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Impact of climate change on infectious diseases of animals in the Norwegian Arctic

Norwegian School of Veterinary Science

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The report has been made in cooperation between Norwegian Arctic Climate Impact Asessment (NorACIA), Norwegian Polar Institute and Norwegian School of Veterinary Science, Section of Arctic Veterinary Medicine, Tromsø, Norway.

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1. Summary

Higher temperatures will cause several pathogens (parasites, bacteria, viruses) to extend their distributions northerly.

The prevalence and abundance of pathogens may also change.

A change of distribution of pathogens may have several consequences for wild and domesticated animals, which may be hard to predict because of lack of data. However, the following responses may be predicted with fair certainty:

- Cod farming will probably become impossible along larger parts of the coast due to more northerly distribution of a highly pathogenic bacterium.
- Proliferative kidney disease, a disease which has been associated with severe declines in salmonid populations in Switzerland and England, will probably become more common.
- Abundance of certain nematodes in musk ox and reindeer will probably increase, resulting in more severe impacts.

Possible effects, that are harder to predict, include invasions of new pathogens in a large number of animal host species and changed abundance/prevalence of established pathogens. In addition to effects on single host species, this may also affect the overall dynamics of aquatic and terrestrial ecosystems, such as for example the ecosystem in the Barents Sea.

Specific priorities for research to predict impacts of climate change on animal diseases in the NorACIA area are:

1. Collection of baseline data on health parameters, as well as distribution, epidemiology and effects of pathogens and diseases in wild animal populations.
2. Studies that are focused on separating the effects of different climate variables on the dynamics of pathogens and disease in animals and humans (zoonoses).
3. Forecasting temporal and spatial effects of climate change on pathogen and host populations.

It is important that scientific investigations benefit from interdisciplinarity through collaborations between ecologists and infectious diseases biologists. Investigations should focus on key host species and key pathogens in given ecosystems (aquatic and terrestrial), and should include screenings and epidemiological studies (retrospective and real time), case studies, dynamic food-web modelling and experimental studies.

2. Summary in Norwegian/Sammendrag

Høyere temperaturer vil forårsake en mer nordlig utbredelse av enkelte patogener (parasitter, bakterier, virus).

Tilstedeværelse og tallrikhet (prevalens) av patogener kan også endre seg.

Endret utbredelse av patogener kan ha konsekvenser for ville dyr og husdyr som kan være vanskelig å forutsi på grunn av mangel på kunnskap. Følgende responser kan likevel forutsies med en viss grad av sikkerhet:

- Oppdrett av torsk vil sannsynligvis bli umulig langs større deler av norskekysten på grunn av en mer nordlig utbredelse av en sterkt sjukdomsfremkallende bakterie.
- Bakteriell nyresyke (proliferative kidney disease), en sjukdom som er assosiert med alvorlig nedgang i laksepopulasjoner i Sveits og England, vil sannsynligvis bli mer vanlig.
- Forekomsten av enkelte parasitter (nematoder) hos moskus og reinsdyr vil sannsynligvis øke, noe som vil øke parasittenes negative betydning for dyrene.

Mulige effekter, som er vanskeligere å forutsi, er invasjon av nye patogener (parasitter, bakterier, virus) i et stort antall vertsdyr og endret forekomst og prevalens av etablerte patogener. I tillegg til effekter på enkelte dyrearter kan dette også ha innvirkning på dynamikken i akvatiske og terrestriske økosystemer, som for eksempel økosystemet i Barentshavet.

For å forutsi effekter av klimaendringer på dyresjukdommer i NorACIA-området må forskning rettes spesielt mot:

1. Innsamling av grunnleggende data med hensyn til helseparametre, samt forekomst, utbredelse, epidemiologi og effekter av patogener og sjukdommer i populasjoner av ville dyr.
2. Studier som skiller effekter av ulike klimaparametre på dynamikken mellom patogener og sjukdom hos dyr og mennesker (zoonoser).
3. Forutsi effekter i tid og rom av klimaendringer i forhold til patogener og vertspopulasjoner.

Det er viktig at slike vitenskapelige undersøkelser skjer ved å kombinere ulike fagområder (multidisiplinære), så som økologer og biologer som jobber med infeksjonssjukdommer. Slike undersøkelser bør fokusere på nøkkelarter (vertsdyr) og nøkkelpatogener i spesifikke økosystemer (akvatiske og terrestriske), og bør inkludere prevalensstudier og epidemiologiske studier (fortid og nåtid), kasus-rapporter, dynamiske næringskjedemodeller og eksperimentelle studier.

3. Definitions

Norwegian Arctic: In this report, we have defined the "Norwegian Arctic" with the same criteria as AMAP and NorACIA: The mainland north of the Arctic circle, and the oceans north of 62ºN.

Pathogen: Any living agent capable of causing disease (viruses, rickettsia, bacteria, fungi, yeasts, protozoa, helminths, and certain insect larval stages).

Infectious disease: A pathological condition of a part, organ, or system of an organism resulting from infection and characterized by an identifiable group of signs or symptoms.

Host: an organism that harbors a pathogen, or a mutual or commensal symbiont, typically providing nourishment and shelter.

Zoonosis (zoonotic disease): an infectious disease that can be transmitted from animals (wild or domesticated) to humans under natural conditions.

Key species: A species that plays a key role in an ecosystem and/or is well monitored over time.

4. Introduction

The definition of "animals in the Norwegian Arctic" in this report mainly refers to wild animals and not to livestock. However, we have included semi-domesticated reindeer and to some extent farmed fish, since they to a great extent are exposed to wildlife pathogens, including vectors, in terrestrial and aquatic ecosystems.

The main question we ask is what the effect of climate change may be on pathogen distribution and impact of infectious diseases in wild animals in the NorACIA area. We give a short outline of the climate changes that are well documented, as well as some general and specific characteristics of pathogens and host animals, and how infectious diseases may interact with animal health on individual and population levels. The report concludes and summarizes research needs to address specific gaps in knowledge related to climate effects on the distribution of pathogens and their impact in the Norwegian Arctic.

4.1. Climate change in the Arctic

4.1.1. Intergovernmental Panel on Climate Change (IPCC)

The IPCC’s Fourth Assessment Report (AR4; 17 Nov. 2007, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf) provides an integrated view of climate change. There is now major consensus of ongoing global warming, as evidenced from observations of increased average air and ocean temperatures in many regions, and increased melting of snow and ice resulting in rising of global average sea level (Figure 1). It is likely that there has been significant warming caused by human activities over the past 50 years averaged over all continents except Antarctica, due to increase in greenhouse gases (GHG). There is a high level of agreement and much evidence that with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades.

