

Parasites in a Changing Climate: Emerging Challenges in the Epidemiology and Control of Vector-Borne Parasitic Diseases

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ABSTRACT

Climate change is influencing the ecological factors that control the incidence and spread of parasitic diseases, posing additional issues for disease monitoring and preparedness within public health. This review highlights the link between climatic variation and vector-borne parasitic diseases by reviewing the recent literature on parasite ecology, vector biology, geographical distribution, modes of transmission, emergence of disease, population susceptibility, and methods of disease control. Special emphasis is placed on how temperature, precipitation, humidity, extreme climatic events, and environmental variations may affect parasite development, vector lifespan and reproduction, competence, host-vector interaction, and seasonal transmission cycles. Previously, it has been demonstrated that environmental changes caused by climatic factors may affect the ability of vectors and parasites to thrive in specific areas, alter transmission seasons, and cause changes in the geographic distribution of malaria, leishmaniasis, lymphatic filariasis, schistosomiasis, and other parasitic diseases. The review also discusses the appearance of parasitic diseases in new geographical regions and the threats posed by them to children, pregnant women, displaced people, poor individuals, and those who lack access to healthcare services. The increased use of geographic information systems, remote sensing, ecological niche modeling, weather forecasting, and early warning systems presents possibilities for identifying changes in disease patterns and providing intervention. But inadequate surveillance systems, limited information about disease distribution, limited modeling tools and an inability to integrate climatic and epidemiologic information pose major hurdles. Overall, the literature suggests that the need for understanding parasite-vector-host interactions in varying environments is vital.

KEYWORDS: Climate Change; Parasitic Diseases; Vector Ecology; Parasite Transmission; Geographic Distribution; Disease Emergence; Climate Surveillance.

1. INTRODUCTION

Climate change is now increasingly being understood as an important factor of influence that could have a significant impact on the epidemiology, geography, seasonality and severity of the parasitic diseases caused by the arthropod vectors and other intermediate hosts. Increased temperatures, changed patterns of precipitation, humidity, droughts, floods, and frequency of extreme events could affect vector survival, reproduction, biting behavior, development of the parasites and host-vector interactions, hence altering the environments suitable for the transmission of the parasites [1,2]. Vector-borne diseases constitute 17% or more of infectious diseases worldwide. Parasitic diseases include malaria, leishmaniasis, lymphatic filariasis, schistosomiasis, onchocerciasis, Chagas disease and African trypanosomiasis. Many people die from these parasitic diseases, especially those who live in tropical and subtropical areas [3]. Recent studies have shown that climate-related environmental changes could increase the geographical and altitude range of vectors and the duration of time suitable for transmission, although this effect varies depending on many factors including the parasite species, ecology of the vectors, climate, land use, socio-economic conditions and current interventions [4,5]. Take malaria as an instance where temperature and rain affect the mosquito population, parasite development, and parasite transmissibility. Moreover, changes in climatic patterns will cause new seasonal or geographical windows of transmission in some areas [2,3]. Notably, one must not view climate change as the lone factor that contributes to the epidemiological situation since there are other factors like urbanization, deforestation, expansion of agriculture, migration, socio-economic disparities, vector evolution, and insecticide/antimalarial drug resistance [1-3].

These impacts have further consequences for a broad array of parasitic diseases, which have traditionally been considered neglected. Recent literature indicates that alterations in temperature, precipitation, vegetation, humidity, and

habitat conditions can shape the prevalence and distribution of sand flies carrying leishmaniasis parasites and may facilitate vector establishment in previously unsuitable habitats [4]. In a similar fashion, climate change-related shifts in freshwater ecosystems will likely have an effect on snail intermediate hosts of schistosomes and will lead to the formation of novel suitable areas for the disease, alongside decreased transmission in other endemic zones [5,6]. The formation of new patterns of distribution and transmission poses a significant challenge for traditional disease control programs due to the fact that surveillance and control mechanisms are typically constructed upon stable distribution patterns and seasonal transmission periods. Additionally, a systematic literature review conducted recently indicates that while climate change-mediated expansion of vector ranges has become a common phenomenon, it cannot be the only one responsible for the shifting range – anthropogenic dispersal of mosquitoes and urbanization have been shown to contribute to distribution expansion as well [7]. In this respect, the control of climate-resistant parasitic diseases needs the integration of climatic and environmental surveillance with traditional epidemiological surveillance, geographical information systems, remote sensing technology, predictive modeling, early warning systems, community-based programs, vector control, diagnosis, and better health infrastructure. These tools are especially significant for vulnerable communities in resource-poor areas, where the combination of climate risks and lack of health services can lead to increased disease prevalence despite efforts toward disease elimination [8-10].

