Environmental Change & Infectious Diseases

JANEY MESSINA, EXPERT – INFECTIOUS DISEASES

8–9 February 2018

The ROCKEFELLER FOUNDATION

OXFORDMARTIN SCHOOL

Rockefeller Foundation Economic Council on Planetary Health
at the Oxford Martin School

Introduction

Since the 1940s, more than 335 infectious diseases have emerged globally[1], 60 to 80 percent of which have originated in animals[2]. Although emergent diseases have caused deadly pandemics for millennia, these figures raise questions as to why zoonotic disease transmission to humans, and the often deadly pandemics which follow, have become the norm. Many factors are to blame, and while rapid and ongoing vaccine development and the strengthening of health systems are necessary channels for tackling the global spread of infectious diseases, we must also urgently address the conditions that allow for diseases to emerge or re-emerge in the first place. Crucially, environmental change and degradation have resulted in the disruption of the natural habitats of many animals. These disruptions mean that barriers between humans, animals, and the pathogens they carry are weakened. In other words, failure to prevent ongoing climate change, deforestation, and degradation of natural ecosystems will lead to a continued regularity of infectious disease outbreaks in humans. This paper outlines four modes of infectious disease transmission and emphasizes several types of environmental change which continue to fuel global disease emergence.

Infectious Disease Transmission

Four Main Types of Transmission

While it is essential to identify the type of pathogen responsible for an infection (e.g. virus, bacteria, protozoa), identifying the source of infection is fundamental to understanding how these pathogens spread to humans. Typically, infections are either anthroponotic (human source) or zoonotic (animal source), and within each of these categories, diseases are transmitted either directly or indirectly to humans[3].

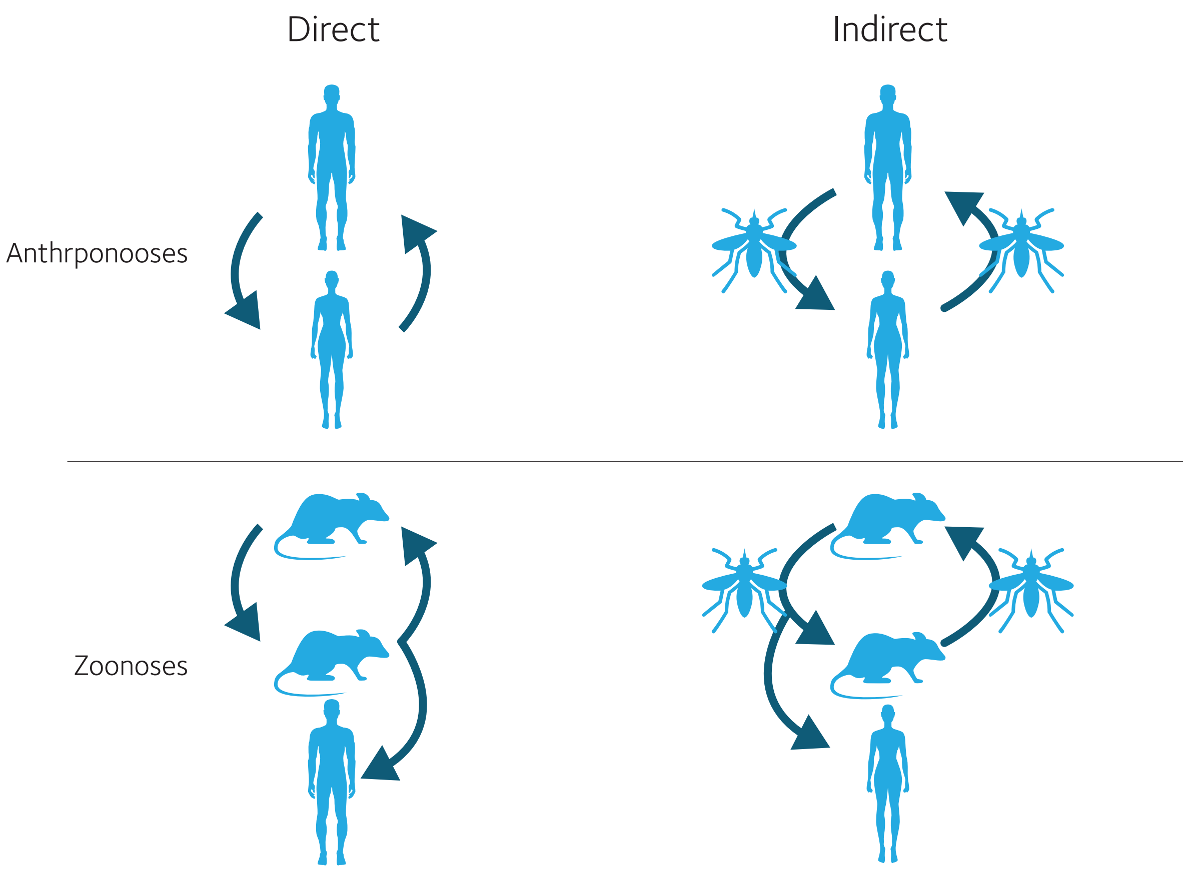


Figure 1: Four types of infectious disease transmission. Rodents represent animal hosts and mosquitoes represent vectors/vehicles of transmission.