Projected patterns of warming and regional-scale features include:
- Strongest degree of warming over land areas and at northernmost latitudes (Figure 2).
- Contraction of snow covered area, increases in thaw depth over most permafrost regions and decrease in sea ice extent.

In polar regions, the main projected biophysical effects are:
- Reductions in thickness and extent of glaciers, ice sheets and sea ice, and changes in natural ecosystems with detrimental effects on many organisms including migratory birds, mammals and higher predators.
- For human communities in the Arctic, impacts are projected to be mixed, particularly those resulting from changing snow and ice conditions.
- Detrimental impacts would include those on infrastructure and traditional indigenous ways of life.
- In both polar regions, specific ecosystems and habitats are projected to be vulnerable, as climatic barriers to species invasions are lowered.

There is new and stronger evidence of impacts of climate change on unique and vulnerable systems, such as polar and high mountain communities and ecosystems, with increasing levels of impacts as temperatures increase further. However, many impacts can be reduced, delayed or avoided by mitigation. Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels. This may be achieved by deployment of technologies that are either currently available or expected to be commercialized in coming decades, assuming appropriate and effective incentives are in place for their development, acquisition, deployment and diffusion.

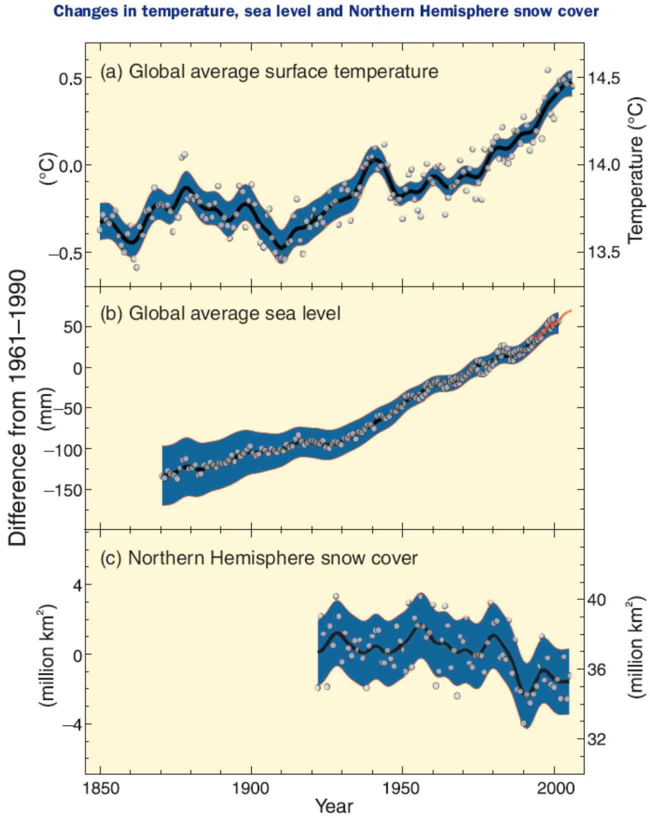

Figure 1: *Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c) (IPCC report).*

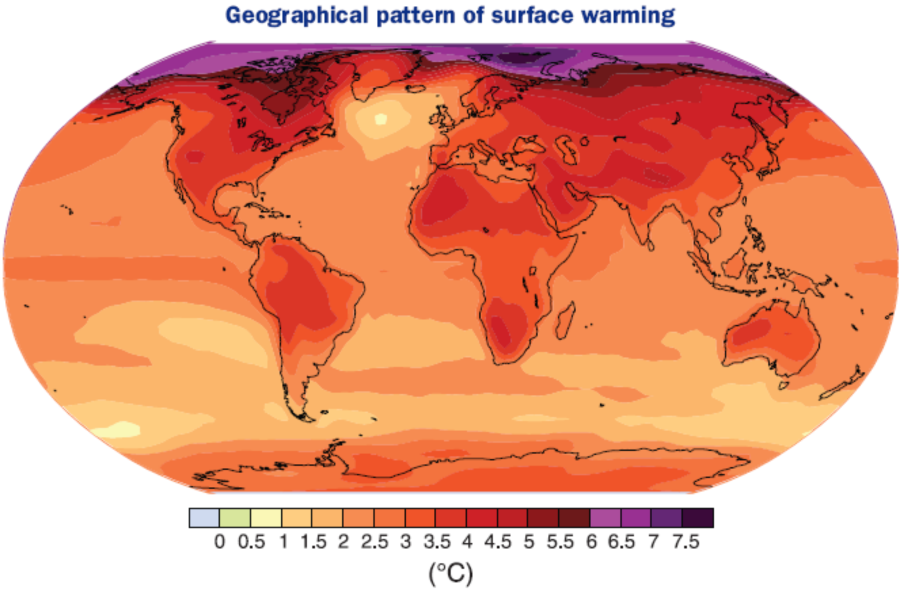

Figure 2: *Projected surface temperature changes for the late 21st century (2090-2099). Temperatures are relative to the period 1980-1999 (IPCC report).*

4.1.2. NorACIA

The reports from both IPCC and ACIA (http://www.acia.uaf.edu/pages/overview.html) predict considerable warming in Arctic regions. For example, scenarios used in the ACIA-report predicts that mean annual Arctic surface temperatures north of 60º N will be 2 to 4 ºC higher by mid-century and 4 to 7 ºC higher toward the end of the 21st century. In general, climate models predict the Arctic to warm twice as much as other regions in the world.

4.1.3. Changes in ecosystems

An evaluation of possible changes in ecosystems caused by climate change was recently conducted for the Barents Sea (Loeng, 2008). The main conclusion in the report was that climate change will lead to colonization by southern species, general shifts in distribution of important fish stocks towards the north and east and changes in interactions between species. Overall consequences are hard to predict, and may also be dependent on other human impact on ecosystems.

4.2. Pathogen – host interactions and possible links to climate change

We will first describe effects that pathogens may have on the structure of entire ecosystems, and then explore how pathogens may change the dynamics of predator-prey interactions. The next subsection describes how temperature may affect the dynamics of cholera pathogens and how this may be affected by changes in zooplankton communities. The fourth subsection (4.2.4) exemplifies how infection dynamics and pathogenicity may vary between pathogen species. The fifth subsection describes pathogens that may be transmitted from animals to man (zoonoses).

