5-2022

Vectors, Pathogens and Climate Change: How Will Human Health be Affected?

Joseph T. Barry
Grand Valley State University

Vectors, Pathogens and Climate Change:

How Will Human Health be Affected?

Honors Senior Project

Joseph T. Barry

Department of Biology

Grand Valley State University

Senior Project Advisor: Dr. Jodee Hunt, Professor of Biology

This project submitted in fulfillment of HNR 499

Introduction: Vectors, Pathogens and Climate Change

Climate change due to anthropogenic activity is an ever-growing, looming threat, and the future of earth's ecosystems. The human population seems unable or unwilling to curb climate change, and so the survival of numerous species instead depends on whether they are able to adapt to that change. Climate change is responsible for an overall warming of earth and myriad sources of severe weather that include increased frequency and severity of storm events, tornadoes, hurricanes, floods, and droughts. These, in turn, link to environmental issues like erosion and loss of vegetation. Anthropogenic climate change primarily results from human activities, particularly the burning of fossil fuels to generate electricity, fuel industry, and support transportation, but also from industrialized agriculture and deforestation and overall degradation of all of earth's ecosystems. These activities release CO_2 into the atmosphere (among other harmful gases), creating a thicker atmosphere that insulates the planet, thereby causing a greenhouse effect.[5]

Barring an abrupt, worldwide shift away from use of fossil fuels- which is almost certainly not coming quickly enough- species' survival instead depends on their ability to adapt to warmer temperatures. Interestingly, while many species of flora and fauna are harmed by warming temperatures and changing patterns of precipitation, other species, such as a variety of agricultural pests, weeds, and pathogens, may thrive in response to the changes. Among the species that may benefit from climate change are parasitic vectors and the vector-borne diseases they carry. These organisms threaten human health, and the effects of climate change may bolster the ability of vector organisms spread diseases across ever-expanding ranges, thereby affecting human populations in larger geographic areas.

Warming temperatures are especially favored by a variety of disease-causing organisms that are adapted to mammalian (and, thus, endothermic) definitive hosts- such as humans.[26] Disease-causing organisms that infect humans tend to thrive in warmer conditions so it stands to reason that a generally warmer climate will spread many pathogens across larger areas, increasing incidences of the diseases they cause. Warmer climates will also favor many species of vector as a great deal of parasitic vectors are insects, which are ectothermic.[22] Due to this reliance on the external temperature, these vectors, as well as other insects, will see an increase in seasonal life cycle time as well as an increase or shift in geographic range, among other benefits, favoring the warmer temperature increase. [25] Subsequently, vector-borne pathogens will in turn experience a greater rate of transmission into humans thus increasing global rates of infection from vector-borne diseases. Vector-borne diseases rely on interspecific host-to-host transfer, which is typically a slower process when compared to human pathogens with direct transmission, as additional specific biological and ecological conditions need to be met.[16] Thus, by increasing the rate of transmission and chance for infection from these pathogens, vector-borne diseases will become even more problematic than they currently are, affecting a greater percentage of the global population while also impacting more vulnerable, unprepared communities.[23] So, while reducing or eliminating many of the harmful causes of rapid climate change, anthropogenic or otherwise, is an important process, remaining aware of the significant impact these organisms will have on human health is notably important as well.

Vectors are organisms that act as a biological vehicle transferring a pathogen from one host to another, typically more desired, host. The process of how these symbiotic relationships form between pathogens and their vectors requires a great deal of time. This commensalism is the result of many different evolutionary adaptations. For example, a pathogen existing in its original host is incidentally taken from that host via a parasitic vector and is then transferred to a new host by the same parasitism of the vector.[22] This pathogen may already have similar adaptations from its original host to help it survive in the new host. Over time, if the pathogen has a high enough fitness, it will colonize and replicate in the new host causing disease. Eventually, the pathogen will become adapted to its new host and the vector transmission process, increasing that pathogens evolutionary success.