Anthroponoses

Direct Transmission

Diseases may be transmitted from human to human through direct physical contact, or else via some type of material surface or matter (such as a door handle or table top). Examples of diseases transmitted directly between humans are HIV/AIDS, herpes, and other sexually-transmitted diseases, as well as tuberculosis, leprosy, and measles. While direct human-to-human transmission is least tied to the physical environment, changes in ecosystems, land use, and weather patterns may affect human behaviours in such a way that risk for contact with pathogens is increased.

Indirect Transmission

Some anthroponoses are transmitted between humans indirectly, either via an intermediate, "vector" host, or via contact with contaminated water. Vector-borne anthroponoses include diseases like malaria, dengue, and Zika. Transmission is closely tied to the natural environment, with temperature, rainfall, and the abundance of vegetation all having an impact on the reproduction, survival, and biting rates of mosquitoes. Consumption of or contact with contaminated water may also result in the transmission of diseases between humans, as is the cases for diseases such as cholera, schistosomiasis, and e. coli.

Zoonoses

Direct Transmission

Some animal diseases can be transmitted directly from animals to humans, often with subsequent human-to-human transmission. Some pathogens infect humans via animal bites or saliva, as is the case with rabies, while others such as avian influenza are airborne, infecting those working in close proximity to infected animals. Ebola is a complex zoonosis, transmitted to humans via close contact with the blood and other bodily fluids of infected wild animals such as primates and fruit bats. Changes to the environment which bring people in closer contact with wild animals are therefore of particular concern.

Indirect Transmission

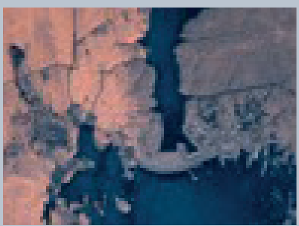
Much like indirectly transmitted anthroponotic diseases, some zoonoses require water or vectors as intermediate pathogen hosts for transmission. Examples include Lyme disease and bubonic plague, transmitted from infected rodents to humans via tick and flea bites (respectively). West Nile virus is spread to humans by the bite of mosquitoes which have fed on infected birds. As with indirectly transmitted anthroponoses, the spread of these zoonoses is strongly linked to the environment and therefore sensitive to environmental changes which affect vector abundance.

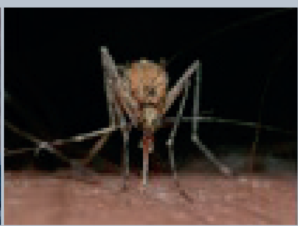
Types of Environmental Change

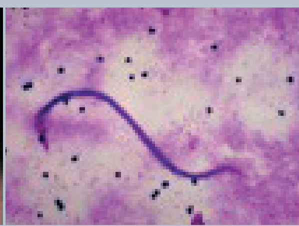
Irrigation

Dramatic increases in the number of water resource development projects over the past seven decades have led to many global environmental transformations which have subsequent negative effects on human health[4]. Irrigation canals and drainage networks can increase the availability of habitats for vector species across wide areas of farming land. Furthermore, the use of dams leads to yearlong water supply in some areas, allowing certain organisms to survive which would have normally perished during dry seasons[5]. Irrigation has been developed in many countries without consideration for the effects on public health. Malaria, schistosomiasis, filariasis, Japanese Encephalitis, and onchocerciasis are all examples of high-burden diseases in such countries.

Resurgence of lymphatic filariasis in Egypt
Lymphatic filariasis (also known as elephantiasis) is a parasitic disease which weakens the lymphatic system and can cause extreme swelling and enlargement of the limbs, breasts, and scrotum. It is caused by microscopic worms which are spread from human to human by *Culex pipiens* mosquito bites. The Aswan High Dam, built in the 1960s in the southern Nile Delta, resulted in increased surface and sub-surface moisture and the subsequent rapid rise in the abundance of these C. pipiens mosquitoes. Consequently, prevalence of lymphatic filariasis in the region rose from less than one percent in 1965 to over twenty percent after the construction of the dam[6].


