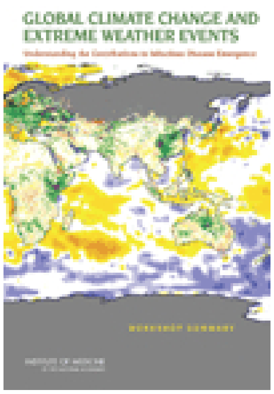

Global Climate Change and Extreme Weather Events: Understanding the Contributions to Infectious Disease Emergence: Workshop Summary

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caused the death of millions of people. The emergence of new pathogens and the increased connectivity of native populations also appear to explain much of the temporal and spatial patterns of famine and epidemic disease in colonial Mexico. To some degree, the globalization of the modern world resembles the colonization of Mexico in the sixteenth to eighteenth centuries. The increased connectivity of populations and the emergence of aerosol-borne pathogens have proven to be a dangerous combination. New roads and trade leveraged the impact of measles and smallpox in colonial Mexico, as globalization has leveraged SARS and influenza in recent times.

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WILDLIFE HEALTH AS AN INDICATOR OF CLIMATE CHANGE

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Introduction

The changes in climate we are experiencing as global warming and disturbance in precipitation regimes (IPCC, 2001) are having an impact on the health of wild animals, with resulting deleterious impacts on major human interests. In this paper, we review the relationship between climate change and wildlife health and argue that monitoring wildlife health provides an effective and sensitive indicator and predictor of climate-related emerging infectious diseases.

[7]Global Health Programs.

Effects of Climate Change on Wildlife Health

After a long period of neglect, pathogens have recently been suggested as important drivers of host population dynamics (Hudson et al., 1998; Tompkins and Begon, 1999). At the same time, disease has been implicated in major wildlife population declines (Pounds et al., 2006; Roelke-Parker et al., 1996). Wildlife health, therefore, is an important factor for population sustainability and system resilience and, hence, is drawing conservation attention. Because most human emerging infectious diseases originate from a wildlife reservoir (Jones et al., 2008), wildlife health is critically linked to public health. Wildlife species may serve as an early warning for some diseases, as is the case for howler monkeys and yellow fever in South America (Rawlins et al., 1990) or great apes and Ebola hemorrhagic fever in central Africa (Karesh and Reed, 2005). In addition, due to the flux of pathogens occurring at the wildlife-livestock interface, wildlife health is also important for domestic animal health.

Suggested Mechanisms

Climate change may affect wildlife health in several ways because the determinants of disease incidence are numerous and specific to the disease in question and climate change may influence each of these factors. Moreover, the direct and indirect impacts of climate change on host-pathogen interactions might favor some host species because they could release hosts from the population control exerted by pathogens by interfering with the precise conditions required for pathogen viability (either directly or indirectly; i.e., changes in vector abundance) and shift host population regulation to other factors, such as food or other resource availability. It is important to recognize that the components of a dynamically functioning ecosystem are interconnected; thus, the influence of climate change on animal distribution, abundance, or demography via infectious disease may be indirect due to shifts in relationships such as competitive advantages among conspecifics, predator-prey dynamics, and so forth.

In the interests of simplification, we propose that climate change may directly modify the patterns of infectious disease basically in two ways:

1. Favoring pathogens (increasing pathogen and/or vector proliferation, or pathogen and/or vector survivability)
2. Increasing the host's susceptibility to infection

Climate Change Favoring Pathogens and Their Vectors

Changes in climate shift the relationship among pathogen, host, and the environment. Focusing first on the pathogen, we know that climatic conditions play a significant role in the geographic and temporal distribution of pathogens and, as appropriate, their vectors. Environmental conditions also affect the viability and reproductive success of both pathogens and vectors, which can be thought of as the nonhost components of severity of infection.

Changes in distribution and seasonality It is known that, within limits, arthropod populations are favored by heat and moisture. Therefore, we anticipate that climate change will influence vector-borne diseases. In fact, a number of vector-borne human and domestic animal diseases have increased in incidence or geographic range in recent decades (e.g., malaria, African trypanosomiasis, tick-borne encephalitis, yellow fever, plague, dengue, African horse sickness, bluetongue) (Harvell et al., 2002). These changes have been or can be identified because the diseases are important for public health or domestic animals, and hence records to detect their occurrence currently exist in many cases. It is close to impossible to know if vector-borne diseases are changing in wildlife unless more widespread, systematic monitoring is put into place.

A large body of research has been conducted to attempt to predict the expansion of vector-borne diseases due to climate change. Largely, these efforts involve modeling. For example, a study addressed how climatic variables determined the abundance of *Ixodes scapularis* (the tick that transmits Lyme disease) and ehrlichiosis and babesiosis in eastern North America (Ogden et al., 2005). The authors used current knowledge of tick biology, originating from empirical and experimental data, to construct a theoretical model that predicted the abundance of ticks based on the climatic and seasonal variables they had measured. In a subsequent study, they used this model to simulate the expansion of tick distribution under two projected climate change scenarios, predicting a substantial northward movement of tick range (Ogden et al., 2006). These examples support the basic concept that climate change is expected to influence the geographic range of vectors and their transmitted diseases.

