

**Effects of climate change and cultural practices on the risk of
human toxoplasmosis in Canada's North: recommendations for
public health**

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Abstract

Toxoplasmosis is a common infection caused by the protozoan parasite, *Toxoplasma gondii*. The parasite can be found in virtually all warm-blooded mammals and birds. Humans become infected mainly through ingestion of food and water contaminated with *T. gondii* oocysts. Changing climate patterns, including intense rainfall and warming, appear to increase the risk of transmission by influencing the fate and transport of this parasite in Canada's North. In addition to extreme weather effects, cultural practices related to consumption of raw and wild meats in northern populations also influence risk. Currently, there is a lack of literature on *T. gondii* oocyst properties and environmental transport in relation to climate change. This literature review examines the interactions between toxoplasmosis, climate change, and cultural practices in Canada's North and identifies priority areas where public health initiatives could be implemented to reduce the risk of human infection. The risk of *T. gondii* transmission can be reduced by improving baseline data and monitoring, strengthening drinking water infrastructure and personal training, and collaborating with communities to develop prevention measures.

Introduction

Toxoplasma gondii is a protozoan parasite responsible for life-long toxoplasmosis infections in an estimated one third of the global population (Weiss & Dubey, 2009). The U.S. Centres for Disease Control (CDC) identifies toxoplasmosis as a Neglected Parasitic Infection (NPI), defined as an infection requiring immediate public health action as little attention has been given to its surveillance and prevention despite the number of people affected by it (CDC,

2017). In Canada, the story is no different; medical professionals are not required to report cases of toxoplasmosis for national monitoring (Bowie et al., 1997; Government of Canada, 2017a; Schurer et al., 2016). This is despite the occurrence of a *T. gondii* drinking water outbreak in Victoria, British Columbia (1995) that resulted in between 2894 to 7718 infections, 100 of which were acute (Bowie et al., 1997). Of these acute toxoplasmosis cases: 51 patients had lymph node disease (lymphadenopathy), 19 had retina disease (retinitis), 11 had other symptoms such as fever, sweats, headache, and 19 had no symptoms or did not provide information (Bowie et al., 1997). 36 woman were identified as pregnant or postnatal cases, and 12 infants were born with congenital toxoplasmosis (Bowie et al., 1997).

Human Health Effects of Toxoplasmosis

As the Victoria outbreak demonstrates, toxoplasmosis can result in human health outcomes that range from mild to severe (CDC, 2017). Typically, toxoplasmosis infections are subclinical (no visible symptoms) or may cause mild fevers or flu-like symptoms that last a few days (Jones et al., 2014). The health effects of toxoplasmosis can be acute in pregnant woman and immunocompromised individuals (CDC, 2017). If acquired during pregnancy, toxoplasmosis can result in miscarriage, stillbirth, or ocular and neurological deficits in the baby (Boyer et al., 2011). In immunocompromised individuals, newly acquired or reactivated toxoplasmosis infections can cause brain encephalitis and death (Pappas et al., 2009). There is also a new body of literature suggesting that human infection with *T. gondii* may be a risk factor for psychological health outcomes, including bipolar disorder and schizophrenia (de Barros et al., 2017; Sutherland et al., 2015; Torrey, Bartko, Lun, & Yolken, 2007). While more research is

needed to establish the possible links between toxoplasmosis and effects on the brain, these new findings highlight that our understanding of the parasite is incomplete.

T. gondii Lifecycle & Human Transmission

The life cycle of *T. gondii* is complex, involving a number of host animals and human exposure pathways (Figure 1). The parasite's lifecycle begins in the small intestine of felines, both wild and domestic (Pappas et al., 2009). Felines are the only known host capable of supporting *T. gondii* sexual reproduction (also defined as the definitive host) (Jenkins et al., 2013). Following reproduction, sexual forms of the parasite transform into unsporulated (immature and non-infective) oocysts (resistant and thick-walled stage of the parasite's life cycle), millions of which are shed in the feces of infected felines (Yan et al., 2016; Jenkins et al., 2013). Once released into the environment, the oocysts become sporulated (infective for other animals) after 1-5 days and available for ingestion by virtually all mammal and bird species, including humans (CDC, 2015; Yan et al., 2016). When ingested, the oocysts develop into tachyzoites (stage in the development of the tissue phase marked by multiplication), which rapidly multiply in cells and travel throughout the animal's body to form tissue cyst bradyzoites (the semi-dormant, slowly dividing stage of the parasite's life cycle) (Dubey, 2004). Tissue cysts are most commonly found in the brain, skeletal and cardiac muscles (Yan et al., 2016). These infected animals (also known as intermediate hosts as they support non-reproductive forms of the parasite) are now carriers and can pass the parasite on to other animals if they (and their cysts) are ingested (VanWormer et al., 2013). When an infected intermediate host is consumed

by a feline, the parasite can once again sexually reproduce and its lifecycle restarts (Pappas et al., 2009).

Human transmission typically occurs through one of three main pathways: (a) oocyst ingestion via contaminated food, water, or soil; (b) consumption of a *T. gondii* infected intermediate host with tissue cysts; or (c) congenital transmission (VanWormer et al., 2013). In more rare cases, *T. gondii* can be transmitted to humans through consumption of unpasteurised milk or blood transfusions or organ transplants from infected donors (CDC, 2017).

T. gondii in the Environment

T. gondii is a resilient parasite and can survive under a range of climate conditions. A few studies (see Simon et al., 2013) have been conducted to assess viability of oocysts in laboratory conditions. Based on this research, oocysts remain infective for 12-18 months in soil and water, but in 4°C seawater they have been found to be viable for longer periods (24-54 months) (Lindsay & Dubey, 2009; Yan et al., 2016). Environmental factors that result in the inactivity of sporulated *T. gondii* oocysts include Ultraviolet (UV) rays (>499 mJ/cm²), dryness, and prolonged exposure to extremely low (<-21°C) and high temperatures (>45°C in water, >67°C in meat, no upper limit data available for soil temperature) (Dubey, 2004; Lelu et al., 2012; Simon et al., 2013; VanWormer et al., 2013). Oocyst resilience is also likely impacted by snow cover as it reduces exposure to UV sunlight, which can act as an insulator against extreme temperature, and may maintain humidity levels in which oocysts thrive (Simon et al., 2013). Oocysts can be transported from terrestrial environments to aquatic ones via water flow,

snowmelt and runoff. (Simon et al., 2013). Definitive and intermediate host animals amplify this effect by carrying the parasite across land and water habitats, further increasing its distribution (Levesque et al., 2007). Changing climate patterns may play a critical role in *T. gondii* transmission as temperature and precipitation facilitate oocyst survival and transport.

