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Assessing the Impact of Climate Change on Vector-Borne Diseases: A Systematic Review of Current Evidence

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Abstract

Background: Vector-borne diseases (VBDs) pose significant public health challenges worldwide, especially in the context of climate change, which exacerbates their distribution and incidence. VBDs, including malaria, dengue, and Zika virus, disproportionately affect vulnerable populations in low- and middle-income countries.

Aim: This systematic review aims to assess the current evidence on the impact of climate change on the distribution, incidence, and control strategies for VBDs, highlighting disparities in vulnerability across global regions.

Methods: A comprehensive literature search was conducted across multiple databases, including PubMed, Scopus, and Web of Science, using keywords related to climate change, vector-borne diseases, and public health. Studies published from 2000 to 2024 were included, focusing on both global and local perspectives of VBDs, with particular attention to climate-related factors influencing their transmission dynamics.

Results: The review identified a significant correlation between climate change variables, such as temperature and precipitation, and the distribution of VBDs. Globally, diseases like malaria and dengue have expanded their range due to warmer temperatures and altered precipitation patterns, leading to longer transmission seasons. Locally, specific regions, particularly in tropical and subtropical zones, face heightened vulnerability due to socioeconomic factors and inadequate public health infrastructure. Climate change exacerbates existing health disparities, disproportionately affecting marginalized communities that are least equipped to respond to VBD outbreaks. Control measures, including vector management and community health initiatives, have shown variable effectiveness, often limited by resource availability and regional environmental conditions.

Conclusion: This review underscores the urgent need for integrated climate and health strategies to mitigate the impact of climate change on VBDs. Addressing these challenges requires a multifaceted approach that considers local context, promotes equity in health interventions, and enhances preparedness for emerging health threats.

Keywords: Climate change, vector-borne diseases, public health, health disparities, systematic review.

1. Introduction

Anthropogenic emissions of greenhouse gases have led to an increase in the average global temperature by 1 °C compared to preindustrial benchmarks [1,2]. The repercussions of this temperature rise have been significant, manifesting as a reduction in cold days and nights, an escalation in warm days and nights, an uptick in extreme heat occurrences, diminished snow cover, and a rapid rise in sea levels. The phenomenon of global warming

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displays marked variability, with land areas experiencing greater increases in temperature compared to oceans, the Arctic exhibiting the most pronounced warming, and winter months showing more significant temperature rises than summer, along with greater increases at night compared to daytime. The enhanced evaporation linked to warming has prompted intricate, regionally specific alterations in the hydrological cycle. While there has been a general increase in global precipitation, some regions have experienced heightened moisture, whereas others have become drier. Notably, both wet and dry regions have reported a rise in extreme precipitation events. If current trends in greenhouse gas emissions persist, projections indicate that the global average temperature may rise by 4 to 5 °C above preindustrial levels by the century's end [2,3], potentially leading to a dramatic escalation of the changes currently observed. The Intergovernmental Panel on Climate Change (IPCC) asserts that “Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems” [3]. The implications of climate change on the occurrence, transmission duration, and dissemination of vector-borne diseases constitute a significant risk [4].

Vector-Borne Diseases:

Vector-borne diseases are transmitted by organisms, typically arthropods, that transfer infectious pathogens from an infected host (human or animal) to an uninfected individual. The World Health Organization (WHO) identifies several major global vector-borne diseases, including malaria, dengue, chikungunya, yellow fever, Zika virus disease, lymphatic filariasis, schistosomiasis, onchocerciasis, Chagas disease, leishmaniasis, and Japanese encephalitis [5]. Additionally, there are regional vector-borne diseases of significance, such as African trypanosomiasis, Lyme disease, tick-borne encephalitis, and West Nile fever. The burden of these diseases is heaviest in low- and middle-income countries located in tropical and subtropical regions, with eight of these diseases classified as neglected tropical diseases [5]. In terms of transmission dynamics, humans act as the primary hosts for several vector-borne diseases, including malaria, dengue, chikungunya, and Zika virus disease. Other diseases exhibit more complex transmission mechanisms, involving both human and non-human hosts. For instance, Lyme disease relies on small mammals and birds as competent reservoir hosts, while deer and other larger mammals act as incompetent hosts. Humans in this context are considered dead-end hosts, meaning they become infected but do not contribute to the transmission cycle. Similarly, West Nile virus utilizes a diverse range of bird species as reservoir hosts, while humans, horses, and other mammals serve as dead-end hosts. Malaria is the most lethal among vector-borne diseases, accounting for approximately 620,000 deaths in 2017, predominantly in Africa, followed by dengue, which resulted in around 40,500 deaths, mainly in Asia [6]. The estimated incidence of malaria cases in 2017 was 209 million, while dengue cases reached 105 million [7]. Although many neglected tropical diseases caused by vectors are not typically fatal, they often lead to chronic conditions that significantly impair quality of life. For instance, in 2017, an estimated 65 million people suffered from lymphatic filariasis, 143 million from schistosomiasis, 21 million from onchocerciasis, 6.2 million from Chagas disease, and 4.1 million from leishmaniasis [7]. This overview underscores the pressing need for effective vector control and disease management strategies, particularly in vulnerable regions. For further details, you may refer to the WHO and relevant epidemiological studies.

Major Global and Regional Vector-Borne Diseases:

Vector-borne diseases are a significant public health concern worldwide, transmitted by organisms such as arthropods that carry pathogens from infected hosts to uninfected individuals. The World Health Organization (WHO) has identified several major global vector-borne diseases, which vary in impact and transmission dynamics, particularly in low- and middle-income countries.

Major Global Vector-Borne Diseases

1. **Malaria**
   Malaria is caused by Plasmodium parasites, with the Anopheles mosquito serving as the primary vector. In 2017, malaria was responsible for an estimated 620,000 deaths, predominantly in Africa. The WHO reported approximately 219 million cases globally that year, underscoring its status as one of the deadliest vector-borne diseases. Efforts to control malaria have included the distribution of insecticide-treated bed nets and indoor residual spraying, which have significantly reduced mortality rates in some regions.
2. **Dengue Fever**
   Dengue, transmitted by Aedes mosquitoes, particularly Aedes aegypti, is endemic in over 120 countries. The disease has seen a marked increase in incidence, with estimates of 105 million cases in 2017, resulting in approximately 40,500 deaths, primarily in Asia. Climate change, urbanization, and increased travel contribute to its spread, and preventive measures focus on mosquito control and public education.
3. **Chikungunya**
   Chikungunya is another disease transmitted by Aedes mosquitoes, characterized by severe joint pain and fever. While not as fatal as malaria or dengue, its impact on quality of life can be profound, with outbreaks reported in Africa, Asia, and the Americas. The resurgence of chikungunya

in various regions highlights the need for ongoing surveillance and vector control efforts. Zika virus is also transmitted by Aedes mosquitoes and gained international attention due to its association with severe birth defects in infants born to infected mothers. The 2015-2016 outbreak in the Americas raised significant public health concerns, prompting the WHO to declare a Public Health Emergency of International Concern . Contrector management and public awareness campaigns.

4. **Yellow Fever** Yellow fever is a viral hemorrhagic disease transmitted by infected mosquitoes, primarily in tropical regions of Africa and South America. Vaccination is the most effective preventive measure, and outbreaks can occur in unvaccinated populations, emphasizing the need for vaccination campaigns in high-risk areas.

