, Jandt, & Klein, 2009). Reindeer farming and caribou hunting are closely intertwined in Arctic regions, as most reindeer farms operate through “loose style” grazing. In subsistence farming operations, reindeer are not kept in pens but left to roam the land, forage for themselves, and interact with caribou. Most of the reindeer farms near the Kobuk Valley are in the Seaward Peninsula, which boasts 14 herds, but the range of these herds is expansive. Though it is still practiced today, Alaskan reindeer farming peaked in the 1930s. Ranchers lost between 75 and 100% of their reindeer herds due to the intermingling of reindeer and caribou, which has resulted in a decrease in reindeer farming in the region (Finstad et al., 2002; Joly et al., 2009).

The Western Arctic Caribou Herd (WACH) consists of over 200,000 caribou, which makes it the world’s largest herd. It ranges approximately 157,000 square miles throughout migration (Figure 2) (Parrett, 2016). Every spring and fall, the group moves across the Kobuk River and grazes on lichens and low shrubs in the Valley (Parrett, 2016; Schock, 2016). The herd is a valuable resource for locals, providing food for 40 subsistence-based communities in their range ("History and Culture"). Despite the herd’s dominance, its population has decreased since 2013, and its migration pattern has changed due to irregular climate patterns (Joly, Klein, Verbyla, Rupp, & Chapin, 2011; Parrett, 2016). Climate change has negatively impacted reindeer and caribou in the region as warm temperatures lead to freezing rain, which traps lichens under sheets of ice (Joly et al., 2011; Schock, 2016). Although many reindeer and caribou are used by consumers, it is likely that reindeer carcasses have been preserved in permafrost throughout history ("Subsistence Practices in the Kobuk Valley").