Building of Aswan dam


Improved habitat for Culex pipiens mosquito vectors


Proliferation of Wuchereria bancrofti parasite

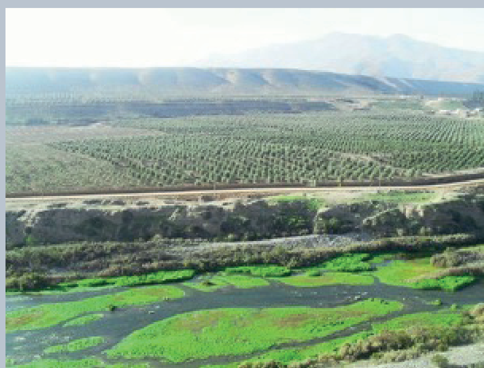

Increased abundance of lymphatic filiariasis in Egyptian population

Agricultural Intensification

There are many examples of agricultural intensification leading to increased risk of zoonotic disease emergence. Intensification of livestock production itself (e.g. of swine and poultry) can facilitate transmission of certain diseases to those who work closely with livestock. However, agricultural intensification also leads to greater interaction between humans, livestock, and wildlife[7] in zones where their ecosystems overlap. This increased interaction means that the spillover of previously unknown animal pathogens into livestock or humans is more likely. Furthermore, agricultural intensification may lead to overall biodiversity loss, causing environments to disproportionately favour specific pathogens, vectors, and/or hosts. Malaria, Venezuelan and Crimean-Congo haemorrhagic fevers, and Chagas disease are all examples of infectious diseases which have been able to spread more easily to humans due to agricultural intensification.

Chagas disease in Chile

Chagas disease is a potentially fatal disease caused by the *Trypanosoma cruzi* protozoan in the Americas. It is an indirectly transmitted zoonosis, primarily transmitted to humans by the insect vector *Triatoma infestans*, also known as the "kissing bug", which is widespread in much of South America. Although Chagas disease is known to have infected humans as long as 9,000 years ago in northern Chile and southern Peru[8], it was primarily a disease of animals, with only accidental infection in humans, for the majority of human history. Only in the past two to three centuries has Chagas disease begun to pose a serious threat to humans. This relatively recent rise in the number of infections is largely due to the clearing of land for agriculture in endemic countries. Originally feeding predominantly on the blood of wild animals, agricultural intensification caused *T. infestans* to adapt to human-dominated environments and feed increasingly on humans and domestic animals. Today, Chagas disease is an endemic zoonosis in Chile and several other Latin American countries, with a reported incidence of up to 11 in 100,000 people in some regions as of 20179.



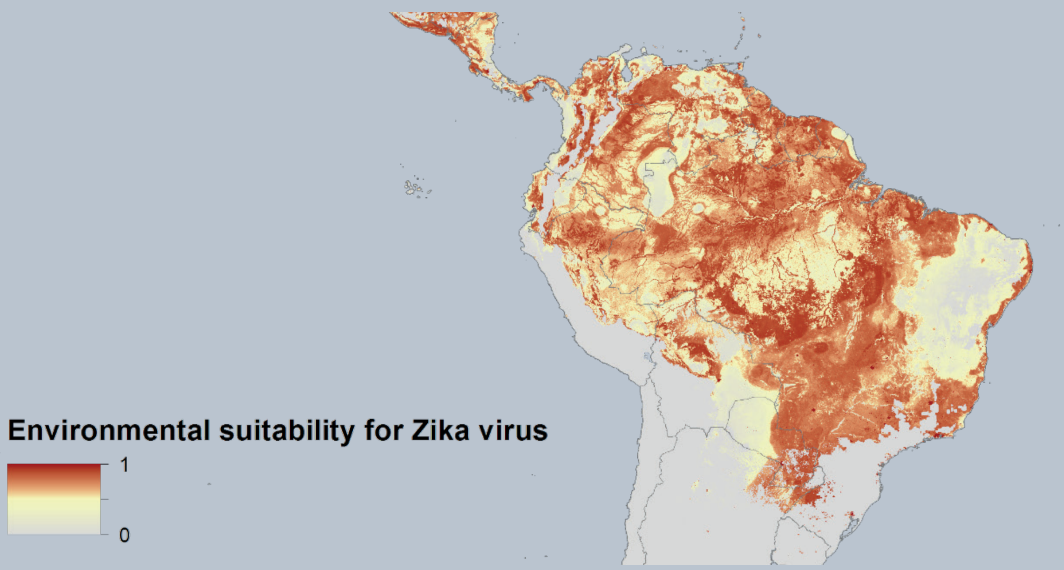
Agricultural land in the Atacama Region of Chile, where Chagas disease is abundant.

Urbanization

There are many ways in which the rapid urbanisation seen across the globe since the 18th century has led to the emergence and re-emergence of infectious diseases. While some aspects of living in a city are beneficial to human health (e.g., via higher incomes and better access to healthcare), there are often large discrepancies in health conditions between neighbourhoods within large cities. Over-crowded slum settlements characteristic of many rapidly expanding cities are often accompanied by poor sanitation, contaminated water supplies, lack of ventilation, and proximity to vectors and their breeding sites. Examples of diseases whose transmission has been facilitated by urbanization include cholera, dengue, Zika, severe acute respiratory syndrome (SARS), chikungunya, and cutaneous leishmaniasis. Alongside urbanization has come an increase in international air travel, which makes it easier for infected populations of mega-cities to come in contact with one another and potential vectors.