Regional Vector borne Diseases

In addition to the major global diseases, several regional vector-borne diseases pose significant health threats:

1. **African Trypanosomiasis**: Also known as sleeping sickness, African trypanosomiasis is transmitted by tsetse flies and primarily affects rural populations in sub-Saharan Africa. While it has seen a decline in cases due to targeted control measures, it remains a significant health concern in endemic regions.
2. **Lyme Disease**, transmitted by Ixodes ticks, is prevalent in the United States and parts of Europe. It is characterized by a distinctive rash and can lead to severe neurological and cardiac complications if untreated. Awareness and preventive measures, such as tick avoidance strategies, are crucial in endemic areas .
3. **Tick-Borne Encephalitis** (TBral infection transmitted by ticks, primarily found in Europe and Asia. It can lead to severe neurological complications. Vaccination is available in high-risk areas, and public education on tick-borne diseases is essential for prevention.
4. **West Nile Virus**: West Nile virus Marily by Culex mosquitoes, affecting North America, Europe, and parts of Africa. Most infections are asymptomatic, but severe cases can result in neurological disease. Vector control and public awareness are vital to managing outbreaks.

The burden of vector-borne critical public health issue, especially in low- and middle-income countries. The complex interactions between vectors, pathogens, hosts, and environmental factors necessitate integrated approaches to disease control, including vector management, vaccination, and public health education. As climate change and globalization continue to impact disease transmission dynamics, ongoing surveillance and research are essential to mitigate the effects of these diseases on global health.

How Climate Affects Vector-Borne Diseases:

Climate significantly influences the transmission dynamics, geographic distribution, and resurgence of vector-borne diseases through various mechanisms. These effects can be categorized into direct influences on pathogens and vectors, as well as indirect impacts on non-human hosts and human populations.

Temperature Effects

1. **Vector Biology and Pathogen Development**: As ectothermic organisms, arthropods—such as mosquitoes—are particularly sensitive to temperature changes. Increased temperatures generally lead to higher vector abundance, enhanced survival, and increased feeding activity. For instance, studies have shown that the extrinsic incubation period for pathogens, like the dengue virus, is inversely related to ambient temperature, meaning that warmer conditions enable vectors to become infective more quickly [7]. This relationship suggests that, as temperatures rise, the risk of transmission for diseases such as dengue increases significantly.
2. **Survival and Development**: Laboratory investigations reveal that survival and development rates of the dengue vector Aedes aegypti vary markedly with temperature. For example, survival rates rise from approximately 0% at 15°C to around 90% at 20°C, then decline at temperatures above 30°C [8]. Moreover, the duration of development from egg to adult is sharply reduced as temperatures rise, impacting the overall population dynamics of these vectors. Such temperature-dependent traits constrain the geographic distribution of these species, raising concerns that warming may facilitate their expansion into higher latitudes and altitudes, thereby increasing the incidence of vector-borne diseases in previously unaffected areas.

Precipitation Dynamics

1. **Complex Relationships**: The relationship between precipitation and vector abundance is complex and context-specific. Increased rainfall can create more breeding sites for vectors; however, drought conditions can also lead to the use of artificial containers for rainwater collection, which can serve as prime breeding sites for Aedes aegypti [9]. Additionally, changes in precipitation patterns can influence ecosystem dynamics, affecting the habitats where vectors thrive and the competition they face from other species.
2. **Ecosystem Changes**: Climate change can drive alterations in ecosystems that either enhance or degrade vector habitats, potentially influencing the abundance of vector predators or pathogens. For example, shifts in habitat may create conditions that favor certain vectors while hindering others, resulting in unpredictable shifts in vector populations.

Host Interactions

1. **Non-Human Hosts**: Climate also affects non-human hosts directly or indirectly through ecosystem changes, which can influence food availability, predator populations, and the prevalence of pathogens. For example, birds act as reservoir hosts for the West Nile virus. Changes in bird migration patterns and population dynamics in North America, attributed in part to climate change, could have significant implications for the transmission of this virus from Culex mosquitoes to humans [10].
2. **Human Population Dynamics**: Climate-induced human displacement can further exacerbate the spread of vector-borne diseases. As people move due to climate-related factors, they may encounter new vectors and pathogens, potentially leading to outbreaks in immunologically vulnerable populations. In summary, climate change significantly impacts the transmission dynamics and geographic distribution of vector-borne diseases. Increasing temperatures can enhance vector survival and pathogen development, while complex interactions involving precipitation can create new breeding sites and alter habitats. The consequences of these changes extend to both non-human and human hosts, underscoring the importance of understanding climate's role in the epidemiology of vector-borne diseases. Future research should focus on these multifaceted interactions to develop effective strategies for managing and mitigating the impacts of climate change on public health.