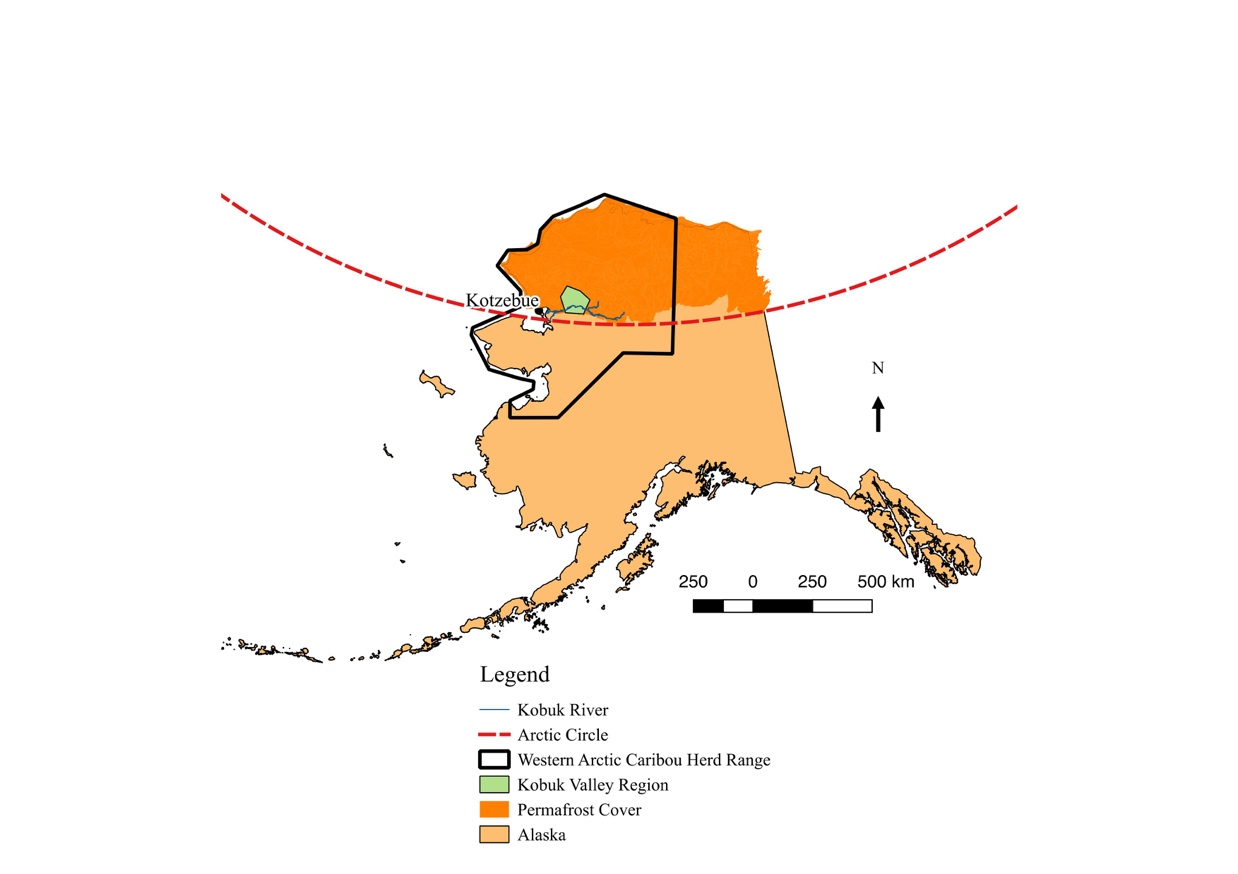


Figure 2. Permafrost Cover and the Western Arctic Caribou Herd's Migratory Range

*(2014-Permafrost Database Development, Characterization and Mapping for Northern Alaska (Ecological Mapping Update), 2014; Alaska Major Rivers, 1998; Cartographic Boundary Shapefiles - States, 2015; "Incorporated City Boundaries of Alaska," 2003; Swanson, 2001).*

Approximately 85% of Northern Alaska’s land area consists of permafrost (Figure 2). Climate change has already impacted on the geological profile of this region, as permafrost temperature has risen an average of 2-3°C overall and up to 5°C in some regions since the 1980s. It is estimated that climate change will lead to the degradation of up to 17% of Alaskan permafrost (Jorgenson & Osterkamp, 2005). Rates of thawing depend on soil profile and terrain, with low lying areas most likely to thaw quickly. Ground warming is also accelerated by flowing water, which increases as thawing begins (Anisimov & Nelson, 1996; Jorgenson & Osterkamp, 2005; Karlsson et al., 2015). As of 2005, the average temperature for Northern Alaska permafrost was -8°C, but it is likely that this temperature has risen more recently (Jorgenson & Osterkamp, 2005).