4.2.1. Role of pathogens in structuring ecosystems

The relationship between a host and an infectious agent has usually developed through evolution, and consists of a balance between the pathogenicity of the agent and the immunity (defence) of the host. Infectious agents have developed a wide range of strategies to infect individuals and populations of hosts, also including one or more intermediate host, and the hosts have developed contra-strategies to improve specific immunity against the pathogens. Depending on these strategies, pathogens may profoundly affect the structure and dynamics of ecosystems.

When the rinderpest virus was introduced to Africa in 1887, it reduced the number of ungulates of the African Savannahs to 20% of their original abundance. Without prey, carnivores starved and their populations declined. Less grazing increased the frequency of fire, which resulted in reduced resources for tree-feeding species such as giraffes (Sinclair, 1979 *in* Lafferty *et al.,* 2008).

Another example is the consequences that followed introduction of the fungal pathogen chestnut blight from Asia to USA around 1890. Within a few years, the fungus eradicated chestnut trees from the eastern parts of the USA, where this species previously constituted up to 25% of the forest (von Broembsen, 1989).

Native pathogens may also cause large changes in ecosystems. This was seen in the 1980s, when epidemic mortality (98% loss) of the Caribbean black-spined sea urchin (*Diadema antillarum*), a keystone herbivore, shifted the reef system from coral-dominated to algae-dominated (Hughes, 1994 *in* Lafferty *et al.,* 2008).

The recent invasion of the midge-borne disease in livestock called bluetongue into Southern Europe is an example of a clear impact of climate change on a vector-borne disease (Purse *et al*., 2008). The epidemic spread in a radial fashion and covers today a large part of Central Europe. Bluetongue virus is transmitted by the vector *Culicoides* (Meiswinkel *et al.,* 2007), and the epidemic is thus restricted to areas where *Culicoides* is present and where the temperature is high enough to ensure that replication in the vector can take place. This requires moisture so that

Culicoides thrives and temperatures above 10 °C, which is regarded as the lower threshold for virus replication (European Food Safety Authority, 2007).

4.2.2. Predator–prey interactions

Determining what drives the magnitude and frequency of population fluctuations is crucial because, within a species, populations that fluctuate dramatically may be more vulnerable to extinction. Increases in climatic variability might result in longer-lasting sequences of favourable or unfavourable conditions for individual species. With few exceptions, current approaches for forecasting community change due to global warming, ignore species interactions. This exclusion is likely to lead to significant errors in predictions of species occurrence and abundance. Furthermore, there have been few theoretical studies examining the effects of climate change on higher-level trophic interactions. Recent empirical work on gray wolf (*Canis lupus*) and the food chains they influence heavily in Isle Royale and Yellowstone National Parks (USA) indicates that predators may buffer the effects of large-scale climate phenomena on the population dynamics of their prey and on the community of scavengers which they subsidize with carrion (Wilmers *et al.*, 2007).

In Yellowstone National Park, winter conditions and reintroduced gray wolves (*Canis lupus*) together determine the availability of winter carrion on which numerous scavenger species depend. Fifty years of weather data from Yellowstone showed that winters were getting shorter. In the absence of wolves, early snow thaw would lead to a substantial reduction in late-winter carrion, causing potential food bottlenecks for scavengers. Wolves, however, largely mitigate late-winter reduction in carrion due to earlier snow thaws. By buffering the effects of climate change on carrion availability, wolves allow scavengers to adapt to a changing environment over a longer time scale more commensurate with natural processes (Wilmers *et al.*, 2006).

Pathogens may change such relationships. In Isle Royale, a canine parvovirus (CPV) epizootic induced a crash in the wolf population. The role of the wolf in regulating the moose population decreased, and then climatic factors exerted a stronger influence on moose population growth rate. Thus, the biotic mechanisms controlling the moose population shifted from top-down (wolf abundance) to bottom-up (moose abundance and their primary winter food resource i.e. balsam fir) factors. Thus, the reduction in control of moose by biotic factors and the corresponding increase in abiotic climatic factors may erode the stability of this community (Wilmers *et al.*, 2005).

4.2.3. Interaction between pathogen and zooplankton: The cholera model

Vibrio cholerae has long been known as a fecal-oral pathogen, and infection rates are significantly greater in areas with poor sanitation, but it is also evident that *V. cholerae* is naturally present in warm, brackish environments, being concentrated on the exoskeleton and gut of copepods. When communities rely on untreated environmental water sources for bathing, cooking, and drinking, the incidental ingestion of copepods, which carry a high “dose” of *V. cholerae,* can initiate an infection. Likewise, the likelihood of consuming an infectious dose is higher when a bloom of copepods occurs in the water. With a changing climate, the geographic range of these pathogens may also change, potentially resulting in increased exposure and risk of infection for humans. Furthermore, changes in plankton populations, and other hosts for which the Vibrio-bacteria are commensals or symbionts, would similarly alter the ecology of these pathogens that are autochthonous to the aquatic environment (Lipp *et al.,* 2002).

4.2.4. Viral infections: different infection biology for morbillivirus and rabies

Some viral infections may cause epizootics and massive mortality, such as the morbillivirus die-offs in harbour seals (*Phoca vitulina*) in north-western Europe, which in two occasions (1988 and 2002) killed more than 20 000 individuals (Visser *et al.,* 1993; Härkönen *et al.,* 2006). The virus, a hitherto unrecognized morbillivirus, spread quickly and caused a high mortality. After the first outbreak, the harbour seals again became immunologically naïve, and thus susceptible for the new outbreak in 2002. This is an example of an infectious agent that may have an epizootic appearance, and have high pathogenicity and mortality when introduced to non-immune hosts.

Rabies virus (genus *Lyssavirus*) is usually described as able to infect all warm-blooded animals, and being lethal to the host, including humans if not vaccinated and treated by hyperimmune serum (Murphy *et al.,* 1991). However, in contrast to the textbooks, there is some evidence that rabies virus may not always be lethal to certain wildlife species. In Alaska, rabies antibodies were detected in a few Arctic foxes, but no virus was found in nervous tissue, which indicated that the animals were exposed to the virus but had survived and cleared the infection (Ballard *et al.,* 2001). In Serengeti, Tanzania, rabies virus RNA (13%) and antibodies against rabies (37%) were detected in a group of spotted hyenas (*Crocuta crocuta*) in which clinical rabies (disease) was never observed during the 13 years study period (East *et al.,* 2001). These examples indicate that the virus–host relationship may be more complex than assumed, even for rabies virus.