Zika virus in Brazil

Zika virus is transmitted to humans by *Aedes* mosquitoes, which also act as vectors for dengue and chikungunya viruses throughout the tropics. Although discovered in 1947 in Uganda, it was only in 2007 that a large outbreak was seen (in the Federated States of Micronesia)[10]. In 2013, the virus began to spread across other parts of Oceania and in 2015, a large outbreak in Latin America began in Brazil. The WHO declared Zika virus a Public Health Emergency of International Concern when it was discovered that infection during pregnancy can cause women to pass the virus to her foetus, potentially causing birth defects such as microcephaly. Although the peak of the outbreak has since passed, long-term disappearance of the disease is unlikely to occur without improvement of living conditions in the many slums across Brazilian and other South American cities.

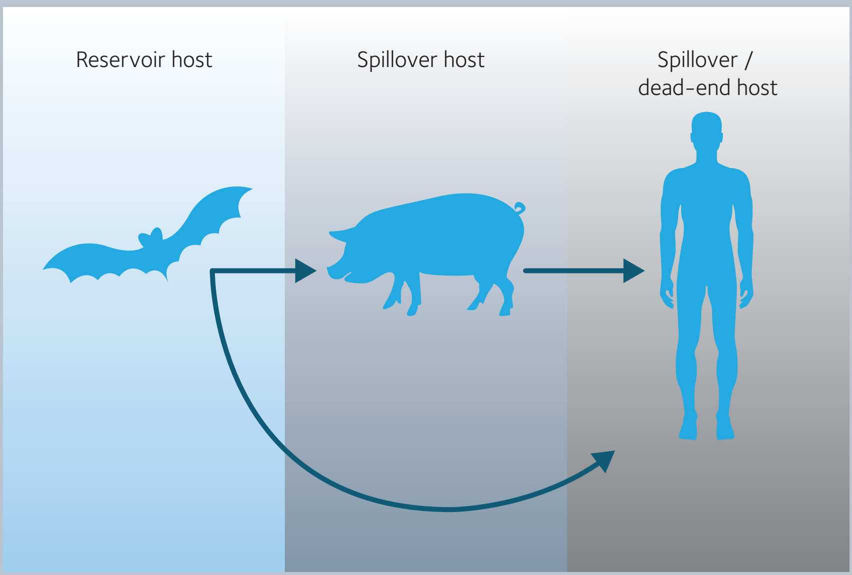


From Messina et al., 2016[11]

Deforestation

Tropical deforestation has occurred at an alarming rate in recent decades, with over 1 million square kilometres of tropical forests cleared globally since 2000[12]. As a consequence of this deforestation, humans have continued to interrupt the ecosystems of animals and insects, which often serve as hosts and vectors of infectious diseases. It is not only the movement of human populations into these ecosystems which causes the pathogens to spread from animals to humans. Forest clearing often results in a greater abundance of surfaces on which standing water may collect, thereby increasing the availability of breeding sites for certain mosquito vectors, for example. The ecosystem disruption caused by deforestation may also result in biodiversity loss, favouring the proliferation of some species of pathogen hosts and vectors over others. Ebola, malaria, visceral leishmaniasis, Lyme disease, Nipah virus, and oropouche are all examples of diseases whose emergence and spread have been affected by deforestation.

Nipah virus in Malaysia
The zoonotic Nipah virus is highly fatal in humans, resulting in a mortality rate of 40-75%*13* with no effective vaccine yet developed. A large outbreak in Malaysia in 1998-1999 caused 265 cases of encephalitis and 105 deaths, with Nipah being spread via the movement of infected pigs between farms across the country[14]. It was later discovered that the initial infection of pigs was likely from fruitbats, large populations of which had migrated in preceding years to orchards and pig farms due to deforestation of their native habitat.



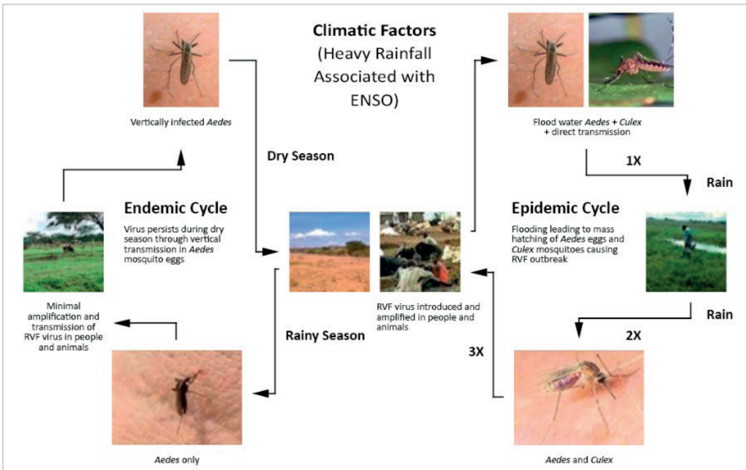
Nipah virus transmission cycle

Climate Change

For at least a decade, scientists have been deliberating the potential effects of climate change on infectious disease emergence and re-emergence[15]. Although the exact response of infectious diseases to climate change will differ in a multitude of ways according pathogen, the message that disease risk will be modified in some way by changes in average temperatures and precipitation is clear. Examples of infectious diseases whose range and rate of spread have been and/or continue to be affected by climate change include hantavirus, red tide poisoning, and most vector-borne diseases.