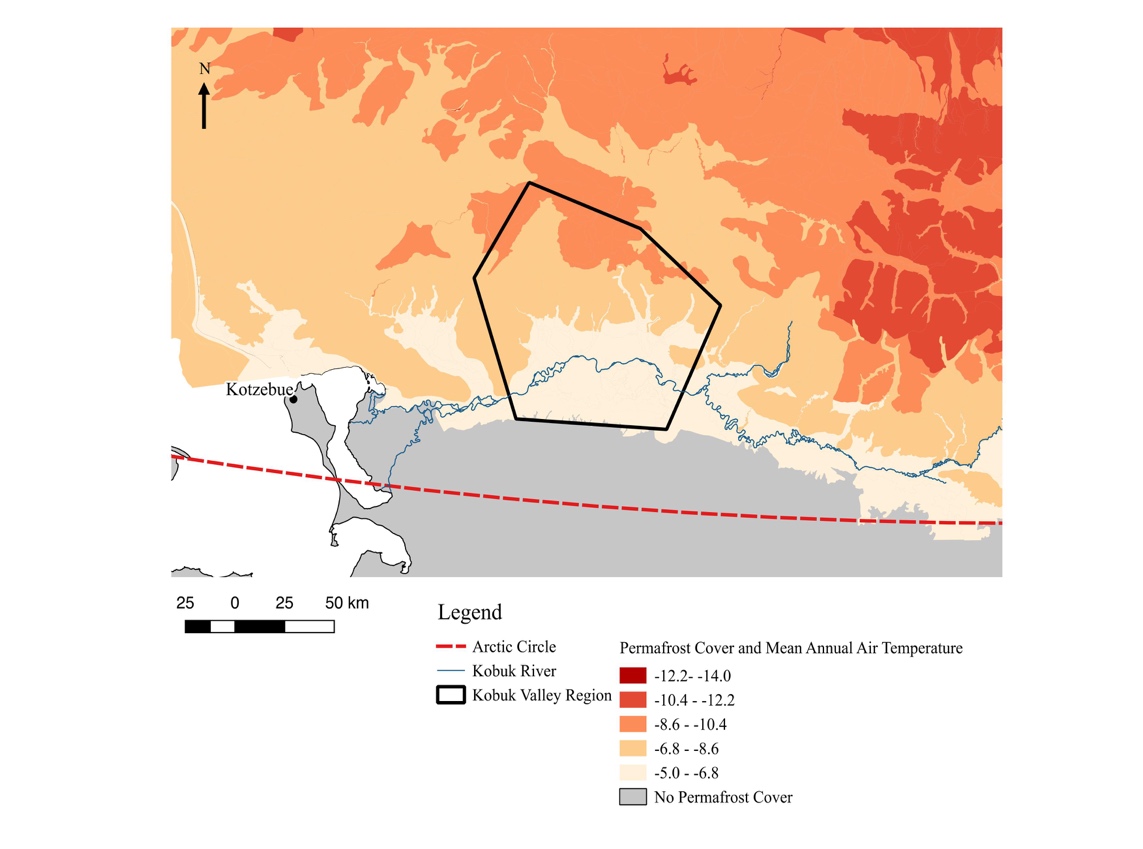


Figure 3. The Kobuk Region, Permafrost Cover, and Mean Annual Air Temperature

(2014-Permafrost Database Development, Characterization and Mapping for Northern Alaska (Ecological Mapping Update), 2014; Alaska Major Rivers, 1998; Cartographic Boundary Shapefiles - States, 2015; "Incorporated City Boundaries of Alaska," 2003; Swanson, 2001)

Human activity in the region is directed mainly by the environment. The land provides food and material goods to residents of the Kobuk Valley. Climate change will impact the Arctic regions earlier and more drastically than anywhere else on earth (Arndt, 2016; Berkes & Jolly, 2002; Schuur et al., 2008). Thus, it is important to assess the risk of climate-mediated environmental changes and their downstream effects on those most vulnerable. Thawing of permafrost directly increases the risk of an environmental Anthrax outbreak, which harms humans both directly through infection and indirectly through the destruction of their primary resources.

# Analysis

The risk of an environmentally-mediated anthrax outbreak in the Kobuk Valley will be examined within the frameworks of historical land use and climate change. Climate change will influence virtually every aspect of an anthrax outbreak and it will be examined in regards to three major impacts: permafrost degradation, decreased resource availability, and changes in caribou dynamics. All factors will be examined with awareness of interconnectedness to provide a comprehensive risk assessment. While this analysis will focus on a specific region, it is likely that other Northern areas will struggle with similar events, especially as climate change progresses.

Before examining the environmental factors that could facilitate an anthrax outbreak, it is important to assess the probability that dormant spores are indeed buried in the permafrost.

*Bacillus anthracis* A.Br.WNA is the most prevalent form of anthrax in North America and is found throughout its arctic and sub-arctic regions. Human development greatly contributed to the diversification of anthrax. Thus it is likely that Alaska hosts an array of anthrax types (Van Ert et al., 2007). As a site of early human settlement, Alaska has hosted indigenous peoples for over 9,000 years. Its role in the domestication of reindeer and human activity during the gold rush likely contributed to an expansion of anthrax, especially in the Kobuk Valley The region was a site of substantial interest during the gold rush, even though only small amounts of gold were found. This lead to an increase in human population and the likely introduction of new bacteria ("History and Culture" ; Van Ert et al., 2007). This human activity, occurring simultaneously with reindeer farming, established two major risk factors for an environmental anthrax outbreak.

Most groups in Alaska depend on caribou, and they were some of the first humans to domesticate reindeer (Arndt, 2016; Finstad et al., 2002; "What Climate Change Means for Alaska," 2016). As seen on a global scale, domestication of animals leads to the transfer of bacteria and other diseases among individuals and across species (Van Ert et al., 2007). It is likely that if anthrax were present in Alaska at the time of reindeer domestication, it would have spread from animal to animal. Caribou and reindeer are at risk of anthrax infection because they are herbivorous grazers who ingest soil on the plants they eat. Domesticated reindeer are at risk of spreading anthrax because they are often left to mingle with wild caribou, graze the soil, and expose humans when their products are eventually consumed (Finstad et al., 2002; Revich & Podolnaya, 2011; Van Ert et al., 2007).

