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Climate Change and Zoonoses: A Review of Concepts and its Expansion

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Abstract:

Climate change (CC) is increasingly recognised as a critical driver in the emergence and re-emergence of infectious diseases. The relationship between CC and infectious diseases is complex and multifaceted, encompassing changes in temperature, precipitation patterns, and extreme weather events. This study describes the role of CC in the emergence and re-emergence of infectious diseases, emphasising zoonoses. It used a mixed methodology, to identify key thematic research areas related to CC and zoonotic diseases and show their connections. In addition, the research selected and analysed twelve literature-supported studies to investigate the relevance of the zoonoses involved in infectious disease emergence and re-emergence linked to CC impacts. Many pathogens and their vectors, such as mosquitoes, ticks, and rodents, are sensitive to temperature and moisture. CC can expand or shift the geographical distribution of these vectors, bringing diseases to new areas. Warmer temperatures may allow mosquitoes that transmit diseases like malaria and dengue fever to survive and reproduce in regions that were previously too cold. Also, extreme events such as floods, droughts, and hurricanes can lead to immediate increases in waterborne and vector-borne diseases (VBD) by facilitating the spread of pathogens. There is a need to better understand the connections between CC and zoonoses. To address the challenges posed by zoonoses linked to CC, international organizations like the WHO should coordinate a global response to provide clear guidance. Governments must integrate CC and zoonoses into national health policies, ensuring that health frameworks address these interconnected risks. Funding should be allocated for research on the root causes of CC and for strengthening defenses, particularly in developing countries with fragile health systems. Finally, zoonotic diseases, which were documented in the literature in the past, have evolved, especially during the years 2010–2015, as evidenced by the sharp augmentation of publications addressing ad-hoc events and peaking in 2020 with the COVID-19 outbreak.

***Keywords**: Zoonosis, Climate Change, Health Hazards, Humans, Animals.*

Introduction:

The current climate crisis significantly impacts all systems of our planet, including human and animal health [25]. One of the main impacts of climate change (CC) on public health is the influence on zoonotic diseases that are transmitted from vertebral animals to humans by parasites, viruses, and bacteria [25], and in particular on vector-borne diseases (VBD) transmission since a warmer climate and changing rainfall patterns may create more hospitable environments for climate-sensitive vectors such as mosquitoes, sand-flies, and ticks [7]. Such diseases are, for example, malaria, dengue, and West Nile fever (transmitted by mosquitos), leishmaniasis (transmitted by sand flies), and Lyme disease (transmitted by ticks).The processes that drive pathogen spillover operate at the nexus of environmental change, socioeconomic structure, and public health (2). There are various other factors associated with the emergence of zoonoses, such as globalization, international trade, land-use changes, and, increasingly, climate change associated with vector-borne zoonoses. Changing climate conditions may also be associated with the spread of hantaviruses through impacts on the hantavirus reservoir host populations.

Zoonotic diseases were defined in 1951 by the Expert Committee on Zoonoses as "diseases and infections that are naturally transmitted between vertebrate animals and man" [3]. Nonetheless, the German physician and pathologist Rudolf Virchow introduced the term "zoonoses" at the end of the 19th century to describe human diseases shared with animals [4,5]. "Zoonoses" derives from ancient Greek (*zoon*: animals, and *noson*: disease). Besides, this term is considered as the most appropriate in comparison to "anthropozoonosis" (from animals to humans) and "zooanthroponosis" (from humans to animals), which are focused on the predominant path of transmission between humans and other vertebrates [4]. Nevertheless, such terms have been synonymously used for all diseases found in animals and humans. Additionally, a third word, "amphixenoses", has been coined to describe infections that can be transmitted in either direction and maintained in humans and lower vertebrate animals [6].

Classification of Zoonoses:

Numerous microorganisms are responsible for zoonotic illnesses. According to their etiological causes, zoonoses can be divided into bacterial, viral, parasitic, fungal, rickettsial, chlamydial, and microbiological zoonoses as shown in Fig. 1. Bacterial zoonoses include illnesses like plague, anthrax, salmonellosis, tuberculosis, Lyme disease, and brucellosis. Among the viral zoonoses is rabies, AIDS and Ebola (11). Therefore, zoonotic illnesses are split into four classes based on epidemiological classification that takes into account the zoonosis maintenance cycle

According to the mode of transmission:

1. Direct Zoonoses (Orthozoonoses) can be transferred mechanically, through direct contact with a fomite, or by contact with an infected vertebrate host. The agent goes through little to no propagative modification and little developmental changes during such a process. Only a few instances are anthrax, brucellosis, trichinosis, and rabies (Grace et al. 2012).