4.2.5. Diseases transmissible from animals to man (zoonoses)

Infectious diseases that are transmissible from animals to humans are called zoonoses. More than 60% of the emerging infectious diseases in humans that have been recorded globally since 1940 were zoonoses, and the majority of these (72%) originated in wildlife (Jones *et al.,* 2008).
In the Arctic, there is a close tie between native communities and wild animals, especially reindeer, caribou and marine mammals, both for nutrition and as an important part of the cultures of the human communities.

The most common zoonoses in Norway are transmitted indirectly through meat, vegetables (poorly washed) and drinking water (campylobacteriosis, salmonellosis, listeriosis, yersiniosis and enterohaemorrhagic colibacillosis). Other zoonotic agents are transferred through contact with animals or via vectors, such as ticks and mosquitoes. It is likely that climate change may affect the presence and distribution of zoonotic agents in Norway.

Toxoplasmosis (*Toxoplasma gondii*) was reported in Norway until 1995 with an annual incidence of 30-40 cases. In the Norwegian Arctic, any bird and mammal, including marine mammals (seals and whales), may potentially be infected by *T. gondii,* and recent serological screenings have shown that *T. gondii* is present in Arctic foxes (*Vulpes lagopus*; 43%), polar bears (*Ursus maritimus*; 76%), walrus (*Rosmarus rosmarus*) and barnacle geese (*Branta leucopsis*) from Svalbard (Prestrud *et al.,* 2007; Oksanen *et al.,* 2008), as well as in wild ruminants in Norway (Vikøren *et al.,* 2004). It is possible that climate change may change distribution patterns of terrestrial animals and migration routes of birds, which may have an impact on the infection biology of this parasite in northern regions.

The parasite causing trichinellosis (*Trichinella* sp.), no longer common in domestic pigs in Norway, occurs in wildlife carnivores like red fox, Arctic fox and polar bear, and has also been detected in walrus and some other seal species. In indigenous human populations with high prevalence of *Trichinella,* the source has mainly been ingestion of undercooked meat from polar bears, seals and beluga whales (*Delphinapterus leucas*) (Rausch, 1970). Screenings of a large number of harp seals (*Phoca groenlandica*) and hooded seals (*Cystophora cristata*) caught during Norwegian commercial sealing revealed no such parasites (Handeland *et al.,* 1995).

Brucellosis (*Brucella* sp.) is an infectious disease that, in addition to man, primarily affects cattle, sheep, goats, swine, horses and dogs, in which it usually causes abortions and infertility. Brucellosis also appears in a wide range of wildlife species, such as reindeer (*Rangifer tarandus tarandus*), caribou (*R.t. caribou*) and brown hare (*Lepus europaeus*). Since 1994, new *Brucella* species have been isolated from seals and whales from many oceans, including Norwegian waters (Clavareau *et al.,* 1998; Tryland *et al.,* 2005). The zoonotic impact of such infections in marine mammals is uncertain.

A wide range of infectious agents (parasites, bacteria, viruses) may be transferred by insect vectors, of which the tick *Ixodes ricinus* is the most important. Examples of tick borne zoonotic agents in Norway are the bacteria "*Borrelia burgdorferi* sensu lato" (a group of bacteria that can cause the disease borreliosis (Lyme disease) in dogs and humans), and the viral disease tick borne encephalitis (TBE). A total of 311 human cases of borreliosis was reported in Norway in 2006

(Folkehelseinstituttet: www.fhi.no) whereas TBE was for the first time diagnosed in 1997 (Skarpaas *et al.,* 2004), with 24 cases in the southernmost regions of Norway. Another tick-species, *Ixodes uria*e, known from Norwegian coast seabirds and capable of transmitting borreliosis (Olsén *et al.,* 1993), was recently reported in seabirds in the Arctic, possibly related to climate change (Larsson *et al.,* 2007).

4.3. Interaction between climate change and other factors affecting pathogens

Translocation of animals as well as the spread of invasive species, such as raccoon dog (*Nyctereutes procyonoides*), feral pigs (*Sus scrofa*) and king crab (*Paralithodes camtschaticus*) may carry pathogens to new host species and populations. Also seasonal migrations (birds, reindeer, marine mammals, fish) or migrations due to stress or food shortage, may contribute to the introduction of pathogens enzootic in these animals to new regions and to new host species and populations that are immunologically naïve. In addition to the presence of the infectious agent itself, other factors may also have impact on their distribution as well as their impact on the host species and populations. These factors may be pollution or other socioeconomic factors such as tourism or fisheries. However, such effects may only appear in certain combinations with other factors or only as long term effects, and identification and prediction of the impact of these factors on infectious agents and disease are complicated.

4.3.1. Pollution

Although regarded as remote and having little production or use of contaminants, the Arctic is exposed to pollutants through transport via rivers, sea currents and winds. Thus, changes of climate factors over time, such as the amount of sea ice, currents, temperature and precipitation, may influence the amounts and distribution patterns of contaminants in the Arctic. The potential impact of each contaminant, either singly or in combination with others, on plants and animals may thus change in the future. The most important of these contaminants are the persistent organic pollutants (POPs), heavy metals, oil spills and radioactivity (Jensson *et al.,* 2002).

4.3.1.1. Persistent organic pollutants

Several studies have indicated that a combination of biological and physical factors, such as bioaccumulation of lipid soluble contaminants in the food chain and their transport by winds, rivers and sea currents, concentrate persistent organic pollutants (POPs) in some species and at some specific locations in the Arctic more than in other regions. Such animal species are usually predators on the top of the food chains, such as seal species, polar bears, Arctic foxes and birds like the Norwegian Arctic glaucous gull (*Larus hyperboreus*). Polar bears in Svalbard were shown to have higher levels of organochlorines than polar bears in Greenland or Canada, and levels of hormones involved in reproduction may be affected by organochlorines (Oskam *et al.,* 2003; Ropstad *et al.,* 2006). It was also shown that such contaminants may have adverse effects on the immune system, in experimental animals and in polar bears and glacous gulls (AMAP, 1998; Sagerup *et al.,* 2000; Lie *et al.,* 2004), possibly resulting in impaired resistance to infections.

4.3.1.2. Other pollutants and radioactivity

Mercury, lead and cadmium are heavy metals that have been shown to have toxicological effects of both acute and chronic nature, and have been monitored in the Arctic for some time (AMAP, 1998; Jensson *et al.,* 2002). Since the concentrations in the environment usually do not change quickly, it is the long term effects that are of most interest. In contrast to POPs which accumulates in adipose tissues, heavy metals usually are concentrated in proteinaceous tissues. Although the environmental concentrations of mercury and lead have decreased during the last decades, they still represent possible health threats to Arctic life (Jensson *et al.*, 2002), and may have immunomodulatory effects (Dietert, 2008).