A variety of parasitic vectors (including diverse mollusks and arthropods) can evolve an adaptive, mutualistic relationship with pathogens. The pathogens and parasites transmitted via animal vectors are even more taxonomically diverse, and include many nematode worms, diverse bacteria, and protozoa like trypanosomes. Perusing the evolutionary legacy of these taxonomically and ecologically diverse relationships, it becomes apparent that vectors are an effective way for pathogenic organisms to disperse among definitive hosts such as humans.[16]

Project Objectives and Focal Species

Given the threat to human health of these diseases, the inevitability of the effects of climate change, and its potential to benefit both vector and disease organisms, this project focuses on three vector-borne diseases. The objectives are to examine the current range, prevalence, and effects of each disease, and to summarize the hypothesized effects of climate change on both vector and disease organism. The vectors species selected for this comparative study are: (i) mosquitoes (Diptera, family Culicine), (ii) ticks (superorder Parasitiformes, order Ixodida), and (iii) kissing bugs (Hemiptera, subfamily Triatominae). These three arthropods each utilize blood-sucking as a trophic role but vary significantly in the disease species that rely on them to disperse among definitive hosts and thereby cause disease. The vector species are generally disjunct in distribution, but experience some overlap in geographic range. They exhibit different adaptations to climate, e.g., to fluctuations in weather and seasonal patterns.

Vector-borne diseases are similarly caused by diverse pathogens that include bacteria, viruses, protozoa, nematode worms, and a variety of other taxa. Vector-borne diseases are typically constrained to live in geographic ranges that overlap with the distributions of the vectors that transmits them. This comparative study focuses on three vector-borne diseases, one per vector taxon. For the mosquito vector, the yellow fever virus was selected; its vector mutualistic partner is the *Aedes aegypti* mosquito. Ticks are widely known for their spread of the bacterium *Borrelia burgdorferi* sensu *lato*, which causes Lyme Disease; the vector species is the black-legged tick, *Ixodes scapularis*. Lastly, over 11 species of Hemiptera bugs in the subfamily Triatominae are responsible for the spread of a protozoan parasite, *Trypanosoma cruzi*, which causes American trypanosomiasis, more commonly known as Chagas Disease.

This comparative study examines the nature of each of these symbiotic pathogen-vector relationships, the distribution and prevalence of the diseases they cause, and the predicted changes in distribution and prevalence of each in the face of climate change.

Aedes aegypti **Mosquitoes and Yellow Fever**

Mosquitoes have been a long-standing threat to human health being indirectly responsible for billions of deaths throughout human history and they continue to be a substantial threat to this day.[6] These insects are evolutionarily successful boasting great adaptability to exist in a myriad of different climatic conditions. This adaptability has allowed the mosquito to exist in virtually every part of the world as a result. Due to this widespread expansion, mosquitoes are the most dominant vectors affecting human health. [21] What makes mosquitoes such a significant threat to our health is their incredible rate of parasitism combined with the several deadly diseases they may carry often in the form of viruses. Among one of those deadly diseases is the yellow fever arbovirus. Yellow fever used to exist mainly in Europe and North America, but it is now mostly endemic to Central America, South America, and Africa due to the tropical temperature of these areas.[1] Unlike some other vector-borne disease yellow fever has seen a more recent reemergence after some time largely due to yellow fever reaching areas of unvaccinated human populations. When a vaccine was created and introduced for the yellow fever virus, it was highly successful nearly eliminating the virus. The vaccine is still effective as yellow fever is rare for Central and South America where it is endemic due to higher vaccination access.[1] However, the virus has rapidly shifted into more poverty-stricken parts of Africa where vaccines can be harder to obtain, and it has reemerged as threatening vector-borne disease.

The mosquito species responsible for yellow fever is *Aedes aegypti.* This particular mosquito species is among the most common mosquito species that exist globally and is pathogenically relevant due to the wide range of arboviruses this species can carry. What makes this species so dangerous to humans is that, unlike other mosquito species, *A. aegypti* actually prefers human blood over other species. This preference for human blood means there is a greater spread of disease wherever these mosquitoes exist. [6]

When talking about the incredibly adaptable mosquito vectors, climate change will only increase the likelihood that mosquitoes transmit vector-borne diseases, especially viruses such as yellow fever. For starters, increasing global average temperatures will lead to an increased geographic range of where yellow fever virus is spread. Currently, the insect poikilotherms rely on generally warmer temperatures for survival. Rising global temperatures mean that *A. aegypti* that can host yellow fever will be able to expand geographically into even more northern and southern subtropic zones where yellow fever vaccinations may not be as commonplace.[1] If no drastic progress is taken against the continually warming temperatures as a result of anthropogenic climate change, the range for the yellow fever vectors will eventually spread into northern and southern temperate zones as well. As the geographic range for *A. aegypti* mosquitoes carrying yellow fever increases, so too will the spread of the virus.[1] These areas where yellow fever is not endemic are unprepared and especially susceptible to outbreaks despite an effective vaccine.