Rift Valley fever in Kenya

Rift Valley fever is a mosquito-borne viral disease transmitted competently to humans by more than 30 species of mosquito[16]. As with other vector-borne diseases, climate changes may impact all aspects of Rift Valley fever transmission, but rises in temperature and the consequent potential for increased mosquito abundance is of particular concern. While a low level of endemic transmission occurs in all rainy seasons, El Niño climate fluctuations have been associated with larger epidemics. An epidemic of haemorrhagic fever caused by Rift Valley fever was experienced in 1997-1998 in East Africa, namely north-eastern Kenya (where the disease was originally discovered in 1931)[17]. Another epidemic was seen in 2006; both were correlated with heavy rainfall due to El Niño. The increasing rainfall anticipated to occur in East Africa due to climate change means that many scientists assume the larger Rift Valley fever epidemics will continue to grow in frequency and severity.



Source: Adapted from Anyamba, A., Linthicum, J.K., Small, J., Britch, S.C., Pak, E., De La Rocque, S. *et al.*, 2010, 'Prediction, assessment of the Rift Valley fever activity in East and Southern Africa 2006–2008 and possible vector control strategies', *American Journal of Tropical Medicine and Hygiene* 83(Suppl. 2), 43–51. http://dx.doi.org/10.4269/ajtmh.2010.09-0289
The epidemic cycle is precipitated by excessive heavy rainfall associated with the El Niño/Southern Oscillation (ENSO) climatic phenomena. The three Xs depicted in the epidemic cycle represent critical pathways, which can be interrupted by targeted and specific mosquito control activities.
ENSO, El Niño/Southern Oscillation; RVF, Rift Valley fever.

FIGURE 3: Endemic (on left) and epidemic (on right) life cycles of Rift Valley fever involving close association between heavy rainfall conditions, vector *Aedes* and *Culex* mosquitoes, domestic animals and humans.

Marine Pollution

Approximately forty percent of the global population lived within 100km from a coastline as of 2010[18]. As such, coastal waters can become contaminated with pathogens via human and agricultural wastewater discharge from nearby communities, as well as from those communities which are near rivers and streams that flow into the sea. Humans then come into contact with these pathogens via recreational coastal activities (e.g., visits to the seashore), as well as via the consumption of seafood harvested from marine waters. These pathogens can result in outbreaks of gastrointestinal illness. Human viruses that have been identified in seawater include adenovirus, norovirus, enteroviruses, and hepatitis A[19]. *Staphylococcus aureus, Salmonella*, and *Pseudomonas* bacteria as well as Cryptosporidia protozoa have also been found in seawater. The increased flooding many predict will be associated with climate change could also result in greater amounts of untreated wastewater discharge into coastal zones.

Norovirus in the United Kingdom

Norovirus, a highly contagious gastrointestinal infection, can lead to severe acute illness in humans characterised by fever, diarrhoea, abdominal pain, nausea, and vomiting. Coastal waters where shellfish are found can become contaminated with norovirus via wastewater discharge. Those marine environments which are near high-density human settlements are more likely to be contaminated, and the virus can persist in these environments for several days. Although proper cooking methods can inactivate norovirus, the consumption of raw shellfish such as oysters causes nearly 75,000 cases of norovirus in the UK each year20. Continued human outbreaks of norovirus not only pose a threat to human health, but also to the UK aquaculture industry.

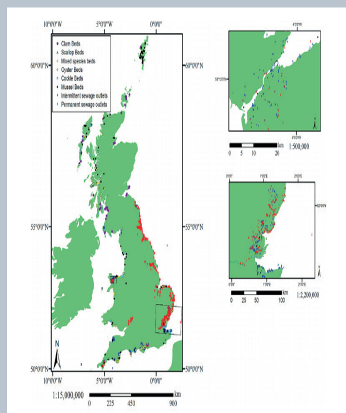


Figure 1. Shellfish areas and sewage outflow distribution in the UK. From Hassard et al. 2017[20].

Ocean Warming

Approximately 90% of the excess heat added to the climate system since the 1960s has been estimated to be stored in the oceans[21]. Bacterial pathogens which prefer warm seawater are of particular concern for human health. As such, certain areas of the globe may begin to see increased occurrence of pathogenic bacteria alongside the ocean warming associated with climate change. Vibrio species bacteria (of which Vibrio cholera is the most commonly associated) in particular have received increased attention as threats to the human populations in higher-latitude regions[22].