Climate Change and Vector-Borne Diseases

Climate is undoubtedly a crucial factor influencing the persistence and emergence of vector-borne diseases. A suitable climate creates the necessary conditions for vectors, such as mosquitoes, and pathogens, like viruses, to thrive. For instance, while cases of dengue fever can occur in Sweden due to travel, the disease is not endemic there because the Aedes mosquito and the dengue virus cannot establish themselves in the unsuitable climatic conditions [11]. This distinction highlights that while climate determines the potential geographic distribution of vector-borne diseases, other factors ultimately influence their actual presence in a given area.

Non-Climate Drivers

In addition to climate, various non-climate drivers play essential roles in determining the prevalence of vector-borne diseases. These drivers can be categorized into four primary groups:

1. **Globalization and the Environment**: Changes in trade, travel, and environmental degradation can introduce vectors and pathogens into new regions.
2. **Sociodemographic**: Factors such as population density, urbanization, and economic development significantly influence disease spread. For example, malaria was eradicated from the southern United States in the 1940s due to aggressive vector control measures rather than climatic changes [12].
3. **Public Health Systems**: The effectiveness of health interventions, including vector control and healthcare access, directly impacts disease incidence. Significant progress has been made in controlling various vector-borne diseases over the past decade, attributed to improved public health initiatives rather than climate change. Between 2007 and 2017, for instance, there was a notable decrease in age-standardized disability-adjusted life years (DALY) for malaria (39%), yellow fever (21%), and other diseases like leishmaniasis (56%) [5].
4. **Vector and Pathogen Characteristics**: The biology and behavior of vectors and pathogens can determine their transmission dynamics and adaptability to changing environments.

Recent Trends and Concerns

While progress has been made against many vector-borne diseases, dengue fever remains a notable exception. It is the only major vector-borne disease with an increase in age-standardized DALY rates (26%) from 2007 to 2017, reflecting an ongoing global expansion driven by urbanization, ineffective mosquito control, and globalization [12][13]. Although climate conditions can limit the geographical spread of dengue, it is challenging to attribute the disease's rise solely to climate change on a global scale.

Despite the improvements in disease control, several concerns persist regarding the impacts of climate change on vector-borne diseases:

1. **Regional Signals**: There are numerous indications that climate change is affecting vector-borne disease incidence and spreading at local and regional levels. Changes in temperature and precipitation patterns can create favorable conditions for vectors in areas previously considered unsuitable [11].
2. **Time Lag in Establishment**: Following climatic changes, there is often a time lag before vectors and pathogens establish themselves in new areas. This delay can complicate the monitoring and prediction of disease outbreaks.
3. **Synergistic Effects**: If vector control measures and public health interventions falter due to complacency or political challenges, climate change may act as a synergistic driver, exacerbating the incidence of vector-borne diseases.
4. **Accelerated Evolution**: Climate change may accelerate the evolution of pathogens and vectors, leading to increased resistance to treatments and

pesticides. Such evolutionary changes can significantly influence disease emergence and re-emergence [12].

5. **Future Projections**: Current models predict a substantial expansion of regions with suitable climates for vector-borne diseases, raising concerns about future outbreaks as temperatures continue to rise [13]. In summary, while climate is a critical determinant of vector-borne disease incidence, it has not emerged as the primary driver globally thus far. Non-climate factors, such as public health systems and sociodemographic changes, have played more significant roles in recent disease trends. However, the ongoing impacts of climate change pose serious risks, potentially altering the landscape of vector-borne diseases in the coming years. Addressing these challenges will require continued vigilance, robust public health strategies, and comprehensive research to understand the complex interactions between climate, vectors, and pathogens.