If a caribou is infected with anthrax, it is likely that spores would multiply, as they begin to grow at 35ºC and caribou body temperature is 38.5ºC (Dieterich & Morton; Inglesby et al., 2002). Once infected, a caribou is likely to be killed either by disease or a subsistence hunter. If the former, its tissues do not decompose and are preserved by permafrost. Its body may be consumed by other animals, which are then exposed to spores. If the latter, infected tissues are handled by humans. When spores are preserved by permafrost, they are saved for decades. If permafrost melts, they are then able to spread through flowing water and air (Dragon et al., 2005; Spencer, 2003). They are also picked up by grazers who stir up soil (Miller, 2011).

Climate change underlies all the processes that would lead up to an environmental anthrax outbreak in the Kobuk Valley. The Kobuk River facilitates many of these climate-related changes. Its volume is likely to fluctuate with increasing temperatures, as rain replaces snow and ice melts upstream. Permafrost covered by flowing water melts at a higher rate than that without, and the intensity of this effect increases exponentially as groundwater from melt is added to the source (Jorgenson & Osterkamp, 2005; Karlsson et al., 2015). Flowing water can also transport *B. anthracis* spores (Van Ert et al., 2007).

The Kobuk River flows to Kotzebue, where coastal erosion is a major concern. Melting sea ice, permafrost, and rising water levels are degrading important habitats and resources for animals and humans alike (Arndt, 2016; "Climate Impacts in Alaska," 2017; Schock, 2016). Increased flow in the Kobuk River caused by climate change and ground thawing would likely intensify coastal degradation, moving the coast farther inshore and reducing available land and resources.

Permafrost melt not only impacts dynamics of flowing water but also increases the risk of an anthrax outbreak by creating an exposure risk. Permafrost in the Kobuk Valley is hospitable for dormant anthrax spores, thus likely to release them upon melting (Revich & Podolnaya, 2011; Van Ert et al., 2007). Alaskan permafrost is already degrading ("Climate Impacts in Alaska," 2017; Joly et al., 2011; Jorgenson & Osterkamp, 2005). Flowing water from this permafrost melt and the Kobuk River, increase the risk of anthrax exposure and transport.

Because of caribou’s migratory behavior, they are exposed to diverse environments that may be hundreds of miles apart (Parrett, 2016). Thus, they can transport bacteria across large distances (Miller, 2011). The Western Arctic Caribou Herd lives above the Arctic Circle in the summer months and moves just below it during the winter (Finstad et al., 2002; Parrett, 2016; Schock, 2016). Thus, they are exposed to warmer ground when they move south. They may pick up bacterial spores from soil and take them north in the summer. This expands the territory at risk for exposure to environmental anthrax. Since anthrax can remain in an organism for months without manifesting, an animal can pick it up in one location and die in another, where its carcass and the spores may be preserved in permafrost (Spencer, 2003).

Consistent climate patterns moderate the WACH’s migration; it depends on water and lichen availability as well as suitable weather for movement (Parrett, 2016). The likelihood of an environmental anthrax outbreak also depends on caribou behavior. As temperatures have risen with climate change, the WACH’s migration has changed. They are exposed to new terrain, much of which is likely to be degrading permafrost (Parrett, 2016; Schock, 2016).

As climate change manifests, unseasonable snow cover, freezing, and flooding interrupt important cycles for humans. Since many in the Kobuk Valley are subsistence-based, they depend on consistent conditions to mediate animal availability and plant growth (Schock, 2016; "Subsistence Practices in the Kobuk Valley"). Many of the effects of climate change disrupt this delicate balance; cycles of rain and freezing temperatures can lock resources under thick ice, flooding washes out crops, and changes in migration patterns can leave hunters without game. Other impacts currently manifesting in the Kobuk Valley include coastal erosion, which decreases useable land (Jorgenson & Osterkamp, 2005). The loss of sea ice, which decreases usable land for fishing and hunting in the winter months, is also of concern for residents. Sea ice is particularly important for salmon fishing, which serves as the main source of food for the majority of Kotzebue residents (Schock, 2016; "Subsistence Practices in the Kobuk Valley"). If residents of Kotzebue are unable to harvest as many salmon, it is likely that they will place more weight on caribou (Berkes & Jolly, 2002). An increase in subsistence caribou hunting not only increases competition with indigenous inland groups but also contributes to the likelihood of exposure to environmental anthrax.