T. gondii in Canada's North

Currently, toxoplasmosis is of concern in Canada's North because of the potential effects of climate change on *T. gondii* exposure. Canada's North will be defined as the southern limit of the distribution of discontinuous permafrost following Jenkins et al. (2013) (Figure 2). In this region, climate change is causing increases in temperature and precipitation at an accelerated rate compared with southern Canada (National Resources Canada, 2016). Climate models predict that by the end of the 21st century, annual mean temperatures in Canada's northwest will rise between 3 and 7°C in winter months, and will rise between 3 and 9°C in more central northern locations such as Hudson Bay (Furgal & Seguin, 2006). Coinciding with this warming, precipitation is expected to increase by 30% across Canada's North (Furgal & Seguin, 2006). These changing climatic patterns appear to increase the risk of transmission by influencing the fate and transport of this parasite (Jenkins et al., 2013). Currently, there is a lack of literature on *T. gondii* oocyst properties and environmental transport in relation to climate change (VanWormer et al., 2013).

Cultural factors further influence the risk of toxoplasmosis in Canada's North. An estimated 2 million people reside in this region, approximately 50% of whom are First Nation, Metis and Inuit (Health Canada, 2008; Jenkins et al., 2013). Communities are culturally diverse

and practise a variety of food preparation and dietary traditions (Health Canada, 2008). Consumption of raw seal meat and the preparation of wild game may help explain the high *T. gondii* seroprevalence (level of antibodies in a population measured in blood serum) rates found in several northern communities compared with the rest of Canada (Shuhaiber et al., 2003; Elmore et al., 2012; Jenkins et al., 2013). Cross-sectional studies have found seroprevalence rates of: 59.8% in an Inuit community in Nunavik, 52.3% in Ungava Bay Coast, and 65.6% in Hudson's Bay coast regions (Messier et al., 2009; Shuhaiber et al., 2003). Comparatively, while baseline data do not exist, it is estimated that seroprevalence in southern Canada is lower, averaging 20% (Shuhaiber et al., 2003).

Objectives

In this literature review I address: (1) the effects of climate change and cultural practices on exposure risk for human toxoplasmosis in Canada's North, and (2) public health strategies that can be used to minimize the human health risks of *T. gondii* in Canada's North. To do this, I present information on the impact of climate change on *T. gondii* distribution and survival and the influence of cultural practices on the transmission of *T. gondii* through food consumption, animal contact and drinking water exposure. With this knowledge, I present recommendations for public health that could help minimize the risk of human infection in these Northern communities.

Methods

I followed the framework provided by the National Collaborating Centre for Environmental Health for performing literature searches (NCCEH, 2017). In this case, the review included the following steps. I conducted an initial literature search on April 25, 2017 using Web of Science, PubMed, and Google Scholar. I carried out subsequent searches up until August 1, 2017 to ensure that relevant, up to date publications were captured. Search queries consisted of various combinations of key terms and Boolean logic. Search terms included the following: toxoplasma*, "climate change", "global warming", "environmental change", Canada, "Canada North", "risk", "drinking water", "meat", "food", "animal", "First Nation", "Inuit", "public health", and "zoonosis". All search queries are presented in Table 1 of the Appendices.

One limitation of this method was that only the first five pages of Google Scholar results were scanned since the search query resulted in thousands of hits. I chose to follow this five page limit based on NCCEH instruction, however it may have resulted in relevant papers being missed (A. Eykelbosh, personal communication). Google Scholar results are sorted by relevance (University of Minnesota, 2017). The relevance algorithm Google Scholar uses searches for key words throughout the full text of an article, the reputation of the publisher, and how often the source has been cited in scholarly literature (University of Minnesota, 2017). Shultz (2007) compared searches in PubMed and Google Scholar and found that Google Scholar can be an effective database to complement databases like Web of Science and PubMed, which have more precise search functions. Thus, while I acknowledge that only reviewing the first five pages of Google Scholar results is a limitation, any systematic bias this may have introduced is lessened by my use of two additional databases.

Searches were not restricted by year and article titles and abstracts were scanned for relevance to the topic. Through this process, I identified 91 articles, 16 of which met the specific inclusion/exclusion criteria of this review. For an article to be included in the review it had to present data on and/or review either of the following topics: (1) The effects of climate change on *T. gondii* or its associated health outcomes; (2) The effects of climate change on general zoonosis in Canada's North. The articles that met the inclusion criteria for this review are listed in Table 2 of the Appendices.

Grey literature (reports and documents not published in academic literature) was also reviewed using Google to identify supporting evidence and documentation on *T. gondii*, toxoplasmosis, and climate change, with a focus on Canada. Information from the following websites was used: Centres for Disease Control and Prevention, Natural Resources Canada, Environment and Climate Change Canada, Health Canada, and the Government of Canada.

Results

1.0 Effects of Climate Change on T. gondii Ecology in Canada's North

1.1 Survival

Rising temperatures and precipitation caused by climate change support increased survivability of *T. gondii* oocysts on land and in water in Canada's North. On land, *T. gondii* oocysts rely on warm and humid soils to survive (Yan et al., 2016). Increasing soil temperatures and humidity resulting from climate change are likely to increase the survivability periods of oocysts (Jenkins et al., 2013). Research on *T. gondii* oocysts in the environment is limited and

currently data on upper bounds of oocyst survivability in soil is unavailable (Lindsay & Dubey, 2009). However, links between soil conditions and oocyst survivability can be made. A seroprevalence study conducted in France found that toxoplasmosis infection rates in felines increased during rainy periods (Afonso et al., 2010). The authors attributed higher feline infection rates to increased oocyst survivability in wetter soil which resulted in more widespread soil contamination (Afonso et al., 2010).

In addition to increased oocyst survivability in soil, climate change is leading to increases in temperatures in fresh and salt water which in turn results in increased oocyst survival time. In the past few decades, the Pacific, Atlantic and Arctic Oceans have warmed between 0.2°C and 0.25°C, a trend that is projected to continue to increase over time (Natural Resources Canada, 2015a). Temperature increases support the survivability of *T. gondii* oocysts, which can survive in saltwater for at least two years (Lindsay & Dubey, 2009). Increases in oocyst survivability in soil and water are important since longer infectious periods mean greater chances of distribution and ultimately transmission.

1.2 Distribution

Oocyst distribution is increasing through altered animal migration patterns and habitats, and melting permafrost. Steep temperature increases on land are pushing animal migration patterns and habitat expansion northwards (Burek, Gulland, & O'Hara, 2008). Of particular importance for *T. gondii* distribution, is the habitat expansion of the lynx, likely the main definitive host in Canada's North as domestic cats are uncommon and feral cats are unlikely to survive outside of human communities (Davidson et al., 2011). Increasing temperature may

further influence the range of other felines such as bobcats and cougars, as well as migratory birds (e.g. arctic nesting geese), which scholars believe are responsible for carrying the parasite to parts of the North where felines are scarce (Hueffer et al., 2013; Jenkins et al., 2013; Utaaker & Robertson, 2015). In the community of Aklavik (Northwest Territories), residents have reported recent cougar sightings, despite cougars not previously being found in the region (Nickels et al., 2005). Climate change effects resulting in permafrost melting have also been identified as a potential way for *T. gondii* oocysts to expand to sub-permafrost aquifers, resulting in increased freshwater contamination (Martin et al., 2007). In turn, changing migration patterns, habitat expansion and melting permafrost are likely to result in increased prevalence of *T. gondii* oocysts in terrestrial and aquatic environments and greater exposure for intermediate host animals (Davidson et al., 2011).

