Climate Change Contribution to the Emergence or Re-Emergence of Parasitic Diseases

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ABSTRACT: The connection between our environment and parasitic diseases may not always be straightforward, but it exists nonetheless. This article highlights how climate as a component of our environment, or more specifically climate change, has the capability to drive parasitic disease incidence and prevalence worldwide. There are both direct and indirect implications of climate change on the scope and distribution of parasitic organisms and their associated vectors and host species. We aim to encompass a large body of literature to demonstrate how a changing climate will perpetuate, or perhaps exacerbate, public health issues and economic stagnation due to parasitic diseases. The diseases examined include those caused by ingested protozoa and soil helminths, malaria, lymphatic filariasis, Chagas disease, human African trypanosomiasis, leishmaniasis, babesiosis, schistosomiasis, and echinococcus, as well as parasites affecting livestock. It is our goal to impress on the scientific community the magnitude a changing climate can have on public health in relation to parasitic disease burden. Once impending climate changes are now upon us, and as we see these events unfold, it is critical to create management plans that will protect the health and quality of life of the people living in the communities that will be significantly affected.

KEYWORDS: Climate change, parasites, diseases, emergence, re-emerging

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Introduction

Climate change is a naturally occurring event, but human activities have significantly contributed to changes in atmospheric conditions, resulting in an accelerated change in this process, and the current precarious state.[1,2] Climate change is increasingly threatening as we continue to realize its potential impacts on global health and security. Global climate experts agree that anthropogenic activities have significantly contributed to the increasing concentration of atmospheric greenhouse gases and destruction of ecosystems.[3–6] Direct consequences of climate change are not difficult to notice through the occurrence of extreme weather events or changes in temperature and precipitation,[7] but indirect consequences are not as easily seen. An increase or change in the endemic range of parasitic diseases as a result of climate change will have very serious repercussions. Now, it is not only our physical footprints prompting the spread of disease through habitat destruction and ecological disruption[8] but possibly our carbon footprints as well. Climate change directly causes increases in temperature and affects weather patterns, which indirectly can change spatial patterns of disease vectors and human populations.[9,10] Increases in temperature facilitate the development of arthropod vectors that carry many parasitic organisms and the parasites themselves.[11] A warm climate also increases the range of reservoir hosts, vector abundance, biting rates and overall survival, and parasitic transmission rates of vectors such as mosquitoes, ticks, and tsetse flies.[12]

Parasitic diseases are often the burden of tropical and subtropical communities because those climates promote species richness[13–16] and therefore can support a multitude of potential hosts to sustain parasitic diseases. Complex host interactions are key to survivability and thrivability of parasites, and these complex interactions can be altered by a changing climate to promote infectious diseases.[17] Climate change has the potential to alter or extend the natural ranges of these organisms and make regions of our globe that were previously uninhabitable for parasites habitable.[18] Increases in temperature affect the life cycles of parasites, which can directly affect how prevalent the organism is within the area, considering many parasitic organisms have a temperature-dependent developmental baseline, either within their host or in the environment.[18]

Although less recognized than some other climate change consequences, emergence and reemergence of parasitic diseases are very concerning. These diseases often go deeper than just

*School of Public Health, University of Pittsburgh, Pittsburgh, PA, USA directly declining human health by promoting a positive feedback loop of poverty and economic stagnation in the communities they are most likely to affect,[18] ultimately declining overall quality of life. This review will explore some of the different parasites whose distributions, severity, or reemergence, in cases that have been previously eradicated, would be affected by climate change as well as some of the risks their associated diseases pose to local and global economies. We will examine vector-borne infections, ingested protozoa, soil-transmitted helminthiasis, and the economic implication of these diseases.

Vector-Borne Parasitic Diseases

Biological systems' changes associated with climate as well as alterations in insect and bird distributions indicate that vector-borne diseases already have the potential to move and spread to different regions.[19]

Insects

Mosquito prevalence is highly dependent on precipitation levels that promote mosquito breeding sites and appropriate temperatures for survivability.[20] Conditions favoring mosquito capacity to transmit infections, for example, malaria, are prevalent in sub-Saharan Africa and other endemic regions of the world and are attributed to the high rates of morbidity and mortality from these infections.[21–24] However, these factors can fluctuate as the climate changes in areas bordering regions where parasitic diseases are endemic and put the communities there at risk.[20,25] Certain diseases will cause even greater threats when they move to new areas because the people there will lack acquired immunity and experience more serious clinical disease.[26]