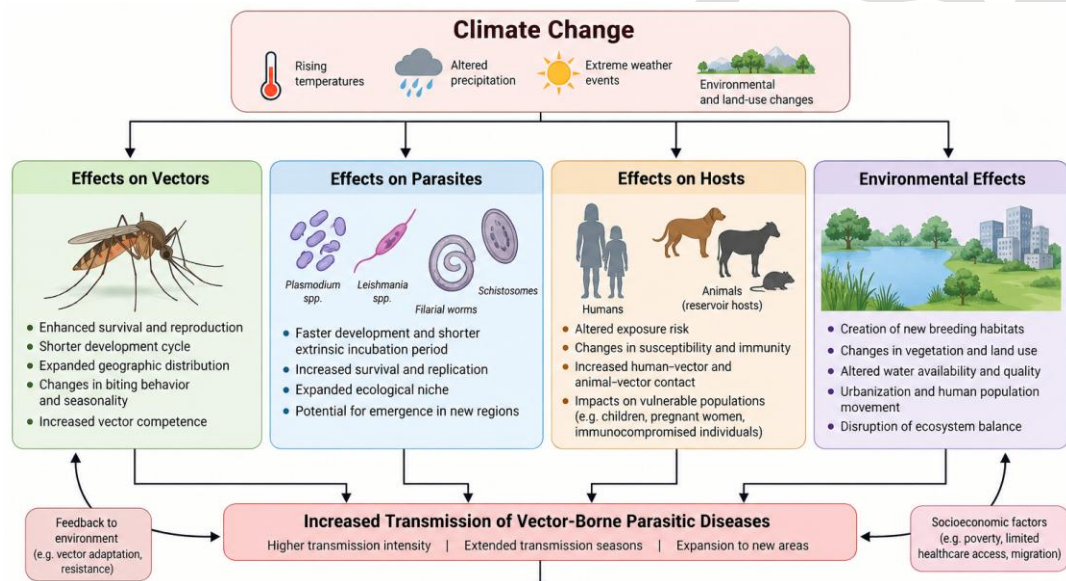


Figure 1: Effects of climate change on vectors, parasites, hosts, and transmission of vector-borne parasitic diseases.

This review explores the ways in which climate variability and climate change impact the epidemiology, geographical spread, seasonality, transmission cycles, and control of some vector-borne parasitic diseases. Special attention is given to malaria, leishmaniasis, lymphatic filariasis, schistosomiasis, Chagas disease, and other neglected tropical parasitic diseases. The review also analyses the role of climate change-based surveillance, forecasting models, vector management, early warning systems, and One Health approaches for improving the prevention and control of these diseases under the conditions of climate change.

2. CLIMATE CHANGE AND THE CHANGING ECOLOGY OF PARASITES

Recent research has increasingly found that climate change is able to affect the ecology of parasites at various levels of biological organization and space through changes in temperature, rainfall, humidity, water flow, seasonality, and extreme climatic conditions. The most relevant is the change in temperature because different parasites have different thermal ranges, which implies that even slight changes in environmental temperature affect the development, maturation, survival, reproduction, infectivity, and transmissibility of parasites. Recently, experimental and theoretical works have revealed that responses to changes in climatic variables are species-specific, meaning that certain parasites will have accelerated development and greater transmission under warming, while other parasites will have increased mortality because of exceeding their optimal thermal range [11,12]. The basis of nine experimental studies of trichostrongylid helminth species

showed that temperature and humidity influence infection risk of various parasites differently, and larval survival is a key factor of climate-related transmission dynamics. The modeling has indicated that climate change may induce changes in the geographic and seasonal patterns of helminth infection and facilitate the spread of certain species into new latitudes [13]. In addition, it has been noted in the case of mosquito-borne pathogens that temperature is combined with host presence and behavior in order to set a thermal optimum and the entire niche for pathogen transmission, as the latter cannot be determined based solely on temperature [14]. On a larger scale, the climatic alterations may significantly affect the dynamics of vector-borne diseases due to the influence of climate on the survival, reproduction, geographic range, and development of vectors [8,9].