Climate change is causing an increase in heavy rainfall events which influence *T. gondii* transport via runoff. In Canada's North, Spring is already marked by larger volumes of freshwater runoff from snowmelt and rainfall (Charron et al., 2014; Simon et al., 2013). This results in the rapid release of oocysts that have accumulated over months in the soil or snowpack into freshwater rivers, lakes, and brooks (Simon et al., 2013). Increased frequency and intensity of precipitation events have been reported, resulting in greater runoff events (Charron et al., 2004). Larger and more frequent runoff and snowmelt events will likely increase oocyst movement from land to aquatic ecosystems raising oocyst load and availability in marine habitats (Simon et al., 2013; Vanwormer et al., 2016).

1.3 Transmission

Climate change could affect *T. gondii* transmission rates through changes in animal interactions that result from sea level rise, erosion, and loss of sea ice (Hueffer et al., 2013). Climate warming has caused sea levels in the North to rise close to 3mm a year for the past two decades which has resulted in loss of land space (Steiner et al., 2013). Increasing frequency and intensity of rainfall events impacts flooding risk as well as coastal erosion, further decreasing available land space in the North (Steiner et al., 2013). Sea ice has decreased an estimated 5 to 10% in recent decades (Health Canada, 2008). Loss of sea ice due to rising temperatures is predicted to result in greater animal crowding on land and remaining sea ice resulting in more interactions between species, such as increased predation and scavenging of dead carcasses (Hueffer et al., 2013; Davidson et al., 2011). The reduction in land space associated with climate induced events has the potential to result in greater animal crowding and interactions between species, increasing the opportunity for transmission of the parasite between species (Polley et al., 2010).

The increased survivability, distribution and transmission of *T. gondii* in Canada's North is supported by regional changes in animal seroprevalence rates and the discovery of infections in new species. Seroprevalence in sentinel species of the North is increasing (Jenkins et al., 2013; Jensen, Aars, Lydersen, Kovacs, & Asbakk, 2010; Kutz, Elkin, Panay, & Dubey, 2001; Measures, Dubey, Labelle, & Martineau, 2004). *T. gondii* seroprevalence in polar bears, for example, has doubled in the last ten years (Hueffer et al., 2013). Geese, muskoxen, caribou, black bear, dogs, wolverines, ptarmigan (bird), harbour seals, and bearded seals have also tested positive for *T. gondii* (Jenkins et al., 2013). Further, infections are being found in new species, such as ring seals (Hueffer et al., 2013). The presence of *T. gondii* in multiple land and

aquatic species increases parasite exposure in other animals in the region, including humans. In addition to the increased prevalence of *T. gondii* in the natural environment, the risk of transmission is exacerbated by cultural practices in Canada's North.

2.0 Cultural Influences on T. gondii Exposure Risk in Canada's North

2.1 Food Consumption & Traditional Practices

It is hypothesized that foodborne transmission of *T. gondii* represents the most significant route of infection in Inuit communities of Canada's North. Traditional practices of consuming raw, fermented or dried meat from wildlife such as seals, caribou, and migratory birds may account for high seroprevalence rates found in certain populations (Jenkins et al., 2013; Messier et al., 2009). In a cross-sectional study (n=917), Inuit seroprevalence was found to be as high as 65.6% and was correlated with increased consumption of marine mammals (seals, whales, beluga) and birds (Messier et al., 2009; Goyette et al., 2014). In a larger cross-sectional seroprevalence study (n=2595), Goyette et al (2014) identified the consumption of >15.9g per day and/or once or more per week of marine mammals as a risk factor for *T. gondii* seroprevalence in Inuit communities of the North. Coinciding with these findings, a study of pregnant women in Nunavik found seroprevalence to be associated with the consumption of raw caribou meat, seal meat and dried seal meat (McDonald et al., 1990). Comparatively, in the Cree of northern Quebec who don't consume raw meat sources, *T. gondii* seroprevalence is much lower, between 4-12% (Levesque et al., 2007). This discrepancy is likely the result of different dietary and culinary habits between the two cultures. The risk associated with these traditional food sources does not negate their importance for the physical, social, spiritual, and

cultural well-being of many northern communities (Pufall et al., 2011). Yet, based on animal seroprevalence studies and the predicted impacts that climate change will have on *T. gondii* transmission, dietary practices that include the consumption of raw or undercooked meat will likely continue to pose increased risk for human toxoplasmosis.

While direct ingestion of *T. gondii* poses the greater risk for infection, improper cleaning following contact with infected animals can result in indirect ingestion and infection. Unlike other parts of Canada, in many northern communities contact with domestic felines present low risk for *T. gondii* transmission as they are rarely kept as pets (Davidson et al., 2011). Instead, animal contact from hunting, gathering and food preparation activities pose greater risk for human exposure through indirect ingestion (Elmore et al., 2012). Specifically, McDonald et al. (1990), identified that skinning animals for fur as associated with higher seroprevalence rates in Nunavik. Following contact with oocysts from wild animals, transmission is likely to occur through a lack of proper hand or food preparation tool washing. The research literature suggests that both food sources and animal preparation practices contribute to *T. gondii* exposure and transmission risk for populations in Canada's North.

2.2 Effects of Climate Change on Traditional Food Practices

Climate change is contributing to human transmission risk by reducing the efficacy of traditional food storage and preparation practices. Keeping food on or near the permafrost in traditional cellars, a common storage method in some northern communities, may no longer be safe (Willows, 2005). The loss of permafrost due to climate change results in warmer temperatures and food spoilage (Parkinson & Evengard, 2009). Additionally, some communities

have reported that warmer summer temperatures have resulted in reduced ability of residents to safely prepare dried fish and meat (Natural Resources Canada, 2015b). The time it takes for fish and meat to dry in the sun has decreased from two days to one afternoon in some parts of the North and residents have noted changes in the consistency of the flesh (Downing & Cuerrier, 2011). Rising temperatures also increase the frequency of meat spoilage during fermentation processes of foods including *igunaag* (fermented seal meat) (Ford, 2009; Willows, 2005). Warmer temperatures can also result in meat rotting during transportation from hunting locations back to communities (Downing & Cuerrier, 2011).