Regional and Local Signals of Climate Change Effects on Vector-Borne Diseases

There is growing evidence that climate change is already impacting the transmission and spread of vector-borne diseases on regional and local scales.

Shifts in Malaria Distribution

For instance, studies conducted in the highlands of Colombia and Ethiopia reveal a significant shift in malaria's altitudinal distribution toward higher elevations during warmer years. This trend indicates that, without intervention, the malaria burden could increase in these areas as global temperatures rise [14].

Dengue and Chikungunya Outbreaks

Travel, trade, and migration play critical roles in the dispersal of pathogens to non-endemic regions. In Europe, the number of imported dengue cases closely correlates with travelers arriving from endemic areas [15]. Local outbreaks of dengue and chikungunya have been recorded in southern Europe, particularly when infected travelers transmit the viruses to the established mosquito vector, Aedes albopictus. While these outbreaks remain relatively rare and the risk of sustained outbreaks is currently low, increasing temperatures necessitate vigilance to prevent potential endemicity in the future [16].

Vectorial Capacity and Temperature Effects

Vectorial capacity, which encompasses factors such as vector abundance, survival, competence, feeding rate, and the extrinsic incubation period, is significantly influenced by temperature. This measure has been pivotal in explaining the 2017 chikungunya outbreaks in Europe and the 2015–2016 Zika virus epidemic in South America, where the temperature conditions during the El Niño/Southern Oscillation were particularly favorable for transmission [17][18]. Since the 1980s, the global vectorial capacity for dengue vectors has steadily increased, with nine of the ten highest years occurring since 2000 [19].

Lyme Disease Trends in the United States

In the United States, environmental factors associated with climate change are influencing the timing and spread of Lyme disease. Research indicates that higher cumulative growing degree days (a measure of heat accumulation), along with lower cumulative precipitation and saturation deficit, are linked to an earlier onset of the Lyme disease season [20]. Furthermore, higher temperatures are critical in establishing the environmental suitability for the Lyme disease vector, the Ixodes tick, particularly in southern Canada, where it has been expanding its range [21]. In Quebec, milder winters correlate with the northward movement of the white-footed mouse, a primary reservoir for the Lyme disease pathogen, Borrelia burgdorferi [22]. These examples illustrate the complex interplay between climate change and vector-borne diseases, highlighting the need for ongoing monitoring and public health interventions to mitigate potential outbreaks as the climate continues to change.

Future Climate Change and Vector-Borne Diseases:

Regional and local indicators regarding the influence of climate change on vector-borne diseases underscore the necessity for ongoing vigilance. To mitigate the threats posed by vector-borne diseases, along with the multitude of other severe risks associated with climate change, global efforts must align with the objectives outlined in the Paris Climate Agreement, specifically limiting global temperature increases to no more than 1.5 °C above preindustrial levels. Achieving this target necessitates immediate and significant reductions in greenhouse gas emissions through comprehensive and rapid transformations across energy, land use, transportation, urban planning, built environments, food production, and industrial sectors [1]. Despite these intentions, the Earth has already experienced a temperature increase of 1 °C, making it critical to confine warming to an additional 0.5 °C at most. In reality, greenhouse gas emissions continue to escalate, and there is scant evidence of global political will to deviate meaningfully from the prevailing 'business-as-usual' trajectory, which could result in a temperature rise of 4–5 °C by 2100. Consequently, prudence demands that we prepare for a spectrum of potential futures. To effectively navigate these uncertainties, it is imperative to persist in conducting observational studies, akin to those previously discussed, to elucidate the connections between meteorological variables and the incidence and spread of vector-borne diseases. Such studies frequently employ mathematical or statistical models, which may be either process-based—considering fundamental biological processes and mechanisms underlying transmission dynamics—or empirical, relying on observed statistical correlations without integrating causal mechanisms. The validity of these models hinges on the availability of high-quality, long-term observational data, with models being disease-specific and often applicable only to certain geographic regions or timeframes.