New literature has not only moved away from the focus on climatic impacts on specific parasite species to looking at how changes affect host-parasite interactions and parasite communities but has also focused on ecological processes. Climatic conditions such as precipitation, drought, flooding, water temperatures, and habitat structures have the ability to change the availability of intermediate and definitive hosts and disrupt the life cycle of parasites whose transmission is complex. The anthropogenic impacts like global warming, changes in habitat, and pollution could significantly impact the composition of aquatic parasite communities; however, those with complex life cycles were most susceptible to ecological perturbation [15,16]. The point that climate change would alter parasitism and animal communities via changes in temperature and other environmental variables, thereby showing that there is an interaction between parasites and ecosystem structure due to climatic conditions [17]. More importantly, a meta-analysis which involved 2,938 observations in 1,497 combinations of hosts and parasites, showed that climatic change, biodiversity loss, chemical pollutants, and the introduction of new species all impacted disease-related consequences positively [18,19]. It has also been demonstrated recently that episodes of excessive warming might interfere with host-parasite interactions by interfering with the synchrony and phenology of host and parasite life cycles, thus leading to ecological maladaptations and unanticipated effects of disease [5]. Altogether, such findings suggest that changes in climate may lead to parasite proliferation and extinction of parasites, depending on specific thermal sensitivity, life cycle complexity, availability of hosts, persistence in the environment, and ecology of the parasites in question. The current paradigm shift makes an attempt to move from correlation-based analysis of the climate-disease relationship to more mechanistic approaches.

3. EFFECTS OF TEMPERATURE ON PARASITE AND VECTOR BIOLOGY

Temperature is one of the most influential environmental factors shaping the development of parasites and their arthropod vectors due to the sensitivity of both of these organisms to temperature conditions. In recent studies, it was revealed that temperature influences vector survival, fecundity, larval development, biting rate, host-seeking behavior, vector competence, and parasite development inside the vector [20,21]. All of these relationships between temperature and parasite-vector systems usually demonstrate non-linear thermal-performance curves where parasite and vector performance increases at favorable temperatures but decreases if temperature gets close to or exceeds upper thermal limits [22]. In malaria systems, temperature impacts population dynamics of *Anopheles* mosquitoes and development of *Plasmodium* in the mosquito and thus affects the extrinsic incubation period, vector competence, and overall transmission potential [23]. According to the study, an environmentally dependent model of *P. falciparum* and *A. gambiae* showed that parasite establishment, developmental conversion, parasite development rate, and vector competence depended on temperature. Moreover, their findings reveal that warming will not lead to a proportionate increase in malaria transmission due to the temperature response differences of the parasite and vector [24,25]. In a similar manner, studies done in Chennai, India, revealed an inverse relationship between EIP of *P. falciparum* and *P. vivax* and increased microclimatic temperatures and temperature ranges on a daily basis, implying that higher temperatures speed up the process of parasite development within *Anopheles stephensi* and might lead to more cases of infective mosquitoes [18]. Such results confirm earlier studies, according to which mosquito biting rate, mortality, parasite development, and vector competence exhibit different reactions to changing temperatures, and it is important to account for such specific traits of each type [6].

The role of temperature fluctuations, instead of mean temperature alone, in impacting the performance of both the parasite and the vector is increasingly gaining scientific recognition. A study investigated the effect of constant vs. fluctuating temperatures on *Anopheles stephensi* mosquitoes and found that the fluctuation in daily temperature strongly affected mosquito biting rate, survival, and fecundity, especially around the thermal optima and thermal upper limits. In their findings, models using constant temperatures were found to overestimate or underestimate the actual thermal suitability of the mosquito population in their naturally fluctuating environment [12,13]. Similarly, a previous study showed that the thermal optimum and thermal niche of mosquito-borne parasite transmission are influenced by host availability and host defensive behavior, showing that vector-parasite-host interaction should be considered in climate change-based transmission models [26]. At the molecular level, a study found that temperature fluctuations affect the transcriptome of *A. stephensi*. The effects of

temperature on the parasite can be through the regulation of its development rate, survival, infectivity, and maturation, with high temperature lowering parasite viability or disrupting synchronization between the parasite and vector life cycle [27,28]. Therefore, recent evidence shows that the influence of temperature on parasitic diseases is context-specific and results from the cumulative responses to temperature by the parasite, vector, and host [16]. The importance of such interactions is especially critical in light of climate change, where higher temperatures, increased variability in diurnal temperature, and an increase in heat waves can influence the geographical range and transmission seasons for parasites.