2.3 Drinking Water Treatment

Inadequate access to safe and clean drinking water increases risk for *T. gondii* transmission. To avoid *T. gondii* infection, drinking water should be treated using multiple barrier treatment (Levesque et al., 2007). The multi-barrier approach involves the use of integrated procedures, processes, and tools to prevent or reduce drinking water contamination from source to tap (Government of Canada, 2010). In this section of the results, the process component of this approach will be highlighted.

T. gondii is highly resistant to common chemical disinfectants such as chlorine or ozone (Dubey, 2004). Infectious *T. gondii* oocysts have been identified in a number of treated drinking water systems that use chlorine or ozone for water treatment (VanWormer et al., 2013). Thus, the oocysts must be removed physically through membrane or filtration techniques, or inactivated using Ultraviolet (UV) disinfection (Dubey, 2004). UV treatment must be administered at significantly higher doses than regularly used and in many cases these high

doses still fail to inactivate its oocysts (VanWormer et al., 2013). Standard filtration is an effective process for removing *T. gondii* oocysts (10–12 µm in size) from drinking water following coagulation, flocculation, and settling (the process by which chemical reagents are used to increase the size of unwanted particles, then mixed to bond together to make larger compounds, and lastly allowed to settle to be easily filtered) (Krueger et al., 2014). Boiling drinking water provides an alternative to filtration that is accessible and cost-effective (Dubey, 2004). In a recent study, the northern territories were ranked as the lowest in Canada in terms of implementation of drinking water standards as well as testing, and certification requirements for water treatment plant workers (Natural Resources Canada, 2015b). Lack of adequate drinking water treatment infrastructure and trained operating technicians could increase likelihood of *T. gondii* transmission.

Consistent with those findings, in Nunavik, *T. gondii* seroprevalence was found to be associated with drinking water from domestic water reservoirs (Martin et al., 2007; Messier et al., 2009). The authors hypothesized that this was a result of improper reservoir cleaning which caused recirculation of oocysts trapped in the biofilm of the reservoir walls (Martin et al., 2007; Messier et al., 2009). Properly destroying *T. gondii* oocysts in drinking water coupled with poor water treatment infrastructure remains a challenge for the risk reduction of human toxoplasmosis in Canada's North.

2.4 Effects of Climate Change on Drinking Water Treatment & Sources

Climate change may be impacting the risk of *T. gondii* contamination of drinking water. Higher levels of oocyst occurrence in source waters and physical damage to water treatment

infrastructure from flooding and permafrost melting could both increase the likelihood of outbreak events. The majority of Canadians in the North consume treated water, yet some northern residents, particularly in First Nation, Inuit and Cree communities drink untreated, raw water (Martin et al., 2007). Martin et al. (2005) found that 31% of Inuit in Nunavik rely on untreated water from lakes, rivers, snow, and ice. Indigenous peoples have stated that they are having to travel increasingly further from their communities to find clean, natural water sources because of climate change (Natural Resources Canada, 2015b). Inuit residents of the North report varying access to safe drinking water (Health Canada, 2008). The 2001 Aboriginal Peoples Survey found that 9% of Inuit in Labrador and 43% in Nunavik felt that their drinking water at home was unsafe to consume (Health Canada, 2008). Climate change is leading to more frequent and extreme rainfall events which in turn leads to increased risk for freshwater contamination with *T. gondii* via runoff (Charron et al., 2004). Increases in rainfall can also cause flooding and damage community water intakes (Hueffer et al., 2013). Like many other pathogens, outbreaks of human toxoplasmosis have been found to correspond with heavy rainfall events contaminating drinking water (Simon et al., 2013). Raises in temperature are also likely to increase the risk of contamination through the melting and loss of permafrost containments of tundra pond water sources and sewage lagoons (Berner et al., 2016). Climate change is reducing water security in Canada's North where drinking water systems are fragile and some people still consume raw untreated water. These challenges will likely increase the risk for human *T. gondii* infection from the consumption of contaminated drinking water.

Discussion: Public Health Recommendations

The complex interactions of climate change and cultural factors in Canada's North are predicted to increase *T. gondii* transmission. Human exposure risk could increase through the consumption of raw or undercooked meat, indirect ingestion following contact with animals, and drinking contaminated water. While work is underway to mitigate climate change effects at a national and international level through the development of renewable energy, and policy changes to reduce greenhouse gas emissions, among others, immediate health impacts from changing patterns of zoonotic diseases may be unavoidable (Natural Resources Canada, 2015b; Environment and Climate Change Canada, 2013). Thus, it is critical for public health organizations and practitioners to employ strategies to reduce risk associated with climate-sensitive zoonoses including toxoplasmosis that can take effect in the short term. From the results of this review, I have identified three main strategies that could be utilized to lower the risk of *T. gondii* infections in the short term. (1) Improve baseline *T. gondii* data through more comprehensive seroprevalence and contamination information collection and monitoring. (2) Strengthen drinking water treatment systems and operator training. (3) Identify community adaptive strategies and prevention tools to address toxoplasmosis risk from climate change.

In terms of my first recommendation, more complete *T. gondii* seroprevalence data for both animals and humans would help to establish baseline data and, therefore, help identify future trends. Such information could be used to trigger timely public health responses (Hueffer et al., 2013; Parkinson et al., 2014; Parkinson & Butler, 2005). Species can be locally monitored for changes in seroprevalence and flagged as posing high or low risk to people. Along these lines, a new serum test for *T. gondii* has been developed specifically for northern regions to

enable hunters to facilitate blood testing of animal species, adding capacity for baseline measurements (Hueffer et al., 2013; Owens et al., 2012). In some cases, certain animal species should not be used for human consumption or must be carefully prepared and fully cooked prior to ingestion. This highlights one of the tensions in reducing exposure and risk for human toxoplasmosis in the North. It is impractical and inappropriate to call for a ban on traditional foods as subsistence hunting and gathering are linked to food security in many communities (Owens et al., 2012; Natural Resources Canada, 2015b). Upholding cultural wellbeing and health must be carefully balanced with the exposure and risk for toxoplasmosis faced by northern communities.

More comprehensive climate and *T. gondii* distribution and transmission data (such as Geographic Information Systems (GIS) data) may also help to identify seasonal periods that correspond with higher or lower *T. gondii* risk, enabling more cost-effective use of public health resources for timely interventions. Improved data and monitoring may also provide stronger evidence linking extreme weather events (such as rainfall) with water contamination, thereby enabling better prediction and early detection of risk. This would allow for emergency response measures to be put in place such as alternative sources of drinking water (e.g. access to bottled water) (Parkinson et al., 2014). With more complete GIS data, and/or the use of other risk predicting tools such as risk mapping feline habitat expansion in the North, public health practitioners would be better able to identify contamination risk in specific regions or communities. In some countries, GIS has been successfully used to integrate raw and drinking water data to monitor contamination events and drinking water related health outbreaks associated with climate change (Kistemann et al., 2001). It is important to note that the

consumption of raw water from lakes, rivers, ice, and snow is an important part of cultural identity in some communities of the North (Health Canada, 2008; Daley et al., 2015). Public health officials must work with this knowledge and with these communities to establish successful water quality monitoring systems that support the safe continuation of this practice (Daley et al., 2015).