2. Cyclozoonoses A few kinds of vertebrate hosts, but no invertebrate hosts, to finish the agent's evolutionary cycle. The three most common cyclozoonoses are pentastomid infections, echinococcosis, and human taeniasis.

3. Metazoonoses These are transmitted biologically by invertebrate vectors, in which the agent multiplies and/or develops and there is always an extrinsic incubation (prepatent) period before transmission to another vertebrate host e.g., plague, arbovirus infections, schistosomiasis, leishmaniasis.

4. Saprozoonoses These require a vertebrate host and a non-animal developmental site like soil, plant material, pigeon dropping etc. for the development of the infectious agent e.g. aspergillosis, coccidioidomycosis, cryptococosis, histoplasmosis, zygomycosis.

According to the Reservoir Host:

1. Anthropozoonoses Infections transmitted to man from lower vertebrate animals e.g. rabies, leptospirosis, plague, arboviral infections, brucellosis and Q-fever.

2. Zooanthroponoses Infections transmitted from man to lower vertebrate animals e.g. streptococci, staphylococci, diphtheria, enterobacteriaceae, human tuberculosis in cattle and parrots.

3. Amphixenoses Infections maintained in both man and lower vertebrate animals and transmitted in either direction e.g. salmonellosis, staphylococcosis

Climate change impacts on zoonoses:

1. Vector-borne zoonoses:

Vector-borne diseases are those transmitted by infected arthropod species such as mosquitoes, ticks, triatomine bugs, sand flies, and blackflies. Arthropod vectors are ectothermic; therefore, temperature directly affects vector survival and reproduction rates, influencing their distribution, abundance, habitat suitability, intensity, and temporal pattern of vector activity (e.g., biting rates), and also rates of development, survival, and reproduction of pathogens within vectors (Martin et al., 2008). Heavy rainfalls generate additional potential breeding sites for vectors such as mosquitoes. Further, dense vegetation created after rainfalls provides shelter and resting sites for vectors (Githeko et al., 2000). Therefore, climate changes are associated with ecological shifts affecting disease incidence and distribution. Furthermore, detrimental impacts of climate change on vector species have also been reported. A study in Kenya identified a significantly lower abundance of *Aedes aegypti* pupae following a heat wave in Chulaimbo, in Western Kenya (Nosrat et al., 2021). Under future climate conditions (high temperatures), Escobar et al. (2016) forecast ed geographic range reductions for vectors of arboviruses (48% for *Aedes aegypti* and 53% for *Aedes albopictus*) and leishmaniasis, and some vector species of Chagas disease (e.g., *Triatoma carrioni*, *Triatoma dispar*, and *Rhodnius ecuadoriensis*) in Ecuador by 2100.

2. Mosquito-borne zoonoses:

Mosquitoes can carry various pathogens, including viruses, protozoa parasites, and bacteria. They are responsible for the amplification and transmission of many zoonotic diseases such as zika, dengue, and chikungunya. Therefore, it is necessary to understand the predictive trends of mosquito-borne diseases in response to the projected climatic changes. Favorable temperatures influence mosquito reproduction, activity, frequency of blood meals, and faster digestion (Martin et al., 2008), whereas high water temperature leads mosquito larvae to develop rapidly. Therefore, climatic changes modify vector capacity and transmission of many diseases altering mosquito-borne disease dynamics (Reiter, 2008). For example, a retrospective study of the West Nile virus (WNV) outbreak in Southern France in 2000 showed that the vector aggressiveness (biting rate of *Culex modestus*) was positively linked with temperature and humidity and also associated with heavy rainfall and sunshine (Ludwig et al., 2005).

Aedes aegypti and *Aedes albopictus* transmit more than 22 arboviruses to humans (Medlock et al., 2015). Therefore, the habitat range of these vectors is much of a concern in public health. Previous studies projected a poleward expansion of suitable habitats for both *Aedes* species in North America (Khan et al., 2020), Australia (Hennessy et al., 2004), and Europe (Fischer et al., 2011). Nevertheless, the climatic suitability of *Aedes* species in Southern Europe is predicted to decline during the 21st century (Fischer et al., 2011), likely due to hotter and drier weather and droughts. A study of dengue fever suggested geographical limits of dengue transmission to be greatly determined by climate (89% accuracy based on vapor pressure). With population and climate change projections for 2085, authors have estimated that about 50–60% of the projected global population (5–6 billion people) would be at risk of dengue transmission, compared to 35% of the population (3.5 billion people), if climate change did not ensue (Hales et al., 2002). Under the most extreme emission scenarios, a study predicted the risk of dengue transmission most likely by *Aedes aegypti* (and less likely by *Aedes albopictus*) during the summer in the UK by 2100 (Liu-Helmersson et al., 2016). According to another study, by 2100, no parts of the UK become fit for dengue virus amplification within *Aedes aegypti* (Thomas et al., 2011), which is not consistent with the previous study.