4. CHANGING GEOGRAPHIC DISTRIBUTION OF VECTOR-BORNE PARASITES

The geographic distribution of vector-borne parasitic diseases is becoming more and more impacted by interrelations between climate change, ecology of vectors, environmental changes, movement of people, and socioeconomic factors. New research shows that variations in temperature, rainfall, humidity, and occurrence of extreme climatic events can alter the suitability of areas for vectors and parasites, leading to a change in the latitudinal, longitudinal, and altitudinal range of vectors and parasites [8,9]. Expansion due to changes in climate conditions has been noted mostly in mosquitoes and mosquito-borne diseases. Modeling showed that rising temperatures would make climatic conditions suitable for mosquitoes outside of their historically endemic areas. Using an ensemble of eight modeling methods and high-resolution climatic data, a study found considerable potential for expansion of the climatic suitability of *Anopheles stephensi*, an increasing vector of malaria in urban areas [21-23]. In another study, 255 studies and over 211,000 observations of *Anopheles coluzzii* and *Anopheles gambiae* in Africa were analyzed, and it was found that climatic conditions would become suitable for *A. coluzzii* in some areas of East Africa in the future. A systematic review of 178 articles from six continents found that 118 medically significant mosquito species had extended their ranges, but less than 10% of articles included a statistical analysis of climate change as the cause of range expansion, while human-assisted transport of the mosquitoes via commercial activity and human movement was commonly cited as an important factor [24,25]. Consequently, there is mounting scientific evidence to support the existence of a complex model, whereby climate change interacts with other factors to influence parasite/vector establishment and persistence [19].

The phenomenon of geographical redistribution is also seen in parasitic infections caused by sand flies and freshwater intermediate hosts. The climatic factors play a role in survival, abundance, seasonal prevalence and geographic distribution of sand flies, thus impacting the distribution of *Leishmania* transmission [11]. One of the previous study explored the climatic suitability for vectors and parasites causing cutaneous leishmaniasis in Western Asia, and found that climate change may alter the patterns of suitability for both vectors and parasite transmission in the middle and later part of the twenty-first century [12]. Similarly, in field studies carried out in Mexico, it was found that sand fly distribution is influenced by temperature and precipitation, and several species had unreported geographical and altitudinal records. It was pointed out that urbanization and climate change could make some new areas favorable for vectors [24]. Geographical redistribution is also observed in schistosomiasis infections, in which rising temperatures, changes in rainfall and modification of freshwater habitats may affect the geographic distribution of the intermediate host snails. A recent scoping review of 121 studies and reports suggests that climate change will likely lead to shifts in the geographic distribution of schistosomiasis infection and possibly the development of new transmission areas in areas that were not conducive to infections before, such as some parts of Southeast Asia, Pacific Islands, the Mediterranean region and the Amazon Basin (2025) [9-11]. Together, these studies prove that the shifting of geographic distribution does not happen simply as a result of rising temperature but occurs due to complicated interactions between climate suitability, vector capacity, hosts, changes in landscapes, water distribution, urbanization and human migration. This means that surveillance programs that rely only on past geographic areas for monitoring can be increasingly ineffective, as climate-based ecological modeling, GIS and remote sensing, as well as systematic vector surveillance and early warning systems become vital [12-14].

5. CLIMATE-DRIVEN CHANGES IN TRANSMISSION DYNAMICS

Climate change is increasingly becoming important in determining the timing, duration, and geographic variation in transmission of parasitic diseases vectored by arthropods. Factors such as temperature, rainfall, humidity, drought, floods, and extreme climatic events can affect parasite development and vector abundance, breeding sites, and interactions with hosts. Studies have shown that the association between climatic factors and vector-borne parasitic diseases is not linear but location- and disease-dependent [3]. In malaria transmission, high temperatures are able to accelerate *Plasmodium* development in the mosquitoes as well as shorten the extrinsic incubation period, while rainfall increases the availability of larval habitats, resulting in higher abundance of mosquitoes. On the other hand, too much heat and drought decrease vector abundance and breeding sites [6]. According to a study, a recent comprehensive scoping review of 511 studies shows that climatic change is likely to result in a longer transmission season in malaria while shifting transmission to regions where there is too much cold for vector

and parasite development. Some regions that currently transmit the disease will be no more conducive because of excess heat or rainfall. More recent studies have further highlighted this [14]. The VECTRI dynamical malaria model simulated changes in the duration and geographic spread of malaria transmission in India, including northward and highland expansion of malaria transmission risk in climate change scenarios [22,23]. Likewise, a study illustrated large variations in future malaria transmission in relation to space and season in different climatic zones in India, with changes in entomological inoculation rate being greatly dependent on temperature and precipitation. Through these studies, it is evident that climate change not only alters the sites of disease transmission but also the timing, duration, and intensity of parasite transmission [13].