In terms of my second recommendation, and vital to mitigating toxoplasmosis risk is that drinking water treatment infrastructure be strengthened in the North. This is critical as climate change is likely to further reduce its currently limited capacity (Furgal & Seguin, 2006). Tackling the infrastructure and human resources issues of drinking water in Canada's North, particularly in First Nation communities, is a critical priority of the Canadian Government (Government of Canada, 2017b). Lack of qualified drinking water operators in many parts of Canada's North constitutes a large part of the challenge (Daley, Castleden, Jamieson, Furgal, & Ell, 2015). It has been suggested that in smaller communities where trained drinking water treatment personnel are harder to find or keep, healthcare workers may be of use in monitoring drinking water quality and disseminating information on contamination events through drinking water testing training (Martin et al., 2007). Infrastructure is also needed to strengthen drinking water treatment facilities that are at highest risk of damage due to increases in coastal erosion, permafrost melting and flooding (Daley et al., 2015; Martin et al., 2007).

T. gondii is notoriously hard to identify in drinking water, and currently no rapid test is available posing an additional challenge in addressing increased drinking water contamination events (Jones & Dubey, 2010). As previously mentioned, oocysts are chlorine resistant but

filtration (absolute 1 µm filter) and boiling render then inactive in water (Jones & Dubey, 2010). Thus, when monitoring climate events and likelihood of drinking water contamination, boil water advisories for raw water and filtration checks of drinking water treatment systems could be employed as precautionary measures.

In terms of my third recommendation, community engagement should be a priority to develop and implement toxoplasmosis prevention initiatives. Prevention is the most effective method to avoid *T. gondii* transmission via contaminated food, contact with animals and drinking water and should be employed by public health professionals (Boyer et al., 2011; Jones et al., 2014). Community engagement is paramount to the success of public health education as a prevention tool, particularly in the context of Canada's North where culture and parasitic risk are inextricable (Pufall et al., 2011). Through engagement initiatives (e.g. meetings, town halls, consultations) communities can debate and decide upon the most effective methods for disseminating pertinent information on the changing patterns of *T. gondii* food and water contaminations resulting from climate change. These information channels may look different between communities but community consultations will likely yield more locally-relevant and effective solutions for reaching at-risk populations. Local education campaigns on proper cleaning of small drinking water reservoirs should be conducted to reduce *T. gondii* oocyst contamination of water tanks (Levesque et al., 2007).

Some preventative education campaigns have already been conducted in the North, but have only targeted pregnant woman as associated risk of adverse health outcomes are high in this population (Boyer et al., 2011; Jenkins et al., 2013; Pappas et al., 2009). One initiative included suggestions to wear gloves when handling carcasses and to carefully wash knives and

hands after contact with raw meat (Jenkins et al., 2013). However, based on the results of this review I believe that prevention measures should target the whole population. Any person can become immunocompromised and develop risk for acute toxoplasmosis and our knowledge of the parasite's effects on the brain are still evolving, indicating the necessity for population wide education (Pappas et al., 2009). There is room for creativity and collaboration when identifying new methods for bettering data collection and monitoring, improving drinking water infrastructure and training, and implementing appropriate prevention measures. If used, innovative and community based approaches can be employed by public health organizations, practitioners and local communities to reduce risk of *T. gondii* transmission in the North.

Conclusion

Climate change appears to increase risk for human exposure to *T. gondii* in Canada's North through greater environmental contamination of oocysts and environment-host as well as host-host transmission. Food preparation practices, consumption of raw or undercooked food sources, contaminated drinking water and contact with animals also contribute to increased infection risk. However, it is difficult to quantify how these factors will translate into adverse human health outcomes since toxoplasmosis is generally subclinical unless acquired during pregnancy or by immunocompromised individuals. However, as our understanding of the parasite's effect on the human body evolves as well as its environmental fate and transport, public health practitioners may be able to better prevent transmission in communities by targeting specific exposure routes.

Public health organizations and practitioners have a critical role to play in reducing *T. gondii* exposure in Canada's North while upholding a holistic view of human health that incorporates local cultural and spiritual practices. By improving baseline data and monitoring, strengthening drinking water infrastructure and water operator training, and collaborating with communities to develop prevention measures, the risk of *T. gondii* transmission can be reduced. While these recommendations are targeted specifically to toxoplasmosis, if implemented they would likely have positive impacts on mitigating other climate-sensitive zoonotic diseases that share transmission routes with *T. gondii*, such as *Giardia* and *Cryptosporidium*. Public health organizations and professionals have the capacity and the unique opportunity to address these shifting patterns of zoonotic risk and disease, to improve community health in a climate changing world.

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Capstone Reflection

I became intrigued by toxoplasmosis during my Masters of Public Health (MPH) practicum placement with the National Collaborating Centre for Environmental Health (NCCEH) in Vancouver, British Columbia. At the NCCEH I worked on a knowledge translation project that evaluated risk factors for toxoplasmosis in Canada. While conducting research for a literature review, I developed a keen interest in the body of literature that explored the impacts of climate change on toxoplasmosis infections around the world. During my practicum placement, the NCCEH also performed key informant interviews with medical health officers across Canada, and multiple officers in the North reported the need for more information on toxoplasmosis. I applied my interest in climate change and toxoplasmosis to a noted problem in Canada and my capstone was born.

Working on the capstone project gave me some insight into the challenges and rewards of conducting literature reviews in a public health context. An obstacle I faced during the project was developing clarity in my ideas and writing. To be an effective public health practitioner working in knowledge translation it is critical that conciseness, thoughtfulness, and preciseness be paramount to conveying information and public health recommendations. Through the capstone feedback processes with my supervisor and second reader, I was able to appreciate this necessity. I hope to be in an employment position where I can continue to develop my writing, presentation, and communication skills as they will help me be more effective in future work I pursue. In addition to this challenge, I also learned more about the complexities of addressing public health problems. Throughout my coursework in the MPH program it was made clear that public health solutions should be culturally appropriate, timely,

evidence-based, sustainable, and use resources effectively. This is a balance that felt nearly impossible to achieve when I was forming my project recommendations. It was clear to me that in the real world, far greater research efforts must to be taken to ensure recommendations are useful.

In terms of rewarding aspects of the capstone, working on this project solidified my interest and excitement for environmental health issues in Canada. It was fun to explore the topic of climate change and toxoplasmosis and learn how environment, animal, and human interactions influence risk for parasitic infections. I acquired both baseline knowledge and a more developed ability to question the information and evidence I read. The capstone project was a both a challenging and rewarding experience and helped me better understand communication skills I can improve on and aspects of environmental health that I want to pursue in my career.