Blow-outs, spills and leakage from handling and transportation of petroleum represent the largest risks of oil pollution in the Arctic. Accidents, like with the tanker Exxon Valdez in Alaska in 1989 (35 000 tons) and the pipeline rupture in Usinsk, Russia, in 1994-95 (100 000 tons), show that these threats are real (AMAP, 1998). Land and sea based oil drilling and transport have increased in Arctic regions, including north-western Russia and the Barents Sea. The Arctic marine and terrestrial environments are especially vulnerable to oil spills, due to their low variety of species and long dark winters and short cold summers, which contribute to long term effects and a slow photo- and bio-degradation of oil hydrocarbons. Effects of oil may be direct toxicity through ingestion of oil with food (Geraci, 1990) or loss of insulation properties of hair and feather coats (Schmidt-Nielsen, 1997).

Most of the radioactivity that can be measured in the Arctic originates from nuclear testing programmes during 1945-1980, from the Chernobyl power plant accident in 1986 and particularly in the marine environment from nuclear fuel reprocessing plants. Also nuclear powered vessels represent important potential threats to marine ecosystems (Jensson *et al.,* 2002).

4.3.2. Other socio-economic driving forces

Global trading and travelling is perhaps the most powerful driver on transfer and introductions of infectious agents throughout the world. An increasing trade of animals, animal products, fruits, vegetables and flowers is not only contributing to the spread of infectious agents (Bernard *et al*., Anderson, 2006) but also the spread of possible biological vectors such as *Culicoides* sp. that may become established and may function as carriers and amplifiers of pathogens (Karesh *et al.,* 2005; Harrus *et al.,* 2005). The Arctic shipping activity is expected to increase, because of increased petroleum activity and the possibilities of opening new navigation routes due to sea ice retraction. In addition, tourism is rapidly increasing in the Norwegian Arctic (Svalbard). Ballast water from ships, sewage and transport of animal products to the region may introduce new organisms and potential pathogens. If they are able to cope with the local conditions and find suitable host species, they may establish in the Arctic fauna, and may also in some cases provoke disease in host populations immunologically naïve to the new variants of pathogens. Fisheries may also be a driving force for changes in the marine ecosystems, through changing the species diversity and population densities, which may interfere with the presence and impact of pathogens.

4.4. Key species of hosts and pathogens relevant for the Norwegian Arctic

For most Arctic wildlife animal species, the presence and impact of infectious agents is largely unknown, and restricted literature is available on the possible impact of climate change on Arctic fauna (Bradley *et al.,* 2005; Burek *et al.,* 2008). Table 1 lists some key host species and key pathogens of the Norwegian Arctic that may be important with regard to changes of distribution and impact due to climate change. A focus has been put on ecologically and/or economically important species, as well as species that already have been monitored over time with regard to population dynamics.

5. Effects of climate change on infectious diseases

Little data exist to evaluate the effects of climate change on infectious diseases of animals in the Norwegian Arctic. However, some data exist from other parts of the world (Khasnis *et al*., 2005; Epstein, 2001; Kutz *et al.,* 2005), and a recent report from the World Organization for Animal Health (OIE) addresses the impact of climate change on the epidemiology and control of animal diseases (OIE, 2008). If we see the same relationship between climate and disease in different parts of the world, it is reasonable to assume that they will hold also for the Norwegian Arctic. Here, we therefore first give a short review of general patterns found globally and use this to make predictions about general trends to be expected for the Norwegian Arctic, and then continue to discuss changes in more detail for terrestrial and marine ecosystems of this region.

5.1. Global patterns

When a pathogen is inside a warm–blooded host, it is not directly exposed to the temperature of the environment. When discussing the effect of temperature on pathogens, it is therefore useful to distinguish between the stages of the pathogen life cycle that occurs within a warm–blooded host, and the parts that occur outside. For example, bacteria and viruses are typically transmitted between warm–blooded hosts through air, soil and water and are exposed to environmental temperatures during these stages. Parasitic worms are transmitted by eggs or larvae that live at least some time in the environment, in water or in a cold–blooded intermediate host[1].

Pathogens of cold–blooded hosts, such as reptiles, fish, insects and zooplankton, are exposed to environmental temperatures throughout their entire life cycle. The only pathogens that live without direct contact with temperatures of the environment are those transmitted by close body contact between warm–blooded hosts, such as sexually transmitted diseases.

When exposed to the environment, some pathogens typically respond positively to increases in temperatures. This means that, within certain limits, pathogens tend to grow faster, survive better and/or transmit faster when temperature increases. In these circumstances, pathogens may therefore be able to survive in areas that were previously too cold. This means that climate change could create conditions favourable for animal diseases will tend to cause diseases of animals in temperate and Arctic regions of the northern hemisphere to acquire a more northerly distribution.

It is important to note that several factors other than temperature typically influence where a pathogen can live. We should therefore not expect simple relationships between temperature increases and distribution shifts towards the north. For example, host population density has to be high enough for a pathogen to get established in a new area, and for pathogens with indirect life cycles, intermediate host species have to be present in sufficient numbers. Some pathogen species may therefore move only a little northwards as a consequence of climate change and increased temperatures. However, for other species, effects may be large. For example, if an intermediate host has a huge leap in distribution towards the north, the pathogen may have a similar large shift.

To summarize, the prediction for the NorACIA area is therefore that pathogens will tend to acquire a more northerly distribution, and that the response for each pathogen species will vary from no response to possible large responses. This is supported, directly or indirectly, by large amounts of data from various parts of the world, and should be considered a robust prediction (for recent summaries of data, see Marcogliese, 2001; Harvell *et al.*, 2002; Parkinson *et al.*, 2005). Because pathogens typically respond positively to environmental temperature, one might also Substantial warming of the climate will cause large changes in natural ecosystems. In addition to direct effects on pathogens discussed above, infectious organisms may be affected indirectly. For example, if the density of a host population is changed as a result of climate change, prevalence/ abundance and persistence of pathogens may be affected indirectly. Such indirect effects may to a certain extent be possible to predict. Other indirect effects may go through several species and involve larger parts of the food web. For example, climate change may affect a prey species, causing a change in density of one of its predators, in turn affecting the pathogens of the predator. At the same time, changes caused by climate change in other parts of the food web may interact with these effects. Such indirect effects, involving large numbers of species, are to a large extent unpredictable (Yodzis, 2000).

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[1] *Trichinella* sp. and other parasites that are transmitted when a host is eaten by another host are possible exceptions to this. This may, however, include scavenging, and therefore the parasites may be exposed to environmental temperatures.