A number of recent studies have also highlighted that climate-driven transmission dynamics result from interactions among climatic factors, vector behavior and physiology, parasite biology, availability of hosts and landscape features. Increased temperature and modified precipitation may influence mosquito behavior, host-seeking, resting-site choice, reproductive cycles, longevity, and resistance to heat, and affect vector competence and likelihood of parasite transmission [8]. Precipitation is especially significant, since increased precipitation can create breeding sites, while excessive precipitation and floods can sometimes destroy breeding sites of larvae or disrupt vector populations; therefore, the relation between precipitation and disease transmission is non-linear and depends on local ecology [14]. Recent research has demonstrated that climate-induced changes can modify the synchronization among vectors, parasites, and hosts, leading to more complex dynamics in transmission effectiveness, rather than increases in disease prevalence only [23,24]. Climate change will increase the periods of malaria transmission in India, while other studies found that there is considerable regional variation, with some regions experiencing increased and others decreased transmission intensity depending on climatic region and season. It is critical to note that, according to the 2025 environmental change review by Baraik *et al.*, many studies have looked into aspects of transmission risk [6-9]. There are a small number of studies that have incorporated hazard, exposure, and vulnerability of populations in their analysis [12]. The current literature is therefore calling for a move away from climate-only predictions to integrated transmission models that include climatic factors, vector biology, parasite life cycle, host behavior, landscape modification, population density, health care services and interventions.

6. EMERGING AND RE-EMERGING PARASITIC DISEASES

Parasitic emerging and re-emerging diseases have emerged as an increasingly important public health issue since environmental, social and behavioral factors may alter parasite transmission and cause the introduction of infections to new populations due to modifications in climate, land use, mobility of people, urbanization, ecological disturbances and socio-economic factors. Climate-sensitive parasites are especially susceptible to environmental changes because their transmission is usually dependent upon vector, intermediate host, reservoir host or environmental life cycle stages, which are very sensitive to temperature, rainfall, humidity, and hydrology [7-10]. The results of the systematic review of climate-sensitive NTDs showed that increased temperature and changed patterns of rainfall increase habitat suitability and contribute to the expansion or re-emergence of such diseases as leishmaniasis, schistosomiasis, lymphatic filariasis, Chagas disease, and others in new geographic areas [7]. Recently, a study performed a large scoping review of climate change, malaria and 20 NTDs, including 511 eligible articles among 42,693 citations. Among the studied articles, there were 185 related to malaria, 53 to leishmaniasis, 29 to schistosomiasis, 19 to Chagas disease, 14 to lymphatic filariasis and 8 to human African trypanosomiasis. The authors stated that the impacts of climate change on the occurrence, transmission, distribution, and prevalence of diseases will be non-linear and heavily influenced by the type of parasite, vector or intermediate host, and the geographical location [22]. This is especially true for re-emerging diseases since the environmental conditions that once posed an obstacle to parasite development might turn out to be permissive after some climatic changes. For instance, the alteration of temperature and rainfall might make it possible for mosquitoes and sandflies to be environmentally suitable hosts and vectors, while freshwater environmental change might affect snail hosts that transmit schistosomiasis. This means that parasites might emerge via geographical spreading, increased local transmission, re-emergence in previously controlled regions, or spill-over following alterations of host/vector species [7,13].

Table 1: Selected vector-borne parasitic diseases affected by climate change, including vectors, geographic shifts, and key environmental drivers.

Parasitic disease	Causative parasite	Primary vector	Geographic shifts	Key environmental drivers
Malaria	<i>Plasmodium falciparum</i> , <i>P.</i>	<i>Anopheles</i> spp. mosquitoes	Expansion toward higher altitudes and	Rising temperature, altered rainfall,