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Appendices

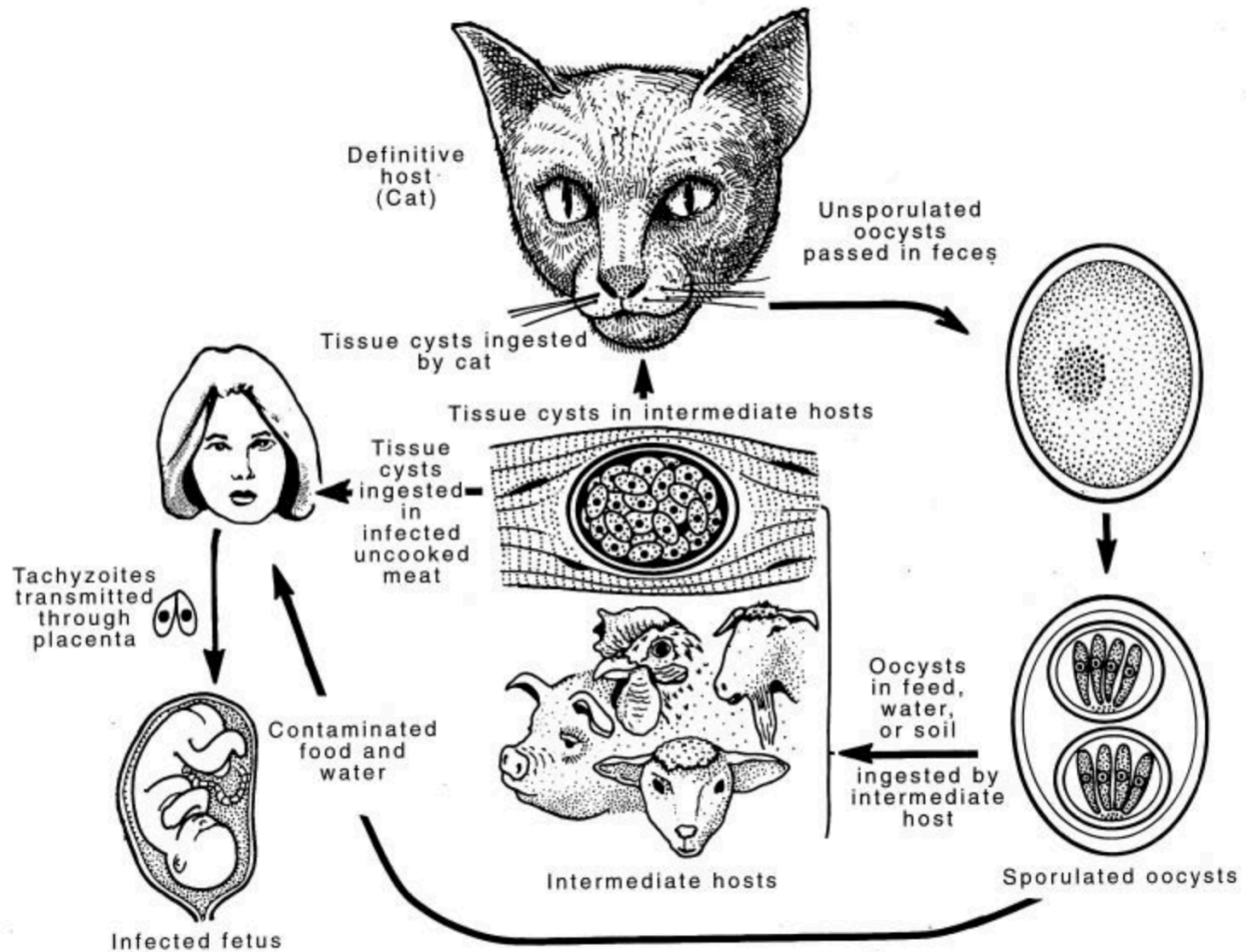


Figure 1. Life cycle of *T. gondii*. Sourced from Dubey et al. (1998).

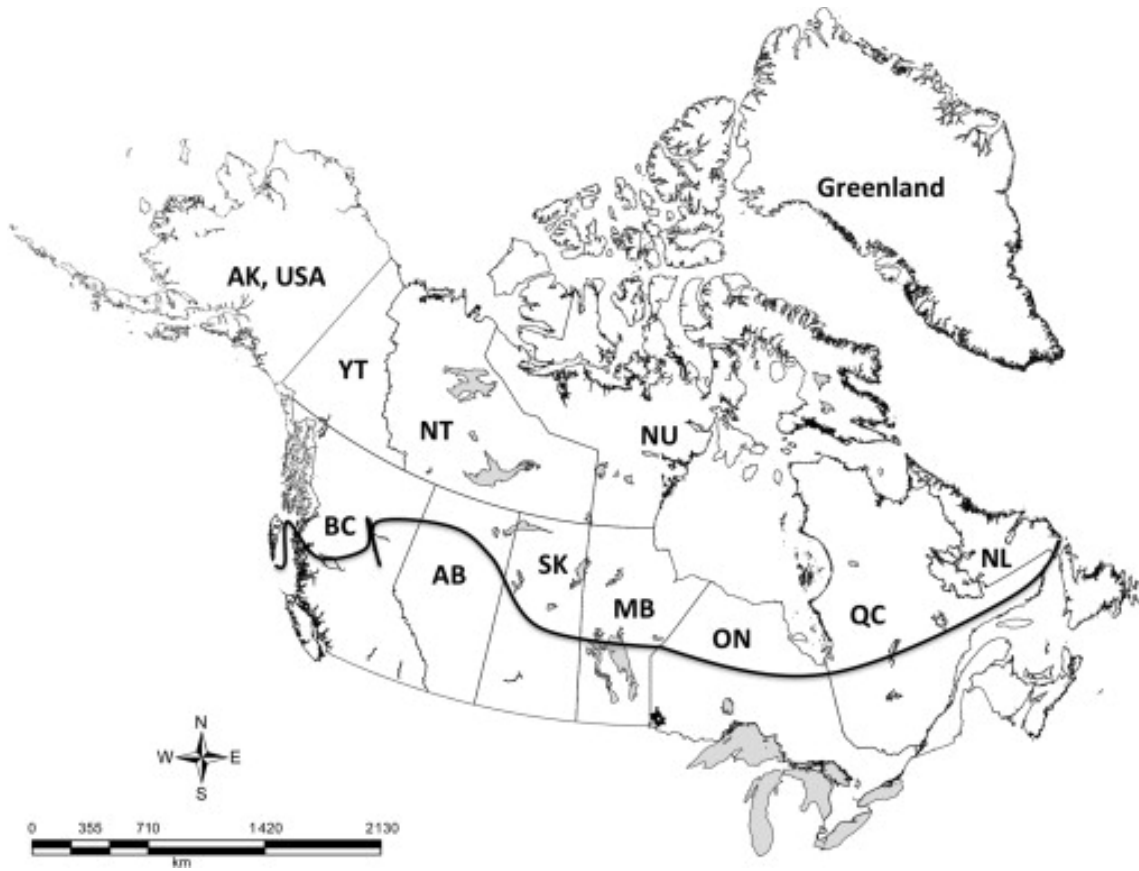


Figure 2. Map of Canada’s North, distinguished as being above the southern limit of discontinuous permafrost (thick black line). Sourced from Jenkins et al., 2013.