The Anhui Province in China has recently seen a dramatic reemergence of malaria cases since 2000, prior to which there was low-level endemicity.[27] The sudden increase in malaria cases was highly associated with temperature, rainfall, relative humidity, and multivariate Southern Oscillation Index.[27] The association between rainfall and malaria transmission was very significant.[27]

It is a known fact, based on written accounts of clinical symptoms and treatments used, that malaria was common in Europe prior to the 19th century.[28] Both Chaucer and Shakespeare alluded to the disease in their works, and the high disease prevalence has now been attributed to the extensive marshlands in England which would have supported the *Anopheles* mosquitoes.[28] The most effective treatment for ague at that time was cinchona powder from the bark of cinchona trees, and this particular tree bark contained quinine,[28] further revealing malaria as the disease being described. Risk modeling for the distribution of one particular *Aedes* mosquito, *Aedes albopictus*, has revealed that the climate of central Northwestern Europe is now warmer, wetter, and more favorable for the mosquitoes while areas with hotter, drier summers in Southern Europe may see a decline in mosquito populations in future.[29,30] Other *Aedes* species can be expected to follow similar patterns. In the future, however, it may be important to consider the possibility of mosquito species adapting to their changing environment, permitting them to remain in hot, southern regions.[31] It is deemed unlikely for malaria to become endemic in England anytime soon due to an advanced health care system,[32] but poorer nations without the luxury of sound infrastructure bear a greater burden, and thus, the cycle of disease and poverty is likely to continue in these countries. Herein lies the significant conundrum of climate change and infectious diseases and its capacity to negatively affect public health.

Even though the health system of the United Kingdom may be up to the task of preventing malaria outbreaks,[32] if weather conditions and competent mosquito populations that can facilitate autochthonous transmission interact, all that is required may just be an influx of subclinically infected immigrants or travelers from endemic regions to be bitten by local mosquitoes and aid the spread of malaria into new regions. These circumstances occurred recently during Greece's economic meltdown, a country within the borders of the European Union, that recorded significant autochthonous transmission of malaria from 2009 to 2011.[33,34] In addition to global travel, importation of certain goods, such as used tires, may help establish invasive mosquito species into new areas such as *Culex modestus* (vector for West Nile vector) and *Aedes albopictus* (vector for Chikungunya, dengue, Zika) which have been recently found in the United Kingdom.[35–38]

Other parasitic diseases with mosquito vectors are at a similar risk of spreading with a changing climate. The distribution of lymphatic filariasis can be determined by looking at soil and plant canopy moisture levels because these can indicate the presence of mosquito larvae breeding sites.[39] As temperature and precipitation patterns change, so will soil moisture levels and the corresponding mosquito populations. An ecological niche model created to scout the potential distribution of lymphatic filariasis in Africa revealed that depending on the severity of future climate change, the number of people at risk of infection could increase from 543 to 804 million to an astounding 1.65 to 1.86 billion as soon as 2050.[40]

In North America, we should perhaps be more concerned about triatomine bugs known to transmit Chagas disease, a common condition in rural areas of Latin America.[41] Triatomine insects are also very common in the Southern United States.[41–45] Now, Chagas is spreading further North, in parts of the Southern United States where the disease has more recently occurred autochthonously, most likely due to increasing temperature, immigration, and global travel.[41,46,47] There are at least 11 different species of triatomine insects in the United States, and many reservoir host species also inhabit this country, such as woodrats, racoons, skunks, and coyotes.[41] Certain counties in Texas are particularly at risk because of low-income neighborhoods called "colonias," which are characterized by poorly constructed residences and sanitation systems that would provide habitat for the insects and easier access into peoples' homes.[48] It is also possible that changing climatic conditions could cause a change in the behavior of triatomine insects.[48–50] Triatomine insects tend to feed more often to avoid dehydration when temperatures are upward of 30°C and humidity levels are low.[49] It has also been found that when indoor temperatures rise, triatomine insects may take on shorter life cycles, allowing them to increase their population density and increase the chances of spreading disease.[49] Other published reports have demonstrated faster development of *Trypanosoma cruzi*, the causative agent of Chagas disease, in some vector hosts when temperatures increase.[50]

Tsetse fly ranges were also modeled under climate change scenarios, and although these ranges are not expected to expand excessively, they are expected to shift significantly, negatively affected by climate change.[11] These range shifts could result in a larger population being at risk of contracting *Trypanosoma brucei* or human African trypanosomiasis.[11] In Zimbabwe, for example, tsetse fly abundance is decreasing due to a combination of vector control and too high temperatures that might negatively affect their survival, however habitat fragmentation, although creating conditions leading to higher populations of older flies, still increases the rate of infection and risk of disease.[51]