Table 1. Key species of hosts and pathogens relevant for the Norwegian Arctic with regard to possible effects of climate change.

Key host species	Key pathogen	Important characteristics
FISH		
Cod	*Anisakis simplex*	Infective to humans via under-cooked fish
	Francisella philomiragia subsp. *noatunensis*	Emerging pathogen in farmed cod
	Cryptocotyle lingua	Subcutaneous black spots cause spoilage in fish flesh, favoured by warmer temperatures
	Lernaeocera branchialis	Blood-feeding parasitic copepod considered to be the most pathogenic metazoan parasite of cod
Capelin	*Eubothrium parvum*	Heavy infections of this tapeworm may lead to obstruction of the intestine
	Trichodina spp.	Motile ectoparasitic protozoans causing epithelium damage and mortalities in heavy infections, especially in stressed fish
	Gyrodactylids (*Gyrodactyloides andriaschewi* and *G. petruschewskii*)	Motile viviparous monogeneans causing epithelium damage and mortalities in heavy infections, especially in stressed fish; often found in mixed infections with *Trichodina* sp.
Herring	Gyrodactylids	See above; more than 10 species have been reported in herring
	Goussia clupearum	Protozoan causing extensive liver pathology
	Eimeria sardinae	Protozoan infecting the testes, resulting in extensive pathology and sterility
	Kudoa clupeidae	Myxosporean infecting muscles, heavy infections have caused mortalities of young herring, favoured by warmer temperatures
Salmon	*Anisakis simplex*	Infective to humans via under-cooked fish
	Proliferative kidney disease (PKD)	Caused by the parasite *Tetracapsuloides bryosalmonae*, distribution unknown, disease associated with high water temperatures (rivers)
	Aeromonas salmonicida	Cause the disease furunculosis, also infecting cod
	Vibrio salmonicida	A psychrophilic bacterium causing cold-water vibriosis in Atlantic salmon, rainbow trout and cod
	Infectious pancreas necrosis virus	Major problem in the fish farming industry
BIRDS		
Goose	*Toxoplasma gondii*	Zoonosis
	Avian influenza virus	Zoonotic potential through viral recombination
	Mycobacteria (*M. avium*)	Common in the environment, primarily affects birds, but also mammals including humans, particularly children and AIDS patients
	Paramyxovirus (Newcastle disease virus)	Possible transmission to poultry
Gull	*Toxoplasma gondii*	Zoonosis
	Salmonella sp.	Zoonotic potential (i.e. drinking water reservoirs)
	Paramyxovirus (Newcastle disease virus)	Potential transmission between poultry and wild birds
	Aspergillus (*A. fumigatus, A. flavus, A. niger*)	Zoonotic potential; opportunistic infection, may cause severe respiratory distress
Ptarmigan *Lagopus lagopus* *Lagopus mutus* *Lagopus muta*	*Trichostrongylus tenuis, Ascaris compar*	Nematodes that are common and may affect survival and reproduction
	Eimeria sp.	Common coccidian parasite
	Avian influenza virus	Zoonotic potential through viral recombination
	Louping ill virus	Tick borne, high mortality in ptarmigan (UK), zoonosis
MAMMALS		
Reindeer	*Ostertagia gruehneri, Setaria tundra, Onchocerca tarsicola*	Calf mortality, peritonitis, periarthritis and granulomas (resp.), reduced food intake and growth
	Hypoderma tarandi, Cephenemyia trompe	Hypodermal and throat infection, respectively
	Pasteurella multocida, Mannheimia haemolytica.	Respiratory disease, haemorrhagic septicaemia
	Peristent virus infections (Alpha- and gammaherpesvirus, pestivirus, parapoxvirus)	Abortion, weak born calves, lesions (skin, mucous membranes)
Polar bear	*Toxoplasma gondii*	Common and prevalent, zoonosis (under-cooked meat)
	Trichinella (*T. spiralis, T. native*)	Common and prevalent, zoonosis (under-cooked meat)
	Giardia sp.	Zoonotic potential
Arctic fox	*Echinococcus* (*E. multilocularis*)	Zoonosis.Arctic fox is main host
	Toxoplasma gondii	Common and prevalent
	Trichinella nativa	Zoonosis
	Rabies virus	Zoonosis (bites), probably endemic status in Svalbard
Seals: Harbour seal Ringed seal Hooded seal Harp seal Walrus	Nematodes	Commonly found in seals
	Brucella pinnipedialis	Zoonotic potential. Commonly isolated from hooded seals, may have an impact on reproductive success
	Morbillivirus	Epizootic outbreaks with high mortality in harbour seals, other seal species may be less susceptible to disease
	Phocine herpesvirus 1	Generalized infection (neonates), respiratory and other symptoms
	Influenza virus	Respiratory infection, generalized infection (young)

5.2. Effects on marine and freshwater systems in the Norwegian Arctic

A pathogen that occurs close to the NorACIA area and that will likely move northwards as a consequence of climate change is the bacterial cod pathogen *Francisella philomiragia* subsp. *noatunensis* subsp.novo (Mikalsen *et al.,* 2007; Olsen *et al.,* 2006). This bacterium causes severe systemic disease in farmed cod and makes cod farming difficult in areas where the bacterium is present. The pathogen is currently limited to waters south of Stadt, thus limiting cod aquaculture to north of Stadt. In a warmer climate, this pathogen will likely move northwards, making larger parts of the Norwegian coast unsuitable for cod farming. However, measurements such as vaccines may change this situation.

The infective cercarial stages of the digenean (fluke) parasite *Cryptocotyle lingua* emerge from the mollusc host only when the water temperature rises above about 10˚C (Sindermann *et al*., 1954). Increasing water temperatures in the NorACIA area therefore mean that this parasite is likely to extend its distribution northwards, with potentially serious consequences for mariculture, particularly of cod. *C. lingua* is the causative agent of “black spot” disease, resulting in spoilage which renders the flesh unmarketable. Temperature is also considered to be the key factor limiting the distribution of the herring pathogen *Kudoa clupeidae* to the southernmost parts of the range of herring (Sindermann, 1957). It too is likely to move northwards with increasing sea temperatures. The distributions of many marine digeneans depend on the distributions of their mollusc first intermediate hosts, to which they are usually highly host-specific. The distributions of many marine molluscs are temperature-dependent and the distributions of their digeneans are therefore likely to follow those of their mollusc hosts.