There are two mechanisms in which anthrax exposure is increased through a demand for caribou. One mechanism is increased contact between humans and caribou. Hides and meat will be handled more frequently, which puts a greater number of people at risk for exposure (Hu et al., 2016; Inglesby et al., 2002). Secondly, reindeer farming will likely re-emerge as a profitable source of both food and income. As seen historically, increased demand for livestock creates conditions hospitable for anthrax infection, transmission, and genetic diversification (Miller, 2011; Van Ert et al., 2007). An increase in caribou consumption may also lead to an increase in caribou material in the soil, as more material will require disposal. If this material is infected with anthrax, it can either preserve dormant cells or enable their spread to a scavenger organism (Revich & Podolnaya, 2011; Spencer, 2003).

The interconnectedness of the Kobuk Valley residents, wildlife, and climate make it susceptible to dramatic changes if constants are disrupted. One such change may be a climate-mediated environmental anthrax outbreak caused by the release of dormant spores. Because there are a number of variables that influence the likelihood of this outcome, there are many ways in which this situation could manifest. The history of the Kobuk Valley suggests that its permafrost may contain anthrax spores, if even in only minute amounts. Although this amount may be minuscule, anthrax’s persistence and ability to colonize make it an extremely contagious agent (Inglesby et al., 2002; Spencer, 2003; Van Ert et al., 2007). Current changes in the Kobuk Valley suggest that permafrost thaws are the most likely mechanism to facilitate an initial risk increase (Arndt, 2016; Parrett, 2016).

The risk in the Kobuk Valley is like that of Yakutia, where the Siberian anthrax outbreak occurred in 2016. Both areas are located on peninsulas above the arctic circle. They are populated by subsistence-based peoples who rely on caribou as a major food source (Doucleff, 2016b; "Subsistence Practices in the Kobuk Valley"). Both areas have experienced warmer temperatures due to climate change, which contributes to permafrost degradation(Brouchkov et al., 2011; Di Liberto, 2016; Revich & Podolnaya, 2011). They have rich histories of reindeer farming and caribou hunting, which left animal material preserved in the permafrost (Finstad et al., 2002; "History and Culture" ; Revich & Podolnaya, 2011). Unlike Yakutia, the Kobuk Valley has not yet experienced an environmental anthrax outbreak. The risk of an outbreak increases as climate change manifests, so it is important to examine prevention and response techniques to limit negative outcomes.

Response to an environmental anthrax outbreak takes place in two stages: treatment and prevention of further damage. Effective treatment, as used in the Yakutia outbreak, includes the dissemination of antibacterial medications and the euthanizing of infected caribou and reindeer (Doucleff, 2016b; Goudarzi, 2016; Miller, 2011). The most important aspect of treatment of anthrax is time; it is essential that an antibiotic course begins as soon as possible (Hicks et al., 2012; Hu et al., 2016; Inglesby et al., 2002; Meselson, 1994; Spencer, 2003). In the United States, penicillin and doxycycline are FDA approved for the treatment of anthrax, and the appropriate course lasts about three months (Inglesby et al., 2002; Spencer, 2003). Luckily, these drugs are common and usually easily accessible. In the remote areas where an environmental anthrax outbreak is likely to occur, however, these medications may not be available in short order.

The removal of infected animals is considered a short-term response to an anthrax outbreak. In Yakutia, over 2,000 reindeer were considered infected and euthanized in response to the outbreak. Russian officials called for the culling of hundreds of thousands more to prevent future outbreaks (Doucleff, 2016b; Goudarzi, 2016). This approach is difficult to justify, however, as it may be overly-protective.