	<i>vivax</i> and other <i>Plasmodium</i> spp.		latitudes; changes in seasonal transmission zones	humidity, extreme weather
Leishmaniasis	<i>Leishmania</i> spp.	<i>Phlebotomus</i> and <i>Lutzomyia</i> sand flies	Potential northward and higher-altitude expansion; emergence in previously unsuitable areas	Temperature, rainfall, humidity, vegetation and land-use change
Lymphatic filariasis	<i>Wuchereria bancrofti</i> , <i>Brugia malayi</i> , <i>B. timori</i>	<i>Culex</i> , <i>Anopheles</i> , <i>Aedes</i> mosquitoes	Potential expansion or intensification in climatically suitable tropical and subtropical areas	Temperature, rainfall variability, flooding, humidity and urbanization
Chagas disease	<i>Trypanosoma cruzi</i>	<i>Triatoma</i> and other triatomine bugs	Potential expansion toward higher latitudes and altitudes in suitable climatic conditions	Temperature, precipitation, deforestation, land-use and habitat changes
Onchocerciasis (river blindness)	<i>Onchocerca volvulus</i>	<i>Simulium</i> spp. black flies	Potential changes in distribution along suitable river systems and higher-altitude areas	Temperature, rainfall, river flow, flooding and drought
Schistosomiasis	<i>Schistosoma mansoni</i> , <i>S. haematobium</i> , <i>S. japonicum</i>	Freshwater snail intermediate hosts; transmission is environmentally mediated	Expansion into newly suitable freshwater habitats and higher latitudes in some regions	Water temperature, rainfall, flooding, drought and freshwater availability
Human African trypanosomiasis	<i>Trypanosoma brucei gambiense</i> , <i>T. b. rhodesiense</i>	<i>Glossina</i> (tsetse flies)	Potential shifts in suitable areas and changes in transmission zones	Temperature, rainfall, vegetation, humidity and land-use change

Moreover, recent literature also suggests that the emergence and re-emergence of parasitic diseases cannot be attributed solely to climate change. Climate-induced environmental changes interact with globalization, international travel, migration, displacement of people, deforestation, agriculture, urbanization, loss of biodiversity, changes in water availability, and poor surveillance systems to produce new epidemiological opportunities for parasites [16,18]. According to the WHO Global Report on Neglected Tropical Diseases 2024, the spread of NTDs beyond their usual geographic areas can be facilitated by such factors as climate change and population displacement, which pose a threat to the progress made towards achieving the target goals [21]. Especially important is the introduction of parasites into communities with no prior experience and poor surveillance systems. According to the scoping review associated with WHO (2024), there have been relatively few studies related to adaptation to parasitic diseases: only 24 out of 511 included studies have addressed adaptation methods [14]. Most research has been dedicated to malaria, dengue/chikungunya, and leishmaniasis. Previous systematic data have indicated that climate change could be one of the reasons for the development and re-emergence of some NTDs, especially

those which are related to vector-borne diseases and those that require an intermediate host in their life cycle; however, they stressed that it was difficult to make accurate predictions about the future due to the complex nature of disease transmission, which is affected by various interacting environmental and socio-economic factors [8]. Thus, it became necessary for researchers to recommend the use of integrated surveillance methods taking into account such aspects as epidemiology, entomology, environment, climate, veterinary, and socio-economic factors. It is especially appropriate to apply the concept of One Health because many emerging parasitic diseases include interconnected human, animal, vector, and environmental components.

7. VULNERABLE POPULATIONS AND PUBLIC HEALTH IMPLICATIONS

Climate change impacts are felt differently in different populations, and the public health effects of climate-sensitive parasitic infections are more concentrated in populations with higher exposure to and lower capacities for preventing, diagnosing, and treating infections. Recent literature reveals that children, pregnant women, elderly, migrants and displaced persons, indigenous populations, ethnic minorities, those in poverty, and isolated or environmentally vulnerable populations are at particular risk from climate-sensitive infectious disease threats [21,15]. Populations at higher risk share multiple factors of vulnerability such as poor quality of housing, poor sanitation, lack of access to clean water, malnutrition, occupation, poor infrastructure of health care services, and reliance on climate-sensitive sources of livelihood [3]. A 2024 scoping review evaluated 42,693 records and selected 511 papers studying climate change and its impact on malaria or neglected tropical diseases (NTDs). The authors found that the populations that currently have high levels of disease burden and poor access to health care will likely experience even more negative effects in response to changing climate conditions [10]. Children are especially vulnerable to malaria due to the persistence of serious disease and death amongst young children, with estimates suggesting that most malaria-related deaths happen in children below the age of five [20]. Pregnancy is another important window of vulnerability, whereby there can be consequences of malaria and other infectious diseases for the mother's well-being and pregnancy, and limited access to preventive services will further contribute to their vulnerability. In addition, older people and people with preexisting conditions are likely to have less biological capacity to withstand infections and the stresses brought about by climate change [20]. There is another avenue of vulnerability, whereby climate-related displacements could lead to increased exposure to infectious diseases. Displacement due to flooding, drought, storms, loss of crops, and livelihood disruption could see vulnerable people settling in places characterized by overcrowding, poor sanitation, standing water, and lack of healthcare services [21,22].