Supporting this notion is the fact that yellow fever virus typically needs a high enough temperature (around 16.5 C°/61.7 °F or higher) in order to properly replicate in both its mosquito vector host and then its intended human host. [25] Therefore, with a global rise in average temperatures it is more likely that yellow fever will be able to replicate in areas that are generally colder than the where yellow fever is currently endemic. Interestingly however, temperatures that are too hot for *A. aegypti* (35 C°/95 °F) can negatively affect the vectors' feeding activity and subsequent survival which in turn will negatively impact the spread of yellow fever in warmer climates. [25] So, while yellow fever will spread along with *A. aegypti* to cooler climates, its current endemic tropical zones may actually see a reduction in the spread of yellow fever.

Yet another factor where climate change plays a prominent role is the influence weather will have on the mosquito vector and its arbovirus survival. Along with warming global temperatures an influx in severe weather patterns is also occurring. This increased severity of unusual weather patterns means greater rainfall even in areas that are typically drier. An increase in rainfall means more areas of stagnant water will be present. This standing water is incredibly important for most mosquitoes especially *A. aegypti*, as mosquitoes use the stagnant water as its primary breeding ground.[6] Mosquito larvae do not need much water to survive either so when moisture inevitably increases due to these changing weather events, mosquitoes will be able to thrive thus increasing their numbers.[24] More *A. aegypti* mosquitoes will only lead to a greater transmission of yellow fever.

Prevention and Human Preparedness

Luckily, an effective vaccine does exist for the yellow fever virus, and it is still the best option in preventing the spread of yellow fever. That said, globally many individuals are not vaccinated against yellow fever either due to a lack of access or simply because yellow fever is not endemic to those areas. However, with an increasing spread of yellow fever into other climate zones, there is an increased risk that outbreaks will occur provided no attention is directed to this arbovirus. In order to prevent such outbreaks from occurring, close attention must be paid to tracking the movement of both *A. aegypti* and yellow fever, to ensure that vaccines are available to potential areas that this vector-borne pathogen might spread.

Black-legged ticks *(Ixodes scapularis)* & Lyme disease (*Borrelia burgdorferi sensu lato*)

Ticks are a group of parasitic arthropods who generally target warm blooded animals. These vectors are widely known for their role in the spread of Lyme disease which is the most common vector borne illness in the United States.[6] Black-legged ticks in particular are commonly known for their affinity for deer, but the ticks that feed on deer (and humans) are generally the adults. In fact, black-legged ticks also feed on a variety of animals including, mice and birds. This species is a three-host parasite requiring three different hosts during each stage of its life cycle.[19] This is important as it increases the adaptability of these parasites while also consequently making it easier for ticks to transfer vector-borne pathogens between hosts. These arachnids are also incredibly resilient in comparison to some other insect vectors as they are able to survive cooler temperate climates making them widely abundant parasites. [21]

Despite their general resilience to colder weather in comparison to other insect vectors, ticks will still die from severe cold especially if there is no available protection.[13] As a result, ticks also favor generally warmer temperatures. As is the case with rising global temperatures, ticks will benefit from a greater geographical range. Ticks will begin to move into higher altitudes which are normally too cold for ticks to reliably live, and to subsequently shift into more northern areas than even now.[13] For example, ticks have become more frequently spotted in Canada to which they are not endemic.[20] Ticks already live in colder climates compared to other vectors.

The reason for this greater survivability in the cold is due to a few prominent adaptations. For starters, due to their close host-parasite relationships, ticks generally will not be too far from their target hosts and will be able to stay warm once feeding. More commonly though, ticks rely on vegetation refuge more than other parasites, instinctually sheltering itself from temperatures that would otherwise be deadly to the tick.[10] For these ticks in particular, there may actually be fewer ticks present in the warmer southern areas of the country as hot temperatures can be detrimental to tick survival. Another pressing change that will occur as the result of higher average temperatures is a longer tick season.[19] Normally tick seasons begin with larvae growth and nymph feeding in March and April and last until about late fall when the weather becomes freezing.[10] Adult ticks feed primarily in the summer but are able to feed during this early spring to late fall period. However, if annual global temperatures continue to increase, ticks will likely adapt to a longer season that could extend closer to a full year of activity where adult ticks are able to be more active during the winter season. Furthermore, a longer tick season means that more ticks will successfully hatch and make it to adulthood instantly increasing the number of ticks in a given area. That said, if ticks remain in an area where temperatures become too high for their most common hosts it might actually lower the fitness of black-legged ticks in those areas.[19]