A similar situation may be observed for pathogens affecting ectothermic (cold-blooded) hosts or those that proliferate outside affected individuals, because the pathogens are more exposed to ambient temperature as opposed to those having a life cycle that is completed almost entirely inside a host that preserves a constant temperature (endothermic). A rise in average temperature may not only affect the proliferation of the pathogen, but also have the potential to modify the seasonality of the disease—which could occur earlier every year—and remain infective or active for a longer period of time (Harvell et al., 2002).

Harmful algal blooms (HABs), also known as "red tides," are events in which single-celled protists (dinoflagellates) proliferate rapidly and accumulate in the water column. These events are associated with wildlife mortalities because under certain circumstances these organisms can produce potent toxins. A systematic increase in seawater temperature may contribute to the occurrence of HABs (Juhl, 2005). For example, the Wildlife Conservation Society investigated an episode of mass bird die-off in the Malvinas-Falkland Islands in which high levels of toxins produced by these dinoflagellates were detected in sick or dead gentoo penguins as well as in the marine prey species found in the digestive tracts of affected animals (Uhart et al., 2004). This was the first report of paralytic shellfish poisoning affecting seabirds in the southwest Atlantic, which might suggest that climate change is aiding the expansion of this type of disease to more extreme latitudes.

Increased severity of disease An increased intensity of parasitism or severity of infection may also result from favorable conditions for pathogens. In the St. Kilda archipelago of Scotland, for example, feral populations of Soay sheep experience periodic mass mortalities (Coulson et al., 2001). Although the proximate cause of death has been determined to be protein-energy malnutrition, parasites have been implicated as a contributory factor (Grenfell et al., 1995). At first observation, the depth of the population crashes was critically dependent on the weather, and large numbers of trichostrongylid[8] nematodes were found in dead animals. An experimental study showed that the administration of antihelminthic therapy reduced mortality considerably (Gulland et al., 1993), which supported the link between parasites and death. Trychostrongylids have a life cycle that involves several stages outside their hosts, making them highly vulnerable to environmental conditions. In particular, larvae are very susceptible to desiccation, so humidity and precipitation regimes are crucial for their survival outside their hosts (Wharton, 1982). The emerging scenario would be that increased precipitation would allow for increased larval survival, which in turn would lead to higher parasite burdens, contributing to elevated mortality.

Climate Change Increasing Host's Susceptibility to Infection

As mentioned, changes in climate shift the relationship among pathogen, host, and the environment. Focusing on the hosts, we know that climatic conditions can affect their behavior and hence susceptibility to infectious organisms due to change in exposure or contact rates. While genetics provides a framework, host immunity or disease resistance is also dependent on physiologic mechanisms affected by environmental conditions. The impact of changes in climate can occur at a rate more rapid than a host's ability to adapt.

Increased exposure to pathogens One way in which climate change can result in an increased susceptibility to infection is by inducing changes in host behavior, which may determine increased exposure to pathogens. While some parts of the world are projected to become more moist, others are projected to become drier (IPCC, 2001). On the Patagonian Steppe, for example, water supplies are threatened (Barros et al., 2000). As a result, the concentration of individuals

[8] A common parasitic gastrointestinal nematode found in many ungulate species.

around water resources may grow, thereby increasing intraspecific interaction and indirect contact rates, and possibly shifting density-dependent infectious disease relationships. Since water supplies are frequently shared among wildlife and domestic animals, these alterations may increase the risk of pathogen exchange at the wildlife-livestock interface.

Another example of the way in which climate change may result in increased susceptibility to infection is its impact on feeding behavior. For instance, the reduction in sea ice is causing a change in the behavior and diet of walruses, which are becoming more pelagic and are preying more on ringed seals (a carnivore) and less on invertebrates. This, in turn, may increase the prevalence of trichinellosis in walruses (Rausch et al., 2007). Finally, climate change may determine that some vertebrate hosts expand their distribution, and thus expose immunologically naïve species to their pathogens and nonpathogenic commensal organisms, as well as expose themselves to new pathogens. For example, tropical deglaciation is causing an increase in the elevational limit of some anurans, which have taken with them the agent of chytridiomycosis (*Batrachochytrium dendrobatidis*) to unprecedented altitudes (Seimon et al., 2007).

Decreased host resistance The susceptibility of hosts may also increase if their intrinsic vulnerability to disease is affected. For many species, climate change will serve as an additional form of stress. The effect of stress on vertebrates is well known: a cascade of neuroendocrine mechanisms triggered by stress resulting in a reduction in immune function (Lochmiller and Dabbert, 1993). Since wild species usually live on tight energy budgets (Beldomenico et al., in press), a number of physiological functions compete for these limited resources. An increased demand by one system results in fewer resources for the rest. If climate change causes resources to become more scarce, or of poor quality, or if other physiological systems increase their demands (reproduction, molting, migration, etc.), then the share left for immunological investment will be reduced.