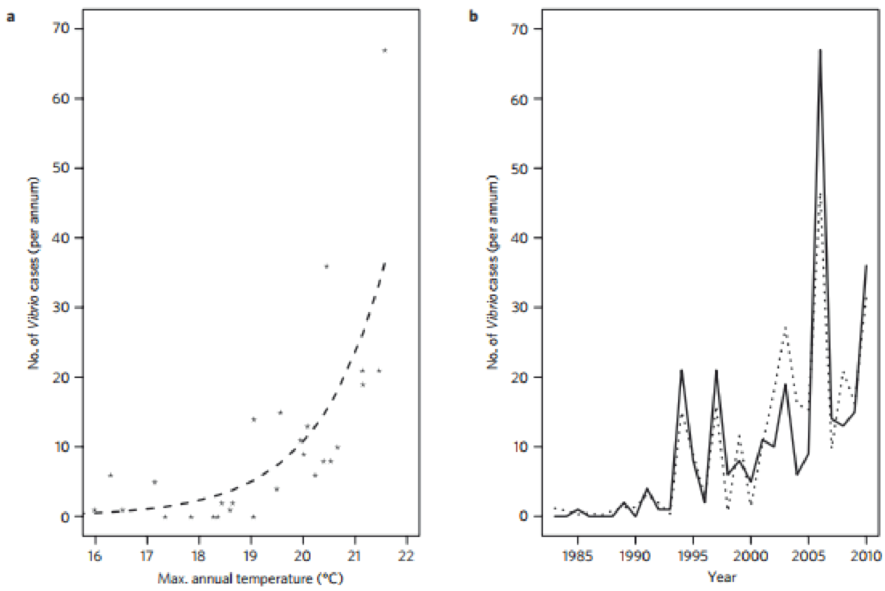


Figure 2 | *Vibrio* cases and SST. a, The relationship between *Vibrio* infections reported around the Baltic Sea area and maximum annual SST. Stars show observed data, dashed line shows GLM model predictions (based on the influence of SST alone). **b**, Time series of Baltic Sea *Vibrio* cases. Solid line shows observed cases and dotted line shows GLM model predictions based on the influence of maximum SST and time.

***Vibrio* bacterial infections in the Baltic Sea region**

People living near the Baltic Sea have been suggested as being at particular risk for increasing illness from pathogenic vibrio bacteria due to ocean warming. The rate of warming of the Baltic Sea between 1987 and 2007 was sevenfold that of the global rate[22], making it the fastest warming marine ecosystem in the world. Although a low number of overall cases of human *Vibrio* infection were seen during these years, they were significantly associated with warmer sea temperatures[23].

Conclusion

Human activities are known to cause many detrimental effects to the environment, from local to global scales. These include biodiversity loss, climate change, species extinction and displacement, and habitat fragmentation. Importantly, ecosystems have been affected such that humans are increasingly coming into contact with the reservoirs and vectors of infectious pathogens. As such, addressing environmental degradation can have multiple benefits to human health, including the prevention of epidemics caused by emerging and re-emerging diseases. Combatting carbon emissions which lead to climate change, protecting biodiversity, supporting the development of clean water sources, and favouring sustainable agricultural and irrigation systems will be important tools in curbing the trend of pandemic disease becoming the global "norm".

References

Altizer, S., R. S. Ostfeld, P. T. Johnson, S. Kutz, and C. D. Harvell. "Climate Change and Infectious Diseases: From Evidence to a Predictive Framework." *Science* 341, no. 6145 (Aug 02 2013): 514-9.

Aufderheide, A. C., W. Salo, M. Madden, J. Streitz, J. Buikstra, F. Guhl, B. Arriaza, et al. "A 9,000-Year Record of Chagas' Disease." *Proc Natl Acad Sci U S A* 101, no. 7 (Feb 17 2004): 2034-9.

Baker-Austin, C., J. A. Trinanes, N. G. H. Taylor, R. Hartnell, A. Siitonen, and J. Martinez-Urtaza. "Emerging Vibrio Risk at High Latitudes in Response to Ocean Warming (Vol 3, Pg 73, 2013)." [In English]. *Nature Climate Change* 6, no. 8 (Aug 2016).

Canals, M., D. Caceres, S. Alvarado, A. Canals, and P. E. Cattan. "Modeling Chagas Disease in Chile: From Vector to Congenital Transmission." *Biosystems* 156-157 (Jun - Jul 2017): 63-71.

Epstein, J. H., H. E. Field, S. Luby, J. R. Pulliam, and P. Daszak. "Nipah Virus: Impact, Origins, and Causes of Emergence." *Curr Infect Dis Rep* 8, no. 1 (Jan 2006): 59-65.