Adding to this is the preponderance of sand flies, an insect vector for leishmaniasis, encompassing a spectrum of clinical manifestations of variable prognosis that range from skin ulcerative lesions around the infection site, called localized cutaneous leishmaniasis, multiple nonulcerative lesions, called diffuse or disseminated cutaneous leishmaniasis, and severe disfiguring mucosal metastatic disease. It is responsible for significant morbidity and gross domestic product loss in many countries. In the United States, cases are recorded yearly in foreign travelers, immigrants, and military personnel.[52–54] Reports of autochthonous leishmanial infections among individuals who have never traveled outside the United States abound.[55–61] With the effect of climate change contributing to an increased range for sand flies, and flies being found in new locales, in addition to servicemen/women who served in the Middle East and may have been exposed to infection returning home, the opportunity for leishmaniasis in North America to expand both substantially and dramatically is now becoming a reality.[62] It has been recognized that in certain areas of the world, *Leishmania* infection rates are associated with seasonal variation.[63,64] Ecological niche models also predicted the expansion of suitable habitat for sand fly vectors, further increasing the risk of leishmaniasis in areas currently not endemic.[63,64] Even under the most restrictive model circumstances, human exposure to leishmaniasis is predicted to at least double by the year 2080 in the United States.[59] However, considering the rates of human migration and global civil unrests leading to massive movement of people from endemic areas to nonendemic regions of the world and international travel, this threshold should be crossed way earlier than predicted.

Ixodes tick species are perhaps best recognized as transmitters of bacteria and viruses such as *Borrelia burgdorferi* (Lyme disease) or *Flaviviridae* (tick-borne encephalitis), but they are also vectors for the protozoa that cause babesiosis. Greater than average precipitation during late spring or early summer likely promotes tick activity and increases survival rates in the Northeastern United States.[65] In Sweden, a northern shift and increase in the density of *Ixodes* tick populations in the 1990s was related to a changing climate, which consisted of milder winters and prolonged spring and autumn seasons compared with the 1980s.[66] Similarly, Canada and parts of subarctic Russia have seen increases in tick populations and tick-transmitted diseases as temperatures have increased.[67,68] Warmer climates have also been associated with better synchrony between larval and nymph stage ticks, and this allows faster disease transmission and more virulent strains of disease to persist in tick vectors.[69] Canine babesiosis cases have occurred under certain local climate constraints, such as a necessary temperature increase to 12 C to initiate soil defrosting and termination with temperature drops, concurrent rainfall, or intense drought.[70] Indirectly, weather conditions change people's behavior and put them at greater exposure to ticks. For example, increased rainfall may aid mushroom growth in Poland, promoting mushroom harvests after rainy weeks when ticks are also more active, thus putting the harvesters at greater risk of being bitten.[71] Combined with land use alterations, climate change is permitting ticks to increase their distribution farther North and pose a threat to new communities previously unexposed to diseases such as babesiosis.[72,73] This has been demonstrated by a noticeable increase in babesiosis incidence in disparate parts of the world such as the United States,[72] Canada, and the United Kingdom,[74] as temperatures warmed. Unfortunately, this trend is set to continue as distribution models have predicted that tick populations will expand further north in upcoming decades due to direct climatic factors and changing movement/migration of wild host species such as birds, deer, and the white-footed mouse.[74–78]

Other hosts

Snails are key intermediate hosts for *Fasciola* and *Schistosoma* parasites, with the local freshwater snail proportion typically directly related to that of the parasites.[79,80] The ability to maintain viable snail populations is dependent on water velocity, rainfall, and temperature.[80] It has been observed that snails require a relatively low water velocity and rainfall with moderate to warm temperatures, as snails in Nigeria were most abundant at the beginning of the dry season, and incidence of schistosomiasis followed this same time trend.[81] It is expected that climate change will cause water stress in some areas which could increase freshwater snail populations and disease incidence. Risk modeling has shown that while some of Northeastern Africa may see a decline in the risk of schistosomiasis infection, Southeastern Africa is at particular risk of increased infection rates of schistosomiasis and new areas are likely to become endemic with warming temperatures.[82] A modeling study for China showed similar trends, with the new areas at risk of schistosomiasis infection due to temperature increase accounting for an additional 8.1% of the surface area of China as expansion occurs north to currently nonendemic areas.[83] Farther from the equator, lymnaeid snails, intermediate hosts for *Fasciola hepatica*, also seem to be benefiting from a changing climate. The abundance of these snails is related to air and water temperature as well as soil evapotranspiration.[84] We will discuss fascioliasis in greater detail in the subsequent section on economic impacts.