The multiple benefits ticks receive from warmer temperatures will also increase the spread of Lyme bacteria. Interestingly, Lyme bacteria induces a tick to become more active, especially when warmer temperatures are present.[21] The reason for this increased activity is likely caused by chemical signaling from the bacteria to the tick, stimulating its feeding drive in order to reach the intended endothermic host. On top of this, generally warmer temperatures will only serve to increase the growth and spread of these bacteria as global temperatures trend towards the bacteria's optimal growth conditions.[21] Plus, with more ticks present and having year-round growing and feeding seasons, it stands to reason that Lyme disease will become even more common and be easily spread between hosts.

Prevention and Human preparedness

While this is certainly frightening, antibiotics are effective against Lyme disease in the early stages of infection. However, if a tick bite and subsequent infection are not noticed soon enough, the risk for more severe and chronic cases of Lyme disease will increase and antibiotics will not be as effective. So, as ticks expand their geographic range into newer areas and become more abundant with longer active seasons, tick prevention and safety will need to increase drastically in order to resist against both parasite and pathogen.

Kissing bugs (subfamily Triatominae) & Chagas disease (*Trypanosoma cruzi*)

Triatominae bugs also known as “kissing bugs” are another blood-sucking parasite that is commonly found in the southern United States, Mexico, Central and South America.[7] These parasites are the vectors responsible for the spread of Chagas disease caused by the protozoan parasite, *Trypanosoma cruzi*. While Chagas disease is spread in humans via triatominae, humans are not the only feeding source for triatominae bugs. [7] In fact, these insects feed on a wide variety of mammals. Several of the animals that triatominae feed on, specifically racoons and opossums in the U.S. and smaller mammals such as bats and rats in Central and South America, are infected with *T. cruzi.* [6] As, the triatominae feeds on these animal hosts, *T. cruzi* is ingested by triatominae via the animal blood meal whereupon *T. cruzi* undergoes rapid reproduction in the gut of the insect.[12]*T. cruzi* surprisingly is not spread directly from the bite of the triatominae bugs ingesting blood as with other vectors like ticks or mosquitoes. Instead, *T. cruzi* is spread from host to host through when feces of triatominae, which contain *T. cruzi*, enters the blood stream of the target host via the feeding site, another open wound, or in mucous membranes. [7]

Triatominae bugs and their associated protozoan parasite will react to climate change in similar to manner to *A. aegypti* and yellow fever. As temperature rises triatominae and *T. cruzi* will inevitably expand its geographic range into a temperate zone shifting upwards into northern part of the United States. This geographic shift will allow triatominae to comfortably exist in both the hemispheres of U.S. and become more prominent in a new population of hosts. [12] Increased temperatures will also favor increased numbers for both triatominae bugs and *T. cruzi* as these temperatures are more optimal for growth and replication.[12] Also, similar to mosquitoes, triatominae may benefit from increased rainfall that results from climate change influenced weather events.[17] More rainfall will lead to a general increase in humidity which can help create more suitable breeding habitats for the insect vector. However, with more severe weather, too much rainfall and flooding can actually remove these suitable breeding grounds. Whether or not rainfall will completely benefit triatominae replication remains to be seen.

Unlike many vector and vector-borne pathogen relationships, triatominae bugs can experience negative impacts on its health as a result of carrying *T. cruzi.*[8] While *T. cruzi* is not always deadly to kissing bugs, in higher numbers, triatominae mortality will increase. Therefore, as temperature increases and *T. cruzi* replicates more frequently more triatominae vectors will die. Though this may appear to work against *T. cruzi* ability to transmit, it will actually do the opposite. Triatominae will likely adapt to this shorter lifespan by shortening its reproduction period and undergoing more rapid reproduction altogether.[8] This means that the triatominae will increase in population size leading to more feeding and, ultimately, more vector-borne transmission of *T. cruzi*.