Hassard, F., J. H. Sharp, H. Taft, L. LeVay, J. P. Harris, J. E. McDonald, K. Tuson, et al. "Critical Review on the Public Health Impact of Norovirus Contamination in Shellfish and the Environment: A Uk Perspective." [In English]. *Food and Environmental Virology* 9, no. 2 (Jun 2017): 123-41.

Hubalek, Z. "Emerging Human Infectious Diseases: Anthroponoses, Zoonoses, and Sapronoses." *Emerg Infect Dis* 9, no. 3 (Mar 2003): 403-4.

Ingram, Jane Carter, Fabrice DeClerck, Cristina Rumbaitis del Rio, and ProQuest (Firm). *Integrating Ecology and Poverty Reduction the Application of Ecology in Development Solutions.* New York: Springer Science+Business Media, LLC,, 2012. Ebook central http://ebookcentral.proquest.com/lib/oxford/detail.action?docID=884032.

Jobin, William R. *Dams and Disease : Ecological Design and Health Impacts of Large Dams, Canals and Irrigation Systems.* London: E & FN Spon, 1999.

Jones, B. A., D. Grace, R. Kock, S. Alonso, J. Rushton, M. Y. Said, D. McKeever, et al. "Zoonosis Emergence Linked to Agricultural Intensification and Environmental Change." *Proc Natl Acad Sci* U S A 110, no. 21 (May 21 2013): 8399-404.

Jones, K. E., N. G. Patel, M. A. Levy, A. Storeygard, D. Balk, J. L. Gittleman, and P. Daszak. "Global Trends in Emerging Infectious Diseases." *Nature* 451, no. 7181 (Feb 21 2008): 990-3.

Keiser, J., M. C. De Castro, M. F. Maltese, R. Bos, M. Tanner, B. H. Singer, and J. Utzinger. "Effect of Irrigation and Large Dams on the Burden of Malaria on a Global and Regional Scale." *Am J Trop Med Hyg* 72, no. 4 (Apr 2005): 392-406.

Linthicum, K. J., A. Anyamba, C. J. Tucker, P. W. Kelley, M. F. Myers, and C. J. Peters. "Climate and Satellite Indicators to Forecast Rift Valley Fever Epidemics in Kenya." *Science* 285, no. 5426 (Jul 16 1999): 397-400.

Looi, L. M., and K. B. Chua. "Lessons from the Nipah Virus Outbreak in Malaysia." *Malays J Pathol* 29, no. 2 (Dec 2007): 63-7.

Martin, V., V. Chevalier, P. Ceccato, A. Anyamba, L. De Simone, J. Lubroth, S. de La Rocque, and J. Domenech. "The Impact of Climate Change on the Epidemiology and Control of Rift Valley Fever." *Rev Sci Tech* 27, no. 2 (Aug 2008): 413-26.

Messina, J. P., M. U. Kraemer, O. J. Brady, D. M. Pigott, F. M. Shearer, D. J. Weiss, N. Golding, et al. "Mapping Global Environmental Suitability for Zika Virus." *Elife* 5 (Apr 19 2016).

Morens, D. M., and A. S. Fauci. "Emerging Infectious Diseases: Threats to Human Health and Global Stability." *PLoS Pathog* 9, no. 7 (2013): e1003467.

Network, Center for International Earth Science Information. "Gridded Population of the World." edited by Columbia University, 2010.

Norris, K. "Ecology: The Tropical Deforestation Debt." *Curr Biol* 26, no. 16 (Aug 22 2016): R770-2.

Roemmich, D., W. J. Gould, and J. Gilson. "135 Years of Global Ocean Warming between the Challenger Expedition and the Argo Programme." [In English]. *Nature Climate Change* 2, no. 6 (Jun 2012): 425-28.

Vezzulli, L., R. R. Colwell, and C. Pruzzo. "Ocean Warming and Spread of Pathogenic Vibrios in the Aquatic Environment." *Microb Ecol* 65, no. 4 (May 2013): 817-25.

Weaver, S. C., C. Charlier, N. Vasilakis, and M. Lecuit. "Zika, Chikungunya, and Other Emerging Vector-Borne Viral Diseases." *Annu Rev Med* (Aug 28 2017).

Young, N. "The Association between Marine Bathing and Infectious Diseases - a Review." [In English]. *Journal of the Marine Biological Association of the United Kingdom* 96, no. 1 (Feb 2016): 93-100.

Endnotes

1 K. E. Jones et al., "Global Trends in Emerging Infectious Diseases," *Nature* 451, no. 7181 (2008).

2 D. M. Morens and A. S. Fauci, "Emerging Infectious Diseases: Threats to Human Health and Global Stability," *PLoS Pathog* 9, no. 7 (2013).

3 Z. Hubalek, "Emerging Human Infectious Diseases: Anthroponoses, Zoonoses, and Sapronoses," *Emerg Infect Dis* 9, no. 3 (2003).