Climate change is not the only threat to changing water velocity and temperature,[40] human activities are also major factors favoring increased snail populations. Through the redirection of available water for irrigation systems and the building of dams, humans may cause slower water currents resulting in warmer water temperatures and a consequent increase in snail populations and its subsequent implication for disease transmission.

Echinococcosis is a disease caused by *Echinococcus granulosus*, with a life cycle requiring no arthropod vectors. However, this parasite does not have a specific intermediate host, rather it uses a variety of organisms such as the fox, cat, and dog.[81] Unfortunately, this parasite has been able to use the raccoon dog as a definitive host, allowing it to expand its geographical range, thus further expanding the range of *Echinococcus* as well.[81] Even without a host, some parasites can survive in resistant, dormant stages until a suitable host is found, and a warmer climate will definitely assist to perpetuate those stages.[81]

Parasites in the Environment

Ingested protozoa

Protozoa that are exposed directly to the environment undergo a cyst or oocyst stage as a part of their life cycle, these stages providing varying degrees of resilience for the parasite and allowing its viability outside of a host species. Giardiasis, cryptosporidiosis, amebiasis, and toxoplasmosis can all be transmitted through contaminated drinking water.[85] Climate change may place a strain on agricultural industries as they try to retain crop productivity during droughts or periods of intense precipitation. To compensate for these crop stresses, increased fertilizer use is encouraged.[86] Animal fertilizers, as well as human biosolids used as fertilizers, have the potential to contain parasitic cysts and oocysts. Heavy rainfall events, which may increase in frequency and intensity due to climate change, will more often wash fertilizers into local waterways.[87] Heavy rainfall events can also simply extract cysts and oocysts from soil and grass,[88] and these events have been associated with outbreaks of cryptosporidiosis and giardiasis.[85,87,88]

A couple of scenarios can take place once these parasites are in a waterway. First, extreme rainfall events and flooding may render some wastewater treatment plants unable to accommodate the amount of influent sewage. Wastewater treatment plants are typically equipped with overflow systems that allow excess sewage to bypass treatment, other than a primary filter that removes large debris. This sewage then gets returned to the waterway untreated and with parasitic organisms still infective. This issue is augmented for island nations that flood easily during extreme weather events, such as hurricanes, and the groundwater may even be contaminated.[89] In 1987, people living on the Chuuk Islands of the Federated States of Micronesia experienced a sudden increase in amebiasis due to flooding from Typhoon Nina.[90] Second to overflows, parasites may not be killed by common disinfectants used at wastewater and drinking water treatment facilities and remain in the water. For example, chlorine is a common disinfectant that is not capable of killing *Cryptosporidium* spp. in oocyst form.[87,91] Even a more revered disinfection method, the usage of UV light, is not always effective at killing these oocysts.[92] Water temperature and UV exposure time play a role in parasite mortality, and for maximum effectiveness, these parameters must be carefully determined.[92] In either case discussed, humans ultimately come into contact with these contaminated waters and drink or otherwise ingest parasites because of climatic events.

Soil-transmitted helminthiases

Macroscopic parasites directly interact with their environments when part of their life cycle occurs outside of a host. Helminths such as hookworms, *Ascaris lumbricoides*, and *Trichuris trichuria* are present in soils before infecting a host, and certain soil components may be fundamentally altered by a changing climate.[93] Higher temperatures can cause faster larvae development and development within eggs for hookworms, which ultimately decreases their time to infectivity.[93,94] Increased precipitation levels could prevent desiccation of eggs/larvae thus allowing greater survival rates of these parasites.[93] Similarly, increased humidity levels would increase larval survival in soil, especially for hookworms as their larvae are at a greater risk of desiccation compared with other helminth species.[93]

After extensive deforestation in Haiti and political turmoil that prevented proper landscape maintenance, the River Royone began to more frequently flood the nearby community, with a resulting significant increase in the prevalence of hookworm infections.[95] Previously, hookworm infections had not been common in the area for some time, and it was determined that the change in soil content and moisture from the flooding river had contributed to and facilitated this reemergence.[95] In the 6 years following the floods, hookworm prevalence increased from 0% to 12% to 15%, whereas other helminthic infections remained relatively constant.[95] This case demonstrates how the combination of altered environments and extreme weather events can have dramatic, lasting effects on community health. With that information, it is possible to assume that climate changes promoting lower precipitation and humidity levels would decrease infection rates with hookworms, *A lumbricoides* or *T trichuria*, but this may not actually ring true. Regions that are likely to receive very little precipitation, thereby experiencing droughts, will have inadequate resources to maintain personal hygiene, potentially exacerbating the prevalence of infections by *A lumbricoides* and *T trichuria*, etc.[96]