Table 1. Search matrix of databases and search terms

Database	Date of Search	Objective	Query	Hits
Web of Science	25/04/17	To broadly identify and explore the literature around <i>Toxoplasma gondii</i> & toxoplasmosis and climate change in Canada	toxoplasm* (“climate change” OR “global warming” OR “environmental change”) Canada	1
PubMed	25/04/17		toxoplasm* (“climate change” OR “global warming” OR “environmental change”) Canada	2
Google Scholar	25/04/17		toxoplasm* (“climate change” OR “global warming” OR “environmental change”) Canada	2,440
Web of Science	25/04/17	To expand the previous search to explore potential impacts of climate change on <i>Toxoplasma gondii</i> & toxoplasmosis in	toxoplasm* (“climate change” OR “global warming” OR “environmental change”)	31
PubMed	25/04/17		toxoplasm* (“climate change” OR “global warming” OR “environmental change”)	11

Google Scholar	25/04/17	northern regions outside of Canada	toxoplasma* ("climate change" OR "global warming" OR "environmental change")	4,500	
Web of Science	25/04/17	To explore if literature is available pertaining to overall risk factors for toxoplasmosis in Canada's North (human and animal)	toxoplasma* risk Canada north	4	
PubMed	25/04/17		toxoplasma* risk Canada north	5	
Google Scholar	25/04/17		toxoplasma* risk Canada north	13,100	
Web of Science	25/04/17	To identify literature around toxoplasmosis for specific human risk factors in the North. Namely: <ul style="list-style-type: none"> • Food (contaminated meat, seafood, unwashed fruits and vegetables) • Drinking water • Contact with animals • First Nations communities 	toxoplasma* North risk food	11	
PubMed	25/04/17		toxoplasma* North risk food	23	
Google Scholar	25/04/17		toxoplasma* North risk food	17,800	
Web of Science	25/04/17		toxoplasma* Canada drinking water	9	
PubMed	25/04/17		toxoplasma* Canada drinking water	8	
Google Scholar	25/04/17		toxoplasma* Canada north drinking water	5,730	
Web of Science	25/04/17		toxoplasma* Canada north animal	7	
PubMed	25/04/17		toxoplasma* Canada north animal	20	
Google Scholar	25/04/17		toxoplasma* Canada north animal	12,200	
Web of Science	25/04/17		toxoplasma* ("First Nation*" OR Inuit)	9	
PubMed	25/04/17		toxoplasma* ("First Nation*" OR Inuit)	10	
Google Scholar	26/04/17		toxoplasma* ("First Nation*" OR Inuit)	913	
Web of Science	25/04/17		To explore the literature around public health responses to climate change and changing patterns of zoonosis in Canada	"public health" AND Canada AND ("climate change" OR "global warming" OR "environmental change") AND (toxoplasma* OR zoonosis)	3
PubMed	25/04/17			"public health" AND Canada AND ("climate change" OR "global warming" OR "environmental change") AND (toxoplasma* OR zoonosis)	25
Google Scholar	26/04/17	"public health" AND Canada AND ("climate change" OR "global warming" OR "environmental change") AND (toxoplasma* OR zoonosis)		1,756	

Table 2. Literature Review Matrix of Papers Selected for the Literature Review

Authors & Year of Publication	Title	Location	Design	Results & Main Discussion Points
Charron et al., 2005	Vulnerability of waterborne diseases to climate change in Canada: a review	Canada	Review	<ul style="list-style-type: none"> • risk of waterborne illness and health impacts of climate change discussed for Canada • weather (particularly extreme precipitation) is frequently a factor in triggering waterborne disease outbreaks • increasing precipitation patterns, floods, high temperatures identified as risk factors for waterborne illness in Canada • discusses mechanisms for people to become sick from contaminated drinking water • discusses climate change in Canada
Dudley et al., 2015	Climate Change in the North American Arctic: A One Health Perspective.	Arctic and Subarctic of North America	Review	<ul style="list-style-type: none"> • describes current evidence and state of climate change in the North American Arctic • climate change impacts on zoonoses (including <i>Toxoplasma</i>) are likely to impact the sustainability and safety of traditional substance resource use by many cultural groups living in this region • <i>claims</i> prevalence toxoplasmosis in pregnant women in northern Canada is increasing • evaluates the potential impacts of climate change on zoonoses from a One Health perspective that integrates ecological health with human health, as defined by the WHO • highlights health disparities and outcomes in the Arctic between indigenous and non-indigenous groups
Gajadhar & Allen, 2004	Factors contributing to the public health and economic importance of waterborne zoonotic parasites	Global	Review	<ul style="list-style-type: none"> • <i>Toxoplasma gondii</i> is chlorine resistant, but can be effectively treated in drinking water with ultraviolet-irradiation • transmission of <i>T. gondii</i> oocysts in water is likely enhanced by transport hosts which collect and concentrate resistant stages • sewage contaminated water use for agricultural irrigation has been found to have transmissible <i>T. gondii</i> oocysts • <i>Toxoplasma</i> is ranked in the second highest category of biological agents capable of causing serious human and animal epidemic outbreaks (according to US CDC classification)