Introductions of *Aedes albopictus* and chikungunya virus into Italy have been documented as accidental events (European Centre for Disease Prevention and Control, 2019). However, the density of the *Aedes albopictus* in Italy was recognized as the main contribution of the first chikungunya outbreak in a temperate climate (Rezza et al., 2007). According to the European center for Disease Prevention and Control (ECDC), further transmission and distribution of *Aedes albopictus* have been predicted under favorable climatic conditions in temperate countries.

Another good example is malaria. Malaria is a contagious parasitic disease caused by *Plasmodium* parasites, often reported in tropical countries (tropical disease). However, an association between meteorological conditions (e.g., temperature and precipitation) and malaria transmission in temperate countries has been discussed in several studies, in which they have described the potential of invading malaria and other “tropical” diseases to Southern Europe, as an example of the geographical expansion of malaria risk due to climate change. A study in Portugal predicted a rise in the number of days per year fits for malaria transmission if infected vectors are present (Casimiro et al., 2006). A study in the UK estimated an 8 to 14% increased risk of local malaria transmission, based on the projected temperature changes to occur by 2050 (European Centre for Disease Prevention and Control, 2019; Kuhn et al., 2003). A study of malaria impact models showed an overall global net increase in climate suitability and a net increase in the annual person-months at risk from the 2050s to the 2080s. The study suggested that future climate might fit more for malaria transmission in the tropical highland regions, particularly the East African highlands (Caminade et al., 2014). Malaria epidemic is predicted to move southward in sub-Saharan Africa and toward higher altitudes in highland regions (Ermert et al., 2012); by the end of the 21st century, temperature conditions in the semiarid region of the Sahel are expected to become unfavorable for the malaria vectors (Caminade et al., 2014). Under a medium-high scenario of climate change, a study projected that the southern half of Great Britain become climatically suitable for *Plasmodium vivax* malaria transmission for two months of the year, and parts of the southeast of England for four months per year, by 2030 (Lindsay et al., 2010). By 2080, Southern Scotland is also predicted to become climatically suitable for two months of the year (Lindsay and Thomas, 2001).

3. Sand fly-borne zoonoses

Like in mosquitoes, temperature impacts the biting rates of sand flies, diapause, and the development of pathogens (protozoa) within the vector. In Europe, sand flies are distributed in the south of latitude 45 °N and less than 800 m above sea level. However, they have recently extended as high as 49 °N (European Centre for Disease Prevention and Control, 2019). According to ECDC, the temperature in Northern Europe is expected to become warmer, and precipitation will increase (European Centre for Disease Prevention and Control, 2019). Also, winter temperatures are expected to elevate at higher altitudes. These climatic changes are predicted to expand the range of sand flies to Northwestern and Central Europe and higher altitudes in the regions where they are already established (Medlock et al., 2014). Projected climatic changes in Europe will provide favorable temperatures for sand flies, thereby they will rapidly establish in countries currently on the perimeter of their geographical range, such as Germany, Austria, Switzerland, and along the Atlantic coast (Naucke et al., 2011, 2008; Ready, 2010). Sand flies are capable of transmission of leishmaniasis, which is a protozoan parasitic infection caused by *Leishmania infantum*. Currently, Central and Northern Europe only have imported cases of leishmaniasis-infected dogs. If the projected climate changes make transmission suitable in northern latitudes, the new endemic foci can be developed by becoming these imported cases as the source of infection. On the other hand, too hot and dry weather is unfavorable to sand flies, which will lead to the disappearance of the disease from southern latitudes. Therefore, projected climate changes will continue to change the distribution of leishmaniasis in Europe (European Centre for Disease Prevention and Control, 2019).