4 J. Keiser et al., "Effect of Irrigation and Large Dams on the Burden of Malaria on a Global and Regional Scale," *Am J Trop Med Hyg* 72, no. 4 (2005).

5 William R. Jobin, *Dams and Disease : Ecological Design and Health Impacts of Large Dams, Canals and Irrigation Systems* (London: E & FN Spon, 1999).

6 Jane Carter Ingram et al., Integrating Ecology and Poverty Reduction the Application of Ecology in Development Solutions, (New York: Springer Science+Business Media, LLC,, 2012), Ebook central http://ebookcentral.proquest.com/lib/oxford/detail.action?docID=884032.

7 B. A. Jones et al., "Zoonosis Emergence Linked to Agricultural Intensification and Environmental Change," *Proc Natl Acad Sci* U S A 110, no. 21 (2013).

8 A. C. Aufderheide et al., "A 9,000-Year Record of Chagas' Disease," ibid.101, no. 7 (2004).

9 M. Canals et al., "Modeling Chagas Disease in Chile: From Vector to Congenital Transmission," *Biosystems* 156-157 (2017).

10 S. C. Weaver et al., "Zika, Chikungunya, and Other Emerging Vector-Borne Viral Diseases," *Annu Rev Med* (2017).

11 J. P. Messina et al., "Mapping Global Environmental Suitability for Zika Virus," *Elife* 5 (2016).

12 K. Norris, "Ecology: The Tropical Deforestation Debt," *Curr Biol* 26, no. 16 (2016).

13 J. H. Epstein et al., "Nipah Virus: Impact, Origins, and Causes of Emergence," *Curr Infect Dis Rep* 8, no. 1 (2006).

14 L. M. Looi and K. B. Chua, "Lessons from the Nipah Virus Outbreak in Malaysia," *Malays J Pathol* 29, no. 2 (2007).

15 S. Altizer et al., "Climate Change and Infectious Diseases: From Evidence to a Predictive Framework," *Science* 341, no. 6145 (2013).

16 V. Martin et al., "The Impact of Climate Change on the Epidemiology and Control of Rift Valley Fever," *Rev Sci Tech* 27, no. 2 (2008).

17 K. J. Linthicum et al., "Climate and Satellite Indicators to Forecast Rift Valley Fever Epidemics in Kenya," *Science* 285, no. 5426 (1999).

18 Center for International Earth Science Information Network, "Gridded Population of the World," ed. Columbia University (2010).

19 N. Young, "The Association between Marine Bathing and Infectious Diseases - a Review," *Journal of the Marine Biological Association of the United Kingdom* 96, no. 1 (2016).

20 F. Hassard et al., "Critical Review on the Public Health Impact of Norovirus Contamination in Shellfish and the Environment: A Uk Perspective," *Food and Environmental Virology* 9, no. 2 (2017).

21 D. Roemmich, W. J. Gould, and J. Gilson, "135 Years of Global Ocean Warming between the Challenger Expedition and the Argo Programme," *Nature Climate Change* 2, no. 6 (2012).

22 L. Vezzulli, R. R. Colwell, and C. Pruzzo, "Ocean Warming and Spread of Pathogenic Vibrios in the Aquatic Environment," *Microb Ecol* 65, no. 4 (2013).

23 C. Baker-Austin et al., "Emerging Vibrio Risk at High Latitudes in Response to Ocean Warming (Vol 3, Pg 73, 2013)," *Nature Climate Change* 6, no. 8 (2016).

About The Rockefeller Foundation

For more than 100 years, The Rockefeller Foundation's mission has been to promote the well-being of humanity throughout the world. Today, The Rockefeller Foundation pursues this mission through dual goals: advancing inclusive economies that expand opportunities for more broadly shared prosperity, and building resilience by helping people, communities and institutions prepare for, withstand, and emerge stronger from acute shocks and chronic stresses. To achieve these goals, The Rockefeller Foundation works at the intersection of four focus areas—advance health, revalue ecosystems, secure livelihoods, and transform cities—to address the root causes of emerging challenges and create systemic change. Together with partners and grantees, The Rockefeller Foundation strives to catalyze and scale transformative innovations, create unlikely partnerships that span sectors, and take risks others cannot—or will not.

About the Oxford Martin School

The Oxford Martin School at the University of Oxford is a world-leading centre of pioneering research that addresses global challenges. It invests in research that cuts across disciplines to tackle a wide range of issues such as climate change, disease and inequality. The School supports novel, high risk and multidisciplinary projects that may not fit within conventional funding channels, because breaking boundaries can produce results that could dramatically improve the wellbeing of this and future generations. Underpinning all our research is the need to translate academic excellence into impact – from innovations in science, medicine and technology, through to providing expert advice and policy recommendations.

The Rockefeller Foundation Economic Council on Planetary Health
Oxford Martin School, University of Oxford, 34 Broad Street, Oxford, OX1 3BD, United Kingdom