The myxozoan parasite *Tetracapsuloides bryosalmonae* is a parasite of both freshwater Bryozoans and the freshwater stages of salmonids. The parasite is widespread in freshwater locations throughout Norway, but typically causes clinical disease only if the temperature remains higher than approximately 14˚ C for prolonged periods. The disease is called proliferative kidney disease (PKD). In recent years this parasite has been associated with severe decline in salmonid populations in England and Switzerland (Feist *et al.,* 2002; Wahli *et al.,* 2002). It is also associated with severe disease and decline in parr populations in at least two Norwegian rivers (Forseth *et al.,* 2007; Sterud *et al.,* 2007). It is to be expected that further temperature increments will favour the occurrence of clinical PKD in juvenile salmonids within the NorACIA area.

Viruses and bacteria of marine mammals are obvious candidates for distribution shifts towards the north, as generally predicted for the marine ecosystems. We may therefore see new such pathogens in marine mammals in the NorACIA area. However, to detect changes in marine mammal health related to climate change, baseline data on histology/pathology, haematology and serum biochemistry are needed, from which change can be evaluated. Numerous reports are available that document concentrations of contaminants for whales, seals and polar bears, but very few data are available evaluating the direct effects of these contaminants on marine mammals or on subsistence consumers, as well as the indirect effects on immunology and infectious disease epidemiology in Arctic marine mammals. Climate influences pathogen distribution, and weather influences the timing of disease outbreaks. Data on the influence of climate on bacterial diseases of marine mammals are lacking. However, the changing epidemiology of *Vibrio* species, a marine group of bacteria infecting a range of animals including humans and marine mammals, may serve as a model according to which changes in distribution of other bacteria may be predicted (see 4.2.3.).

Climate change may cause substantial changes in marine ecosystems in the NorACIA area. This has recently been evaluated for the Barents Sea (Loeng, 2008). In the report it is concluded that warming will cause large numbers of boreal species to become established in the Barents Sea. It is reasonable to assume that a significant portion of the pathogens of these species will follow into the Barents Sea. Among these pathogens, those with a broad host specificity may infect already established Arctic species.

In the Barents Sea, climate change may cause mismatch of prey–predator interactions that are synchronized today (Loeng, 2008). If so, pathogens transmitted through such interaction may experience substantially lower transmission rates, giving lower infection levels.

The amount of sea ice has been reduced substantially in the Arctic during the last decades. In a warmer climate, this trend is expected to continue. For species that haul out on ice, fewer suitable haul-outs could increase haul-out densities, increasing transmission rates. Changes in haul-out patterns may also increase risk of contact between marine mammals and terrestrial mammals harbouring pathogens to which the former are susceptible but rarely exposed. In the Beaufort Sea region of northern Alaska (Fischbach *et al.*, 2007) and in the Chukchi Sea region of eastern Siberia (Kochnev, 2006), increasing numbers of polar bears are remaining on land in summer and early autumn in years with little sea ice close to the shore. Because these coastal regions are already occupied by grizzly bears, this more regular co-occurrence could increase the likelihood of disease transmission between these two closely related but normally spatially separated species.

Infectious disease outbreaks can occur when carrier animals in which the pathogen is generally "non-pathogenic" come in contact with a susceptible host species in which clinical disease occurs. During the morbillivirus outbreaks in seals in north-western Europe, migrating Arctic and subarctic seal species, such as harp seals (*Phoca groenlandicus)* from Greenland or gray seals (*Halichoerus grypus*) may have been carriers that introduced a morbillivirus into immunologically naïve harbor seals (*Phoca vitulina*) (see 4.2.4.). If northern expansion of subarctic species occurred into the Arctic regions due to changes in air and water temperatures, there would be the potential for contact between carrier and naive host species.

Food depletion and stress are well-known causes of immune suppression in humans, laboratory rodents, and terrestrial mammals. Although the effects of food depletion and stress on marine mammal immune responses have not been well investigated, the few data available suggest marine mammal immunity is affected by factors similar to those affecting terrestrial mammals (Sagerup *et al.*, 2000; Lie *et al.*, 2004). These changes in immune function may increase host susceptibility to endemic pathogens, thus increasing the prevalence of diseased individuals in these populations.

A number of other changes in pathogen distribution and infection levels may occur as indirect effects of other trophic changes caused by climate change in the Barents Sea. As discussed above, these may to a large extent be unpredictable. For fish and marine mammals, migration routes, seasonal or connected to search for food, may change, due to changes in currents, temperatures or prevalence of prey.

5.3 Effects on terrestrial systems in the Norwegian Arctic

To explore the impacts of climate change on host–parasite systems in the Arctic, the ecology of an important protostrongylid lung-dwelling nematode, *Umingmakstrongylus pallikuukensis*, in muskoxen from the Canadian Arctic was investigated. Retrospective analysis for *U. pallikuukensis* suggests that, as a result of climate change, development of infective larvae has already shifted from a two year cycle to a predominantly one year cycle. These infective larvae emerge from the gastropod intermediate host and are free in the environment. Should these one year cycles become typical of the future, this will extend the window of availability of infective larvae in slugs, thereby augmenting the numbers of infective larvae available and possibly leading to increased intensity of infection in muskoxen, with adverse effects on their fecundity and survival. This is consistent with overall climate change predictions for amplification of parasite populations through increased rates of development, reduction in generation times, and broadened seasonal windows for transmission. The *U. pallikuukensis* model quantifies the effects of climate on critical life history stages of a nematode parasite, and explores responses of host–parasite assemblages to climate change. Although the potential for protostrongylids to cause disease in individual hosts is apparent, but unequivocal evidence linking infection to declines in population health, numbers or both remains to be demonstrated (Kutz *et al.*, 2005).

It is possible that changes in temperature, humidity, precipitation patterns etc., as indicated for the musk ox, may have substantial impact on presence and load of parasites and other infectious agents also for other terrestrial animals (Kutz *et al.*, 2005). The recently reported impact of the nematode parasite *Setaria tundra* in semi-domesticated reindeer in Finland (Laaksonen *et al.*, 2007) indicates that the biology of parasites transmitted by insect vectors may change. Also with regard to food availability for reindeer, warmer and wetter weather may increase episodes of a combination of snow, rain and shifting temperatures, creating ice covers that make the winter pastures unavailable for the animals. This may have dramatic effects on the energy balance for reindeer, especially during late winter and spring, when a sum of conditions, such as parasite burdens, handling and transport to summer pastures, predators as well as pregnancy for females, appear in the same period as the animals normally are in a negative energy balance. This may also have implications for the reproduction and survival rates of calves (Weladji *et al.*, 2003), and may indirectly also affect the immune system and the ability to handle infections, such as persistent viral infections.