Other than increased cases of infection, the public health implications of climatic impacts on parasitic diseases include more strain on the health system, increased needs for medical interventions, nutrition problems, development problems, disabilities, lost productivity, and exacerbation of health inequalities. Climate changes affecting temperature and precipitation levels can lead to wider distribution of vectors, leading to new exposure to certain types of parasitic diseases among populations that have not been exposed to these diseases before and therefore have neither acquired immunity nor diagnostic or coping mechanisms [11]. As WHO has stressed, vector-borne diseases are common in the tropics and subtropics, and climate change, urbanization, international mobility of people, as well as international trade, can contribute to the spread of these diseases geographically [20]. The impact is especially severe on low-income families, because climate shocks will lead to an increase in disease exposure as well as a decrease in households' access to healthcare services. Other groups vulnerable to the negative health effects of climate change, according to WHO, include women, children, migrants, refugees, the elderly, poorer populations, and those with underlying diseases [21]. It is noteworthy that the Lancet Planetary Health perspective published in 2024 on community-engaged research pointed to the inequitable distribution of climate-related impacts of vector-borne diseases and highlighted the need for conducting research and interventions engaging affected communities rather than imposing solutions on them. According to a study, another important research gap in adaptation to climate change is that only 24 out of 511 studies considered the question of adaptation measures, which may jeopardize efforts aimed at malaria and NTD elimination due to climate change. Hence, the emerging public health priority consists of not only identifying where parasitic diseases may increase but also predicting which groups of people would suffer the most and why [5-7]. This would help to conduct targeted surveillance, early warning systems informed by climate data, diagnosis and treatment, vector control, provision of clean water and sanitation, nutrition, education of communities, and robust infrastructure [26]. Thus, it is evident that a health equity and One Health approach that incorporates climate, environment, epidemiology and socioeconomic surveillance is necessary to protect vulnerable populations and prevent the exacerbation of disparities in parasitic disease burden caused by climate change.

8. CLIMATE-INFORMED SURVEILLANCE AND CONTROL STRATEGIES

Climate-informed surveillance has been gaining importance as a strategy for forecasting and managing vector-transmitted parasitic diseases because traditional surveillance is generally reactive in nature and tends to respond only to an increase in cases or vectors in the population. Several studies have shown that the inclusion of information regarding meteorology, environment, entomology, and epidemiology can be helpful in improving the chances for public-health programs to determine periods and sites where transmission risks are higher and implement preventive actions beforehand [25-28].

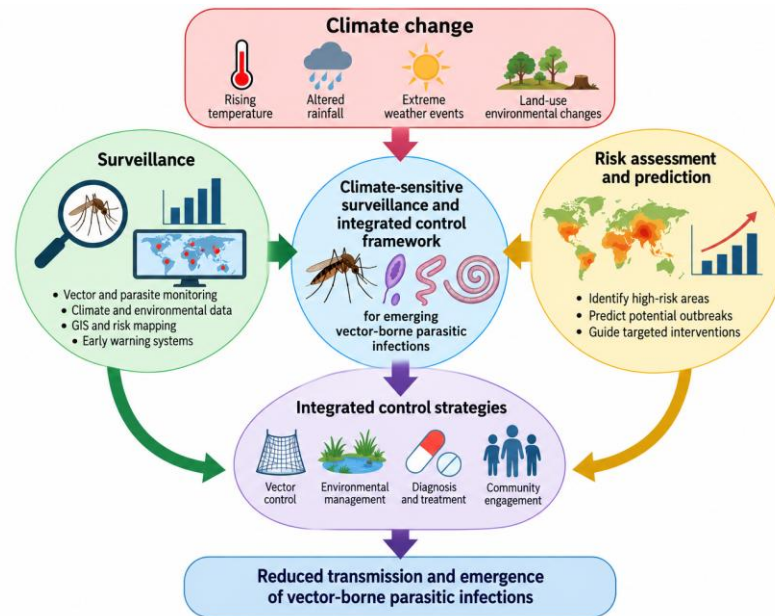


Figure 2: Climate-sensitive surveillance and integrated control framework for emerging vector-borne parasitic infections.