Vaccines have proven useful for anthrax prevention in both humans and animals (Inglesby et al., 2002; Miller, 2011). The vaccine is given to humans in six stages, which consist of varying doses of inactivated *B. anthracis*. The vaccine is safe and effective for anthrax obtained though varying exposure routes. The human vaccine has also been approved for use simultaneously with antibiotics after exposure (Inglesby et al., 2002). Livestock is often vaccinated against anthrax with an ineffective strain of *B. anthracis*. This allows for the development of herd immunity and the prevention of anthrax outbreaks in agricultural and industrial settings. Wildlife can be vaccinated against anthrax, but it occurs only rarely, and must be performed yearly for full effectiveness. The most efficient way to vaccinate caribou is to capture them in groups and administer the vaccine individually (Miller, 2011). In the case of the Yakutia outbreak, both humans and reindeer were vaccinated against anthrax (Doucleff, 2016a).

Because of unique conditions in the Arctic, response to an environmental anthrax outbreak can be complicated. Affected people may find it difficult to access medical care because of their remote locations, and responders may find it similarly difficult to access patients. However, antibiotic medicines should always be kept on hand in medical clinics and emergency outposts in areas at risk of anthrax exposure. Luckily, the medicines used to treat anthrax are useful for many illnesses, so it is likely they will be on hand in medical facilities. The anthrax vaccine may be more difficult to access, so it would be useful to keep stock available.

Handling infected caribou and reindeer proves a daunting task because if they die, their carcasses still hold the bacteria (Revich & Podolnaya, 2011; Spencer, 2003). Proper disposal of carcasses is essential for preventing the continuation of an outbreak or development of a new one. It is recommended that an infected carcass remains intact for disposal and no cuts be made into the tissue (Miller, 2011). While burial is also recommended for anthrax-exposed animals, this technique would not be effective in the Arctic, where organic material rarely decomposes (Mackelprang et al., 2011; Miller, 2011). Incineration is also recommended and would likely be the most useful technique for this situation (Miller, 2011).

Methods for preventing an anthrax outbreak include the use of PPE or at least wearing clothes that cover potentially-exposed areas, burning unused animal material, and watching livestock for signs of change in health (Hu et al., 2016; Inglesby et al., 2002; Miller, 2011). Soil and permafrost monitoring can prove useful in both predicting permafrost thaws and recognizing bacterial potential (Anisimov & Nelson, 1996; Brouchkov et al., 2011; Jorgenson & Osterkamp, 2005; Revich & Podolnaya, 2011).

The most effective way to prevent an environmentally-mediated anthrax outbreak is to prevent climate change. While behavior changes like riding a bike, buying local food, and using energy efficient light bulbs can reduce personal carbon emissions, they are unlikely to influence large-scale climate shifts. Systemic change would be a far more efficient way to affect a decrease in climate change. The promotion of climate-literate education, divestment from polluters, and incorporation of green infrastructure are all ways that large entities can reduce the impacts of climate change. Unfortunately, not enough was done to prevent climate change, and many of its effects are now inevitable (Arndt, 2016; Berkes & Jolly, 2002; "Climate Impacts in Alaska," 2017; Di Liberto, 2016; Rosenzweig et al., 2008; Schuur et al., 2008). The Arctic feels the effects of climate change more intensely than anywhere on earth, and climate-mediated anthrax outbreaks are one such impact.

# Concluding Remarks

Despite the melting permafrost, flooding, and disruptions in caribou behavior, the Kobuk Valley’s risk of an immediate environmental anthrax outbreak can be qualified as low. Very specific conditions are necessary for the onset of an outbreak and transmission to humans, and an outbreak takes time to develop. The long-term risk of an environmental anthrax outbreak, however, is much higher. With time, the effects of climate change become more severe, and they will contribute further to the risk of an environmental anthrax outbreak. Overall, the most influential contributor to an anthrax outbreak in an area with dormant spores is melting permafrost, so prevention and remediation efforts should focus on this issue.