In a longer perspective, climate change may lead to permanent changes of vegetation, which may increase the summer period and the availability of summer pasture, but may also have impact on the abundance of lichen, which reindeer to various extents are dependent on as winter pasture. Supplemental feeding of semi-domesticated reindeer in winter is not as common in Norway yet as in Sweden and Finland, but increased corralling and feeding of animals will increase the contact between animals and increase the general infection pressure for viruses and bacteria. Also, parasites in particular, may have better opportunities when the same land areas are used for reindeer for increased periods of time, as commonly known for pastures for domestic animals (Moen, 2008).

Climate change may also change migration patterns of birds, reindeer and other terrestrial animals in the NorACIA area. Birds may be particularly important from a human health perspective, because they can transport important zoonotic pathogens, such as avian flu, over large distances. Changes in bird migration patterns may thus alter such transport.

6. Conclusions

A northwards shift in the distribution of pathogens may be a valid prediction for both aquatic and terrestrial ecosystems. Further, it seems likely that we may see direct effects of climate change on survival of pathogens, and also on interactions between climate factors and other drivers and stressors, which may lead to indirect effects. Such changes may be combinations of many factors and may only be detectable over a long time scale. Thus, studies to address such effects may be extremely complicated to conduct.

Very few empirical studies directly explore the relationship between climate and transmission of or resistance to disease, and even fewer explore interactions between temperature and components of a pathogen’s life cycle. The numerous mechanisms linking climate change and disease spread support the hypothesis that climate change is contributing to ongoing range expansions, although there may be few unequivocal examples of natural changes in severity or prevalence resulting from directional climate change per se.

Given the challenge of linking disease impacts and directional climate change for well studied agricultural, maricultural, and human diseases, it is not yet possible to predict the consequences for biodiversity.

6.1. Consequences of pathogen changes for biodiversity and society

The effects that can be predicted with least uncertainty are for aquaculture. As outlined above, the southern limit for where it is possible to farm cod is likely to move northwards, although measurements such as vaccines etc. may change this situation.

For biodiversity in general, there will likely be effects, but it is harder to predict what these may be. If keystone species, such as for example capelin, herring and cod are affected, the consequences may be large. For example, if capelin acquires new pathogen species or existing diseases become more prevalent, a possible scenario may be that population dynamics of this important species is affected. If so, this may have large consequences for herring, cod, several species of sea birds and a number of other species in the Barents Sea ecosystem, for which capelin is a major food source.

For marine mammals, the possible effects of new infectious agents and diseases through altered distribution pattern and susceptibility (host) or pathogenicity (infectious agent) may be a different disease pattern. For native communities dependent on marine mammals, such changes may have impact on human health, although such effects may not be crucial in the Norwegian NorACIA area due to restricted dependency on consumption of marine mammals.

6.2. Policy and management implications

6.2.1. Increasing awareness of new pathogens

New diagnostic techniques, including molecular biological tools, have made it easier to address infectious agents in animals and man. The amount of reference data is increasing, but it is still evident that such data for wildlife are scarce. It will be difficult to address changes in the future, if such data are not available. It is therefore necessary to address the presence of infectious agents and their possible impact, on individuals, populations, ecosystems and as potential zoonoses, in wildlife species in the Norwegian Arctic. Increased awareness of emerging pathogens is also necessary to understand the underlying infection biology mechanisms, and to predict epizootics. During and after a disease outbreak, background and baseline data on the host and pathogen in question would be extremely valuable tools.

6.2.2. Wildlife–domestic animal–human interface

The areas of the Norwegian Arctic untouched by humans ("villmark") are shrinking, and the contact between animals and man increases, both through wildlife being "trapped" between infrastructure (roads, pipelines etc.), through increased tourism and through hunting. For the hunting season 2006-07, approximately 35 000 moose (*Alces alces*), 29 000 deer (*Cervus elaphus*), 25 000 roe deer (*Capreolus capreolus*), 5 000 wild reindeer and 312 000 ptarmigans (*Lagopus* sp.) were killed and presumably consumed in Norway. For the semi-domestic reindeer, a total of 77 100 animals were slaughtered in 2006-07. Wild animals, semi-domesticated reindeer and domestic animals may have contact with each other by exploiting the same pastures and waters and being a part of common ecosystems, facilitating the transmission of infectious agents. The need for documentation of a national "free-of" status with regard to certain infectious agents, such as *Brucella* sp., *Mycobacterium* sp. and prion disease etc., contributes to an increased focus on the interface between wildlife, domestic animals and humans in the future.

6.2.3. Fish in aquaculture versus natural environment

Fish farming is a fast-growing industry and there is pressure from the industry to move more aquaculture operations further north. One of the implications of this is that the interface between farmed fish and wild fish within the NorACIA area will increase and thereby facilitate the possible exchange of pathogens between wild and farmed fish. Detailed mapping, characterization and classification of possible sites should therefore be undertaken prior to giving permissions for farming in the North. Size of operations, their location and species to be farmed should be carefully evaluated.

6.2.4 Ecosystem based management

The ecosystem approach to management should be based on extensive knowledge about the ecosystem to be managed. Ideally, we should have a fairly good picture of what the combined effects of various anthropogenic activities on the system might be. This report shows that humans may affect pathogen dynamics through climate change as well as through other types of activities/impact, such as pollution and fisheries. Because pathogens may have huge impacts on ecological interactions (such as predator–prey relationships) and even on the structure of entire ecosystems (see 4.2), pathogens therefore clearly need to be considered in ecosystem based management.

7. The way forward: Research needs

Through the workshop and the work on this report, and based on available knowledge in the field, three specific priorities for research have been identified to improve our ability to predict impacts of climate change on disease in the NorACIA region:

1. Collection of baseline data on health parameters, as well as on distribution, epidemiology and effects of pathogens and diseases in wild animal populations.
2. Studies that are focused on separating the effects of different climate variables on the dynamics of pathogens and disease in animals and humans.
3. Forecasting temporal and spatial effects of climate change on pathogen and host populations.

As the interactions between climate factors and other drivers on pathogens are complex, it will be a huge challenge to design and conduct investigations to better understand the effects of climate change on infectious diseases, and its interactions with the presence of multiple pathogens, nutrition factors, stress, pollution and other environmental factors.

It is important that such scientific investigations benefit from interdisciplinarity through collaborations between ecologists and infectious diseases biologists. Investigations should focus on key host species and key pathogens in given ecosystems (aquatic and terrestrial), and should include screenings and epidemiological studies (retrospective and real time), case studies, dynamic food-web modelling and experimental studies.

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