Climate-informed early warning systems (EWS) usually include factors like temperature, precipitation, humidity, vegetation indices, soil moisture and remote sensing information on the environment, together with data from disease surveillance using statistical, mechanistic, and machine learning techniques. A recent scoping review of malaria EWS revealed 30 different studies from 16 countries and applications like outbreak prediction, early detection, resource allocation, vector control, and case management planning; however, differences in the modeling strategies and evaluation methods make direct comparison of the systems challenging [1]. In addition, a previous study stressed that the process of integrating multiple sources of data, including those from epidemiological surveillance, vector monitoring, meteorology, earth observation data and land use, is crucial in the development of decision support systems for malaria and dengue and in turning climate information into actionable risk management strategies [7,9]. There have been recent modeling studies carried out in India that have shown the potential usefulness of such models that combine climate and entomology information. The study of the VECTRI dynamical malaria model showed potential changes in the duration and geography of transmission periods and possible northward and highland expansions of malaria risk, demonstrating how climate information can help identify regions of emergent surveillance and interventions. Such advances suggest that climate-based surveillance can help move the disease control paradigm from reactive public health measures to proactive geographically focused efforts, especially if forecasts are tied to specific response thresholds [10-13].

However, current literature has noted several challenges associated with using climate information for parasite and vector control. In particular, a previous study carried out a systematic review of climate-informed EWS for vector-borne diseases and noted that lack of integration between forecasting and the health system, fragmentary epidemiological, entomological and meteorological data, low quality of data, limited technical capabilities and inability to use climate forecasts for early warning system creation represent important barriers in practical application [16]. The authors further highlighted the point that having accurate forecasts is not enough; the EWS need risk communication, response plans, involvement of stakeholders, community engagement and resources necessary for intervention after issuing the alert. The same constraints have been identified in the context of vector control in South Asia and the Middle East, where significant gaps in vector surveillance, entomological capacity, insecticide resistance surveillance, community engagement and multisector coordination

were found [24]. As a result, contemporary approaches include the use of IVM, including climate-based risk assessment and larval source management, environmental management, insecticide-treated nets, indoor residual spraying, targeted insecticide application, personal protection and prompt diagnostics and treatment. Climate data would help to establish the right places and time for increasing efforts, whereas entomological surveillance would confirm the response of vector populations to such efforts [28]. Further, according to a study, it is necessary to improve the use of multisource surveillance systems by improving their operational efficiency through creating additional digital infrastructure, standardizing data procedures, implementing Earth observation and fostering interdisciplinary collaborations [13]. In turn, the review carried out by WHO of the current climate-change evidence base for malaria and NTDs showed that only a small share of studies considered the adaptation strategies and, therefore, there was a large gap in terms of evidence on climate change impacts on health and what interventions protect people from those impacts [21]. This suggests that future climate-proofing efforts for controlling parasites would require the combination of real-time disease and vector surveillance with climate forecasting, GIS and remote sensing, predictive models, community surveillance and collaboration within the One Health approach.

9. CONCLUSIONS AND FUTURE PERSPECTIVES

Global warming is currently changing the ecology, spread, transmission dynamics, and the disease burden of vector-borne parasitic diseases by modifying temperature, rainfall, humidity, the population density of the vector, the development of the parasite, host-vector relationships, and environmental suitability. Overall, there is sufficient evidence to show that the impact of these changes would include the extension of the transmission seasons, expansion in geographic range of the vector and parasite, creation of new transmission foci, and increased risk of disease among vulnerable groups, but this varies from one parasite to another, depending on vector competency, local environmental factors, and socioeconomic factors. Hence, emerging and re-emerging parasitic diseases present a great challenge to traditional disease control programs which rely heavily on previous patterns of disease epidemiology. Climate-resistant vector management, better diagnostics and treatment capabilities, continued surveillance of vector and drug resistance, upgraded water and sanitation services, community-level intervention measures, and targeted interventions for vulnerable groups will be vital. There will also need to be more focus on field investigations, standardized data sets, fine-scale climate and ecological modeling, and approaches that have the ability to differentiate the impacts of climate change from the impacts of urbanization, land use changes, biodiversity loss, migration, and mobility. There will be a need for an integrated approach in the form of One Health involving human, animal, vector, and environmental health, along with greater international cooperation and equal access to technology and resources, to be able to anticipate new parasite threats under a rapidly changing climate.

CONFLICT OF INTEREST

None.

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