Prevention and Human Preparedness for Chagas Disease

Currently the best defense against this vector and its pathogen is prevention. This exists in the form of insecticides and infestation prevention to reduce or eliminate triatominae populations. Antiparasitic medication is effective against Chagas disease, but only in the very early stages of infection. This can be problematic since *T. cruzi* will initially infect the blood, but eventually disappear from the blood. This disappearance is a latent period where Chagas disease can no longer be effectively treated with antiparasitic medication. After this point Chagas is considered chronic and around 30% of people infected will experience symptoms later in life.[12] Furthermore, since *T. cruzi* can also be passed from infected individuals' blood from blood transfusions, infection rate will inevitably increase as people who are unaware, they are infected could be putting others at risk. Overall, there is currently a significant a lack of research on these parasites and Chagas disease in general which could prove problematic as this vector-borne disease becomes more common. [12]

Conclusions

Climate change will influence the geographic distribution of each of these vectors and their vector-borne diseases trending to more northward and southward expansion, while simultaneously remaining a threat in current geographic locations. There are a few measures in place that may improve preparedness against these diseases such as the yellow fever vaccine for example, but just like with a vaccine, prevention is better than treatment. Reversing the course of climate change will slow or stop the current damage and prevent many potential ecological disasters including the spread of vectors and vector-borne pathogens.

References

1. Barnett, E. D. (2007). Yellow Fever: Epidemiology and Prevention. *Clinical Infectious Diseases*, 44(6), 850–856. https://doi.org/10.1086/511869

2. Brun, R., Blum, J., Chappuis, F., & Burri, C. (2010). Human African trypanosomiasis. *The Lancelet*, 375(9709), 148–159. https://doi.org/10.1016/S0140-6736(09)60829-1

3. Burkett-Cadena, N. D., & Vittor, A. Y. (2018). Deforestation and vector-borne disease: Forest conversion favors important mosquito vectors of human pathogens. *Basic and Applied Ecology*, 26, 101–110. https://doi.org/10.1016/j.baae.2017.09.012

4. Caminade, C., McIntyre, K. M., & Jones, A. E. (2019). Impact of recent and future climate change on vector-borne diseases. *Annals of the New York Academy of Sciences*, 36(1), 157–173. https://doi.org/10.1111/nyas.13950

5. Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, Lars. R., Baylis, M., & Behrenfeld, M. J. (2019). Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, 17, 569–586. https://doi.org/10.1038/s41579-019-0222-5

6. Centers for Disease Control and Prevention, National Center for Emerging and Zoonotic Infectious Diseases (NCEZID), Division of Vector-Borne Diseases (DVBD). https://www.cdc.gov

7. Clayton, J. (2010). Chagas disease 101. *Nature*, 465. https://doi.org/10.1038/nature09220

8. Cruz-Lopez, L., Malo, E. A., Rojas, J. C., & Morgan, E. D. (2002). Chemical ecology of triatomine bugs: vectors of Chagas disease. *Medical and Veterinary Entomology*, 15(4), 351–357. https://doi.org/https://doi.org/10.1046/j.0269-283x.2001.00340.x

9. Diniz, D. F. A., Alburquerque, C. M. R., Olivia, L. O., Melo-Santos, M. A. V., & Ayres, C. F. J. (2017). Diapause and quiescence: dormancy mechanisms that contribute to the geographical expansion of mosquitoes and their evolutionary success. *Parasites & Vectors*, 10, 310. https://doi.org/https://doi.org/10.1186/s13071-017-2235-0

10. Fieler, A. M., Rosendale, A. J., Farrow, D. W., Dunlevy, M. D., Davies, B., Oyen, K., Xiao, Y., & Benoit, J. B. (2021). Larval thermal characteristics of multiple ixodid ticks. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,* 257. https://doi.org/10.1016/j.cbpa.2021.110939

11. Fouque, F., & Reeder, J. C. (2019). Impact of past and on-going changes on climate and weather on vector-borne diseases transmission: a look at the evidence. *Infectious Diseases of Poverty*, 8(1), 51. https://doi.org/10.1186/s40249-019-0565-1

12. Garza, M., Arroyo, T. P. F., Casillas, E. A., Sanchez-Cordero, V., Rivaldi, C., & Sarkar, S. (2014). Projected Future Distributions of Vectors of Trypanosoma cruzi in North America under Climate Change Scenarios. *PLOS Neglected Tropical Diseases*, 8(5). https://doi.org/10.1371/journal.pntd.0002818