Hueffer et al., 2013	Zoonotic infections in Alaska: disease prevalence, potential impact of climate change and recommended actions for earlier disease detection, research, prevention and control.	Alaska	Review	<ul style="list-style-type: none"> observed effects from climate change in Alaska include an increase in precipitation, longer frost-free seasons, decrease in sea ice, glacial and snow cover, increase in sea level and an increase in river outflow discusses need for public health to alert vulnerable populations (particularly pregnant woman) that ingesting contaminated and undercooked or raw meat is a primary risk factor, and that transmission of the parasite is not only associated with felines higher humidity and warmer soil may increase rate of sporulation and oocyst survival time increased storm events and precipitation may be hazardous to drinking water supplies (compromising filtration systems, increasing likelihood of oocysts appearing in drinking water) damage to water and sanitation plants may result from permafrost melting loss of sea ice may result in animal crowding on land, increasing transmission rates between animal species authors call for increased surveillance action for human toxoplasmosis to address gap in knowledge concerning unknown levels of infection and disease outcomes (not a notifiable disease in the United States)
Jenkins et al., 2015	Wildlife parasites in a One Health world	Canadian North	Review	<ul style="list-style-type: none"> climate change is likely to worsen toxoplasma which is already a threat to health, food security and culture in Canada's North, particularly where Inuit people strongly rely on substance food sources and have cultural ties to the land Arctic ecosystems are undergoing accelerated change due to global warming which may reduce the adaptive capacity of northern communities to respond to parasitic threats like toxoplasma Uses One Health as a framework for risk communication and management of toxoplasmosis in Canada's north
Jenkins et al., 2013	Tradition and Transition: Parasitic Zoonoses of People and Animals in Alaska, Northern Canada, and Greenland	Alaska, Northern Canada, Greenland	Systematic review	<ul style="list-style-type: none"> due to significant public health impact of zoonotic diseases there is increasing interest in predicting effects of climate and land use change on animal hosts and human health outcomes in vulnerable regions like the North health disparities between communities in the North and the rest of Canada in terms of exposure to zoonoses discusses transmission, prevalence and public health impact in the North briefly discusses impact of climate on future oocyst transmission, waterborne outbreaks and in terms of wildlife
Kutz et al., 2009	The Arctic as a model for anticipating, preventing, and mitigating climate change impacts on host-parasite interactions	Arctic and Subarctic	Review	<ul style="list-style-type: none"> discusses effects of climate change on parasite transmission patterns in the Arctic discusses monitoring and early detection programs as well as evidence-based prevention methods and responses to outbreaks resulting from host-parasite system changes due to climate change

Martin et al., 2007	Drinking water and potential threats to human health in Nunavik: Adaptation strategies under climate change conditions	Nunavik, Canada	Cross-sectional	<ul style="list-style-type: none"> discusses climate changes in the region over the past few decades authors monitored drinking water habits in the region and where residents acquired drinking water from - to assess risk for waterborne disease through a climate change lens interviews were also conducted and resident's observations of climate change were recorded (deterioration of water quality, higher turbidity of running water, major shoreline erosion, early melting of snow and ice, rapid changes in weather conditions, etc.) authors recommend involving healthcare workers in the water treatment/testing process water from home storage containers was found to be more contaminated than raw water
Meerburg & Kijlstra, 2009	Changing climate-changing pathogens: <i>Toxoplasma gondii</i> in North-Western Europe.	North-Western Europe	Review	<ul style="list-style-type: none"> Global Climate Change model used to predict impact of climate change on <i>T. gondii</i> prevalence in humans for the region of study Based on the model, increases in total precipitation, mean temperature and weather extremes are predicted The authors provide risk maps and predict changes to the range and prevalence of <i>T. gondii</i> in the environment Climate change may affect contamination of drinking water sources (run-off, increased drainage, increased precipitation), changing ecological patterns of host species Authors predict that based on their climate models and future anthropogenic change, the range of toxoplasma is likely to expand and people will be more likely to be exposed through a variety of factors
Parkinson et al., 2014	Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group	North American Arctic	Conference and Workshop Report	<ul style="list-style-type: none"> toxoplasma risk to human and animal populations is largely unknown as surveillance and reporting systems are inadequate authors postulate that under-reporting and under-diagnosing is an issue due to lack of diagnostic infrastructure, staff capacity and remoteness of many communities in the Arctic call for baseline assessments of infection in humans and animals in this region authors also propose several activities to assess the health impacts of climate change that also include the establishment of a communication strategy between indigenous communities and other organizations (government and well as non-government)
Polley et al., 2010	Climate change, parasites and shifting boundaries	Circumpolar North		<ul style="list-style-type: none"> explores host-parasite relationships in a climate change context keystone wildlife species are at risk on land and in oceans (caribou, reindeer, moose, polar bears, seals, walrus, seabirds, etc.) warming climate is shifting boundaries for flora and fauna, causing sea level rise and therefore erosion and flooding of coastal regions for toxoplasma host species (definitive and non-definitive) climate change may result in expansion of their geographic ranges and distribution, changes in opportunities for contact between wild and domestic animals, potential increases in host abundance

				<ul style="list-style-type: none"> availability and quality of host animals as food for human populations maybe be affected
Simon et al., 2013	Fate and Transport of <i>Toxoplasma gondii</i> Oocysts in Seasonally Snow Covered Watersheds: A Conceptual Framework from a Melting Snowpack to the Canadian Arctic Coasts	Canadian Arctic		<ul style="list-style-type: none"> presentation of a framework and hypothesis to explain the transport of <i>T. gondii</i> oocysts in the Canadian Arctic environment, where humans may then be exposed rapid release of oocysts following snowmelt and health rainfall (where they have accumulated for months in soil and snowpack) may cause significant contamination of arctic coastline discusses survival of oocysts under different environmental conditions exposure rate in marine mammals likely higher when runoff is high
Utaaker & Robertson, 2014	Climate change and foodborne transmission of parasites: A consideration of possible interactions and impacts for selected parasites	Global	Review	<ul style="list-style-type: none"> foodborne parasites are often neglected compared to viral, bacterial and vector infections when it comes to research on climate change and infectious disease heavy rainfall and runoff from melting snow can increase the likelihood of waterborne outbreaks of protozoa including toxoplasma climate events likely impact the prevalence and transmission in intermediate and definitive hosts for toxoplasma melting of tundra may also change habitation patterns of definitive hosts in northern regions of the world as it creates new habitat for felines
VanWormer et al., 2016	Coastal development and precipitation drive pathogen flow from land to sea: evidence from a <i>Toxoplasma gondii</i> and felid host system	California, United States		<ul style="list-style-type: none"> watersheds with the highest levels of oocyst runoff were found to align closely with increased toxoplasma infection in marine mammals in corresponding regions increases in precipitation and coastal developments independently increased oocyst transport to oceans
VanWormer et al., 2013	Molecules to modeling: <i>Toxoplasma gondii</i> oocysts at the human-animal-environment interface	Global	Review	<ul style="list-style-type: none"> discusses importance of oocyst transmission patterns (waterborne, oocyst survival and success, factors impacting terrestrial to aquatic transmission,) for human and animal host exposure gives overview of published methods for detecting toxoplasma in water discusses impacts of climate change and land use change on transmission of oocysts

Yan et al., 2016	Impact of environmental factors on the emergence, transmission and distribution of <i>Toxoplasma gondii</i>	Global	Review	<ul style="list-style-type: none"> • Predict that climate effects will influence “occurrence, survival, distribution and transmission” of toxoplasma in 3 main ways: (1) oocyst sporulation depends partially on local temperature and humidity, (2) oocyst in the environment are influenced by precipitation, river flow, and terrestrial-marine interactions, (3) geographic distribution and transmission of the parasite impacted by migration patterns of host species • Authors also put forward a hypothesis that environmental degradation likely increases oocyst transport into coastal water systems
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