A recent study on rodents demonstrates that poor body condition predisposes individuals to a variety of infections, and these infections further decrease the condition of individuals, triggering a "vicious cycle" that eventually ends up in death and, therefore, population declines (Beldomenico et al., 2008). Thus, maintaining good body condition is important to reducing infection, and avoiding infection is essential to maintaining good condition. If climate change-induced food resource limitations or stress impoverish the condition of many individuals in a population, this type of infection-declining condition cycle may be triggered and the population will fail.

Amphibians are particularly sensitive to climate disturbance. In the last three decades, thousands of species have experienced population declines worldwide and more than 100 have disappeared (Stuart et al., 2004), many of them in seemingly undisturbed environments. The chytrid fungus *B. dendrobatidis* has been implicated in many of these amphibian population crashes (Berger et al., 1998;

Weldon et al., 2004); however, amphibians have also been declining in regions where the fungus is absent, and the fungus has been found in places with no affected frogs (Di Rosa et al., 2007). In declining populations where the chytrid fungus was not present, other pathogens were found at high prevalences, namely, *Saprolegnia ferax* (Kiesecker et al., 2001), *Amphibiocystidium ranae* (Di Rosa et al., 2007), ranaviral disease (Bollinger et al., 1999), and metazoan parasites (García et al., 2007).

Amphibian declines have been correlated with climatic change, and a hypothesis for climate-driven epidemics arising from climate favoring pathogens differentially over hosts has been proposed to explain amphibian declines (Pounds et al., 2006). However, the vicious cycle hypothesis (Beldomenico et al., 2008) may also be a satisfactory explanation. Reading (2007) presents evidence that environmental warming negatively affects the body condition of toads. Alford et al. (2007) observed that frog population declines are preceded by an increase in indicators of stress. The emerging vicious cycle hypothesis proposes that climate disturbance is affecting the condition of amphibians, which predisposes them to more frequent infections and/or infections of increased severity, which triggers a vicious cycle with the potential to cause amphibian population declines. Thus, while the synergy between poor condition and infection may be a proximate cause of these declines, the ultimate cause would be a condition impoverished by climatic changes.

In summary, there are multiple mechanisms by which climate change could affect wildlife health including, but not limited to, the following:

- Expansion in the geographic distribution of pathogens, vectors, or hosts
- Changes in the seasonality of some diseases
- Increased severity of disease
- Increased exposure to pathogens
- Decreased host immunity

All may result in a disruption of population and system health dynamics. Thus, independent of mechanism, monitoring the health of wildlife populations provides a sensitive and quantitative method to detect changes and serve as an early warning system.

One subject in need of further investigation is the relationship between evolution and an organism's ability to adapt to these rapid changes. It is possible that genetic shifts will modulate local effects of climate change. However, there is little evidence that evolution will mitigate negative effects of climate change at the species level (Parmesan, 2006). Moreover, it should be considered that the speed of evolution is different among different taxa. Bacteria and viruses, for example, have the capacity to evolve rapidly, adapting to environmental changes before their hosts. This might result in a differential adaptation favoring pathogens and inadvertently causing host population declines or extinctions.

Summary

Many studies have shown that climate change can influence the dynamics of wildlife diseases. The question is: Can this relationship be utilized to monitor the ecological effects of climate change and to predict and prevent the emergence of new diseases threatening wildlife, livestock, and human health? We argue that in the context of health and climate change, monitoring wildlife health is of direct relevance for several reasons. First, the emergence of human and livestock diseases is closely tied to wildlife health (Jones et al., 2008; Karesh and Cook, 2005). As a result, detection of climate-related emergence of disease in wildlife populations provides an early warning of system disturbance and, thus, potential human and domestic animal health concerns (early-warning capability being the useful feature of any indicator of ecological change [Carignan and Villard, 2002]). Second, the range of population turnover times in hosts and wildlife pathogens, from short generation times in bacterial and viral pathogens to relatively longer generation times in helminths and other parasites, and even decades in some hosts, provides an opportunity to evaluate change at a variety of temporal scales. Third, for some wildlife populations—particularly hunted or managed populations—good long-term baseline health data exist. Consequently, we know the range of what is normal and can more easily determine what is abnormal or different. Finally, and most relevant to this discussion, as "system integrators," the health of wild animals is tuned to a set range of natural variation and, therefore, provides a sensitive indicator of change.

USE OF CLIMATE VARIATION IN VECTOR-BORNE DISEASE DECISION SUPPORT SYSTEMS

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Introduction

Vector-borne pathogen transmission cycles minimally consist of an arthropod vector, a vertebrate host, and a pathogen, but many are zoonotic and transmitted among a complex array of vectors and vertebrate hosts (e.g., West Nile virus; see Figure 3-2). For most zoonotic arboviruses, transmission to humans and to

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