4. Waterborne zoonoses:

Increased precipitations, flooding, and extreme events can result in run-off and loading water sources with various harmful pathogens, nutrients, and toxins, which elevate the disease burden due to waterborne pathogens. Waterborne diseases spread to humans, mainly via drinking, food processing, and recreational use of contaminated water. A substantial number of emerging and re-emerging waterborne zoonotic pathogens, such as *Campylobacter*, *E. coli* O157: H7, *Cryptosporidium*, and *Leptospira*, have been documented over recent decades. Prolonged periods of hot weather will raise the mean temperature of water bodies, which increases the reproduction cycles of pathogens. An increased growth rate of *Vibrio* species indigenous to the Baltic and the North Sea has been observed during unusually hot summers (Sterk et al., 2015). The risk related to infectious diseases was doubled with the exposure to Southern California coastal waters during an El Niño winter, compared to a La Niña winter (Dwight et al., 2004).

A study projected an increase in precipitation in the central watershed in Vancouver, Canada, during the wet season (October to March) and a decline in the dry season (April to September) in the 2080s. Therefore, the combined incidence of cryptosporidiosis and giardiasis in the wet season was projected to increase by 5.9–16.3% (averaged across twelve projection models) in the 21st century relative to the 1970–2000 period (Chhetri et al., 2019). Campylobacteriosis is one of the most reported zoonotic diseases in New Zealand (Ministry of Health of New Zealand, 2018). It is associated with increased rainfall, especially in agricultural landscapes. In New Zealand, human exposure to *Campylobacter* pathogens occurs mainly via recreational use of the contaminated water or via drinking insufficiently treated water. On the other hand, schistosomiasis is an acute and chronic disease caused by freshwater parasitic worms that live in certain aquatic snails (intermediate hosts). These parasites require specific water temperature conditions for survival. Schistosomiasis infection risk in East Africa is predicted to significantly increase by 20% over the next 20–50 years due to climate change (McCreesh et al., 2015).

5. Foodborne zoonoses:

Foodborne illness is caused primarily by consuming food contaminated with pathogens or toxins. Climatic factors such as high temperature can increase replication cycles and the growth, survival, and transmission of foodborne pathogens. Therefore, prolonged high-temperature seasons can alter the risk of foodborne diseases. The risk of campylobacteriosis in the European Union (EU) was positively correlated with mean weekly temperatures (European Centre for Disease Prevention and Control 2021b)(). A recent study predicted a doubling of *Campylobacter* cases in four Northern European countries (Denmark, Finland, Norway, and Sweden) by the end of the 2080s, with an additional 6000 cases/year due to climate change (Kuhn et al., 2020). For the ambient temperatures above 5 °C, 5–10% higher salmonellosis notifications have been identified for each degree increase in weekly temperature in the EU member countries (European Centre for Disease Prevention and Control, 2019; Kovats et al., 2004). Salmonellosis is a primary cause of foodborne outbreaks worldwide. According to a study of climate change projections, the mean annual number of temperature-related salmonellosis cases in Europe may increase by around 20,000 by the 2020s, in addition to the other means, such as future population changes. By the end of the 21st century, 50% more temperature-related cases are predicted than that based on population change alone (Watkiss and Hunt, 2012). Food and waterborne norovirus outbreaks have been associated with climatic events such as heavy rainfall and floods, which cause wastewater overflow contaminating fresh and marine water sources and aquatic species (Miossec et al., 2000; Schmid et al., 2005). The projected upsurge of heavy precipitations due to climate change will lead to an increase in norovirus infections.

6. Rodent-borne zoonoses:

Rodents are primary reservoirs in various zoonotic diseases such as hantavirus infection and plague. Climatic factors have a notable impact on rodent populations. For instance, recently warm, wet winters and springs have been observed expanding rodent populations. Additionally, harsh weather conditions, including heat waves, are unfavorable to rodents, causing them to move indoors in search of water and food, which elevate human-rodent interactions (European Centre for Disease Prevention and Control, 2019). Further, heavy rainfalls produce more crops and foods, promoting rodents to breed more often and expand the population. Plague is a zoonosis caused by the bacterium *Yersinia pestis*, spread by fleas feeding on rodents. Plague is currently not a primary threat in Europe, following the last major plague outbreak in 1720 (European Centre for Disease Prevention and Control, 2019). Previous studies have identified a strong association between ENSO-induced climate anomalies, temperature and precipitation anomalies, and plague activities in the United States (Anyamba et al., 2019; Enscore et al., 2002) and Madagascar (Kreppel et al., 2014). Also, climatic changes in Central Asia have driven the plague propagation (Stenseth et al., 2006). It has been estimated that a 1 °C degree increase in spring temperatures could result in a >50% increase in *Y. pestis* prevalence in its reservoir host. A study in California revealed that the projected climatic variations increase plague risk along the northern coast and Sierras and lower plague risk in the southern parts of California (Holt et al., 2009). Another study predicted to reduce periods of high plague activity in the Western United States and move plague to higher latitudes and altitudes due to climate change (Ari et al., 2008; Nakazawa et al., 2007).