While climate change manifests in northwest Alaska, few are paying attention to the risk of an environmentally-mediated anthrax outbreak. It is unwise to ignore a potential outbreak because it can happen so suddenly and spread quickly. The effects of an anthrax outbreak would be absolutely deleterious to communities that depend on caribou and reindeer. Because of its history of domesticating livestock, its caribou population, geological features, and melting permafrost, the Kobuk Valley is at risk for a future environmental anthrax outbreak. An outbreak is likely to be particularly detrimental because of the culture of subsistence in the region. Public health outreach is necessary for outbreak preparation and response, as appropriate antibiotics should be stockpiled before an outbreak.

Little effort has been made towards quantifying a risk of an anthrax outbreak in North America, likely because of the immediacy of other effects of climate change. While the loss of coastal ice, rising sea levels, and extreme shifts in temperature are environmental emergencies, it is important to study the impacts these events may have in the future. General climate shifts such as rising temperatures and unseasonable weather events contribute to an environment perfect for an anthrax outbreak through melting permafrost, flooding, and shifts in caribou and human behavior. When considering climate change in arctic and sub-arctic regions, it is essential to exercise the precautionary principle against environmental anthrax outbreak. The immediate impacts of an outbreak on the animal and human communities are far too great to ignore.

Environmental anthrax outbreaks are rarely labeled health disparities, but in the case of permafrost-mediated outbreaks, they will disproportionately impact indigenous people in rural communities who rely on caribou and reindeer for subsistence. The most effective treatment of anthrax takes place immediately after exposure, which is virtually impossible for those exposed miles away from medical care. Despite the potential for significant human illness, removal of caribou in response to an outbreak may be most deleterious to the communities of the Kobuk Valley.

In the case of the Yakutia outbreak, massive numbers of caribou were killed due to fears of possible infection. However, the loss of hundreds of thousands of caribou and reindeer in an area that depends on them for resources likely does more damage than good. Not only does it remove resources from communities, but it would also create an insurmountable number of carcasses that may or may not be infected with anthrax. In an area dealing with an outbreak stemming from exposed carcasses in the soil, the answer is not to put more carcasses in the soil. The answer is also not to be overly-cautious and remove resources from indigenous peoples when their entire way of life depends on reindeer availability.

It is important to find an appropriate level of precaution with which to approach the issue of a potential environmental anthrax outbreak. In the case of the Kobuk Valley, quick detection of anthrax may be of most value. Data collected on permafrost melts, historical caribou and reindeer burial sites, and perhaps the development of a notification system that labels exposed carcasses could be utilized to develop real-time risk assessment measures. Outreach to educate community members on the signs of anthrax infection in animals and proper prevention techniques would allow for community-level monitoring and increase the likelihood of case recognition. Vaccination of meat and hide handlers may also be of value, for they are at the greatest risk of exposure. Stocks of appropriate antibiotics should be maintained in medical facilities and kits for field deployment.

While this review may be considered thorough, it is overall incomplete. Little data is available on anthrax activity in the Kobuk Valley, so risk of its presence was extrapolated from historical context and similar areas. Permafrost melts are recognized in the Arctic region, but specific data on trends in the Kobuk Valley was not available. This data would serve useful for future study, as it will provide more comprehensive information on the likelihood of an environmental anthrax outbreak. Again, temporal and spatial monitoring may be the best way to collect this data, which can provide insights to which areas may be at greatest risk.

Climate change is a real and human-mediated phenomenon (Di Liberto, 2016; Joly et al., 2011; Rosenzweig et al., 2008; Schuur et al., 2008; Walker et al., 2010; "What Climate Change Means for Alaska," 2016). It will impact nearly every aspect of the natural world, but the Arctic will feel its effects with the greatest intensity. The effects of climate change have already begun to influence the arctic region, and as they magnify, they create conditions that are hospitable for an environmental anthrax outbreak. An outbreak of this magnitude will especially disrupt the lives of indigenous communities, who depend on reindeer and caribou for their way of life. An anthrax outbreak is absolutely a public health issue because of its physical effects on the exposed and the health impacts that come with the removal of vital resources like food and shelter. It is essential to consider the risk of an environmental anthrax outbreak in arctic and sub-arctic regions. While the Kobuk Valley is at low risk of an immediate environmental anthrax outbreak, its risk level is not fixed. Risk will likely increase as climate change manifests, bringing winter rain, melting permafrost, and disrupting the lives of thousands in the Kobuk Valley.

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