13. Gilbert, L. (January). Altitudinal patterns of tick and host abundance: a potential role for climate change in regulating tick-borne diseases? *Oecologia*, 162(1), 217–225. https://doi.org/10.1007/s00442-009-1430-x

14. Greer, A., Ng, V., & Fisman, D. (2008). Climate change and infectious diseases in North America: the road ahead. *Canadian Medical Association Journal*, 178(6), 715–722. https://doi.org/10.1503/cmaj.081325

15. Kuhn, K., Campbell-Lendrum, D., Haines, A., & Cox, J. (2005). Using climate to predict infectious disease epidemics. *World Health Organization*, Geneva. https://www.academia.edu/29743327/Using_climate_to_predict_infectious_disease_epidemics

16. Lafferty, K. D. (2009). The ecology of climate change and infectious diseases. *Ecology*, 90(4), 888–900. https://doi.org/10.1890/08-0079.1

17. McMichael, A. J. (2014). Extreme weather events and infectious disease outbreaks. *Virulence*, 6(6), 543–547. https://doi.org/10.4161/21505594.2014.975022

18. Moore, S., Shrestha, S., Tomlinson, K. W., & Vuong, H. (2011). Predicting the effect of climate change on African trypanosomiasis: integrating epidemiology with parasite and vector biology. *The Royal Society Interface*, 9(70). https://doi.org/10.1098/rsif.2011.0654

19. Ogden, N. H., Beard, C. B., Ginsberg, H. S., & Tsao, J. I. (2021). Possible Effects of Climate Change on Ixodid Ticks and the Pathogens They Transmit: Predictions and Observations. *Journal of Medical Entomology*, 58(4), 1536–1545. https://doi.org/10.1093/jme/tjaa220

20. Ogden, N. H., & Gachon, P. (2019). Climate change and infectious diseases: What can we expect? *Canada Communicable Disease Report*, 45(4), 76–80. https://doi.org/10.14745/ccdr.v45i04a01

21. Ogden, N. H., Mechai, S., & Margos, G. (2013). Changing geographic ranges of ticks and tick-borne pathogens: drivers, mechanisms and consequences for pathogen diversity. *Frontiers in Cellular and Infection Microbiology*, 3(46). 2022-02-13. https://doi.org/10.3389/fcimb.2013.00046

22. Olmos, M. B., & Bostik, V. (2021). Climate Change and Human Security -The Proliferation of Vector-Borne Diseases Due to Climate Change. *Military Medical Science Letters*, 90(2), 100–106. https://doi.org/10.31482/mmsl.2021.011

23. Rahmstorf, S., & Coumou, D. (2011). Increase of extreme events in a warming world. *Proceedings of the National Academy of Sciences of the United States of America,* 108(4), 17905–17909. https://doi.org/10.1073/pnas.1101766108

24. Reinhold, J. M., Lazzari, C. R., & Lahondere, C. (2018). Effects of the Environmental Temperature on Aedes aegypti and Aedes albopictus Mosquitoes: A Review. *Insects*, 9(4), 158. https://doi.org/10.3390/insects9040158

25. Samuel, G. H., Adelman, Z. N., & Myles, K. M. (2016). Temperature-dependent effects on the replication and transmission of arthropod-borne viruses in their insect hosts. *Current Opinion in Insect Science*, 16, 108–113. https://doi.org/10.1016/j.cois.2016.06.005

26. Sutherst Robert W. (2004). Global Change and Human Vulnerability to Vector-Borne Diseases. *Clinical Microbiology Reviews*, 17(1), 136–173. https://doi.org/10.1128/CMR.17.1.136-173.2004

27. Terblanche, J. S., Clusella-Trullas, S., Deere, J. A., & Chown, S. L. (2008). Thermal tolerance in a south-east African population of the tsetse fly Glossina pallidipes (Diptera, Glossinidae): Implications for forecasting climate change impacts. *Journal of Insect Physiology*, 54(1), 114–127. https://doi.org/10.1016/j.jinsphys.2007.08.007

28. Ware-Gilmore, F., Sgro, C. M., Xi, Z., Dutra, H. L. C., Jones, M. J., Shea, K., Hall, M. D., Thomas, M. B., & McGraw, E. A. (n.d.). Microbes increase thermal sensitivity in the mosquito Aedes aegypti, with the potential to change disease distributions. *PLOS Neglected Tropical Diseases*, 15(7). https://doi.org/10.1371/journal.pntd.0009548