7. Airborne zoonoses:

Meningococcal meningitis is an infection of meninges, caused by the bacteria Neisseria meningitidis, that causes high death rates in developing countries. It is believed that increased concentration of dust, high winds, elevated temperatures, and low humidity may cause damage to nasopharyngeal mucosa leading to increased susceptibility to meningitis[22]. COVID-19 cases and temperature have also shown a positive correlation[23]. It is possible that extreme heat forces people indoors which can increase the risk of virus transmission.

Conclusions and Outlook:

Climate change is one of the most concerning issues threatening our planet and humanity in the 21st century. The impacts of climate change are well beyond the temperature increases, changes in rainfall patterns, increased frequency of extreme events, or changes in ecosystems. Human health is considerably affected by climate change in many ways, including the development of respiratory and cardiovascular problems, heat stroke, dehydration, and mental health issues; moreover, zoonotic diseases are becoming a major threat due to the drastic changes in ecosystems and exceedingly closeness of the people with the other species. Therefore, the impact of climate change on zoonoses is a rapidly growing area of research.

This review highlights significant regional changes in zoonoses reported throughout the world and changes that have been predicted by scientists worldwide. In this study, we reviewed several climate-change models and scenarios to evaluate the future projections of various zoonoses in response to the anticipated climate variations. Many climate models predict that geographic changes will occur in several vector-borne (e.g., malaria, yellow fever, dengue, and leishmaniasis) and waterborne (e.g., cholera) zoonoses. However, there is no consensus for certain diseases modeled by different authors. Nevertheless, this review summarizes that climate change may cause poleward expansion of various disease transmission (e.g., leishmaniasis, Lyme disease, schistosomiasis, plague, HPAI, and malaria) and alterations in timing and seasonality of some diseases (e.g., dengue fever and HPAI) in future. According to Nandi and Allen (2021), seasonality plays a crucial role in the timing and the severity of the risk of human spillover events in zoonoses. Among the publications used in this review, there were only a few studies that had incorporated the other cofactors such as human population projections in the models. Other risk factors, such as urbanization, population growth, land use, and migration, should also be considered for further assessments since they may limit or intensify the likelihood of climate-related emergence of zoonotic diseases. There are many studies focused on climate change projections for vector-borne, waterborne, and foodborne diseases worldwide. Only limited studies have been conducted on climate projections on airborne diseases, although several epidemiological studies showed an association between airborne diseases and meteorological conditions. Moreover, elevated temperatures and drought increase the frequency, extent, and severity of wildfires, which will alter the distribution of reservoir hosts and biological vectors of many zoonoses. Yet, there are fewer studies, modeling the impacts of wildfires on zoonoses.

This review captured various studies within a comprehensive time frame of 21 years which disclosed imperative predictions covering various zoonoses and geographical regions. However, the quality of the publications has not been assessed in this review. Validation of the findings of these models is also essential to negate skeptic dialog and present credible scientific predictions to the debate of climate change and zoonoses and for policymakers to initiate effective control solutions. The significance of climate change on human health has already been acknowledged by regional and global level policymakers. World Health Organization (WHO) Executive Board endorsed a work plan in 2015 on climate change and health, which includes partnerships, awareness-raising, science and evidence, and support for the implementation of the public health response to climate change (World Health Organization, 2018). Thus, these scientific predictions will be crucial for policymakers to assist the targeted countries/regions in building capacity to lower zoonosis vulnerability due to climate change and promote human health while developing and facilitating a global agenda to minimize the causes that are leading to the current drastic changes in the climate (e.g., carbon emissions). The geographical regions/countries can be prioritized in control programs based on the severity of the impact (e.g., human health, quality of life, economy, epidemic and pandemic potentials) expected in the future and the level of assistance and resources that would necessitate to effectively alleviate the detrimental impacts of zoonoses. Therefore, monitoring short-, medium- and long-term changes in meteorological conditions can be a valuable tool for public health practice. For example, it can help detect epidemic precursors of vector-borne disease outbreaks and serve as early warning systems for risk reduction. Therefore, integrated animal disease and vector surveillance, outreaching to the public and health care providers, execution of mitigation and control programs, such as vector surveillance and abatement activities, can be implemented early to prevent future occurrence. Hence, future studies are required to address the above research gaps, and thereby, to be more prepared for incoming zoonotic threats by planning and executing control programs for a healthy planet.

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