It is important to note that deforestation and other such exploitations and alterations of the natural environment, including climate change, influence biodiversity, another major factor connected with increases in zoonotic and vector-borne diseases.[66,97]

Economics

Not only are these emerging and reemerging parasitic diseases negatively affecting human health, but they also have the potential to affect local and global economies. Broadly speaking, the debilitating nature of parasitic diseases prevents community productivity and advancement. Neglected tropical diseases, such as those caused by parasites, have resulted in losses of millions of working days and subsequently billions of dollars in economic growth each year.[98] Furthermore, parasites also affect the livestock on which people depend. It is important to note that the following 2 cases presented are neither isolated incidents nor exclusive examples of livestock deterioration due to parasitic infections.

The United Kingdom has seen a 20% increase in annual rainfall, fewer ground thaws, and warmer winters compared with 50 years ago, and there is a concern that these climate characteristics are beginning to negatively affect the sheep farming industry.[99] Unpredicted parasitic disease outbreaks caused by *Haemonchus contortus, Nematodirus battus, Teladorsagia circumcincta*, and *Fasciola hepatica* have been occurring in the United Kingdom.[84,99–102] Such outbreaks have indicated that these parasites are able to exploit the changing climate, and models have shown that Wales and Scotland are at particular risk with outbreaks occurring earlier in the year.[99,100,103] *Haemonchus contortus* is now able to complete its life cycle and expand farther north, exerting infection pressure in a bimodal fashion.[102,104] It has been estimated that climate change could extend the season of *F hepatica* development by up to 4 months in northwestern regions of the United Kingdom and allow fascioliasis transmission to occur during winter months in southern regions.[100,101] Although some areas may experience above optimal temperatures and droughts, it is unfortunately those areas predicted to have changes favorable to parasite development that overlap with high densities of cattle and sheep.[101] Growing degree-day modeling for New Zealand showed risk of infection in some regions may rise over 100% by 2090.[105] Although some regions had little change, it was again regions with sheep and cattle that typically saw risk increases.[105]

At present, there are more sheep in Scotland than there are people, and the approximate income value from sheep in 2015 was around 195 million Euros.[103] The dairy and sheep industries are similarly important in New Zealand. Cattle and sheep production is severely inhibited by parasitic diseases, and they easily spread throughout a flock without proper management.[99] These infections would significantly hinder the export potential of such countries with serious adverse effect on their economy and gross domestic product. It is easy to see how climate change favoring these parasites has the potential to cause serious damage to the Scottish economy.

Parasites can be just as damaging to an economy in water as they are on land. Just this year, *Diphyllobothrium nihonkaiense* tapeworm larvae were found in wild pink salmon off the coast of Alaska.[106] The possibility that climate change and corresponding ocean current events facilitated the parasite's presence in the Alaskan region cannot be ruled out. This is concerning because it means both wild-caught and farm-raised salmon are at risk of contracting this parasite, which certainly has a negative impact on the species' health but could have a negative impact on the salmon fishing industry as well. Parasitic diseases, vector-borne and helminthic alike, can seriously deteriorate livestock health and production and prove detrimental to local and global economies while also posing a significant threat to future food security.

Conclusions

Accumulating evidence has begun to show that climate change is altering the spread and distribution of parasitic diseases and their associated vectors.[19,29,31,40,48,67,84,99–102,104,105] This poses both a direct and indirect threat to human quality of life. Directly, these parasites may have the ability to infect a greater number of people through emergence and reemergence in areas made hospitable by a changing climate.[19,20,25,40] Indirectly, advancement and development of communities may slow due to infection of crops and livestock which could hinder, or even stifle, economic growth.[99,106]

Parasitic diseases may not always cause high mortality rates, but they can be very debilitating, preventing economic growth and advancement and keeping the communities affected in a positive feedback loop of poverty.[18] The areas of the world likely to be most affected by climate change are those still developing, with inadequate waste management systems,[89] medical supplies, and education to effectively subdue parasitic diseases. Climate change has the potential to further ramp up, in a negative way, the issues already faced because of parasitic diseases. It is therefore crucial and imperative that we consider these possibilities and begin to prepare for these changes that are already underway, planning for methods to limit epidemic eruptions and prevalence and incidence of parasitic diseases on a global scale.

Author Contributions

EES and BNT conceived the idea, gathered materials and wrote the manuscript; CC contributed to scientific content. All authors read and approved the final version of the manuscript.

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