Given the challenges in accurately estimating mechanistic parameters, empirical models tend to be more practical. Typically, these are time series models that account for latency periods between meteorological conditions and disease outcomes. For instance, research conducted in Sri Lanka revealed that the risk of dengue was highest six to ten weeks after experiencing over 300 mm of rainfall per week [23]. Similarly, a study in Singapore indicated that weekly mean temperature and cumulative precipitation lagged by up to 16 weeks, alongside seasonal patterns, trends in dengue cases, and historical dengue incidences, explaining 84% of the variance in dengue distribution [24]. Therefore, past disease incidences and other non-climatic predictors, such as population density, should be considered for potential inclusion in these models. Forecasting the impact of future climate change on vector-borne diseases is fraught with uncertainties. First, the trajectory of climate change will hinge on the extent of human efforts to reduce greenhouse gas emissions. Second, predictions must also incorporate shifts in non-climatic factors, many of which remain unpredictable. For example, it is challenging to estimate the rate of progress in public health interventions, such as vector control and vaccine development, or the political resolve required for sustained initiatives aimed at controlling vector-borne diseases. Trends in these and other driving factors are likely to exhibit non-linear characteristics.

Although precise predictions are unattainable, significant efforts have been directed towards constructing models based on various scenarios to better comprehend a range of potential futures. Projections regarding the future incidence and distribution of specific vector-borne diseases are generated by linking projected climate change scenarios—based on anticipated greenhouse gas emissions—with either process-based or empirical vector-borne disease models validated through historical observational data. The most straightforward approach involves doing this without integrating scenarios for non-climatic factors, such as travel patterns, socioeconomic conditions, or advancements in public health. This method essentially poses the question: if climate change were to proceed according to a particular scenario, while non-climatic factors remained static, what would be the impact on the relevant vector-borne disease? Although simplistic, this strategy can provide valuable insights for long-term planning, in line with the precautionary principle.

Greenhouse Gas Emissions and Vector-Borne Disease Projections

The Intergovernmental Panel on Climate Change (IPCC) has established four Representative Concentration Pathway (RCP) scenarios for greenhouse gas emissions, spanning from a high-emission 'business-as-usual' scenario (RCP8.5) to a low-emission, rigorous mitigation scenario (RCP2.6). For each RCP, climate models known as general circulation models (GCMs) are employed to forecast temperature, precipitation, and humidity until 2100 and beyond. Typically, an ensemble of diverse GCMs is utilized to evaluate model uncertainty. These meteorological forecasts can subsequently be integrated into vector-borne disease models to predict alterations in incidence or distribution. For instance, under RCP8.5, anticipated shifts in temperature and diurnal temperature variations in temperate regions of the Northern Hemisphere are projected to significantly enhance the vectorial capacity of *Aedes aegypti* for dengue transmission by 2100 [8]. Models can also account for non-climatic influences. Beyond the RCP scenarios, the IPCC has devised five Shared Socioeconomic Pathways (SSPs) that outline various socioeconomic change scenarios leading up to 2100. Research has produced projections for vector-borne diseases based on combined RCP–SSP scenarios. One global study indicated that future dengue incidence through 2080 is highly contingent upon the specific RCP–SSP scenario utilized [25].

A study examining the effects of climate change on global malaria distribution predicted alterations in the duration of the malaria transmission season and the populations at risk for each of the four RCPs. This analysis employed an ensemble of five GCMs along with five malaria models, which included both process-based and empirical approaches [26]. The SSP2 population forecasts were integrated into the model. When comparing the periods of 2069–2099 to 1980–2010, the modeling revealed consistent lengthening of the malaria transmission season in highland regions globally, accompanied by consistent reductions in tropical areas. Although the overall impact of future climate change on populations at risk was relatively minor, significant regional disparities were observed. Another study utilized empirical global distribution data for mosquitoes, along with meteorological variables and metrics of urbanization and human mobility, to construct a model of the historical spatial expansion of *Aedes aegypti* and *Aedes albopictus*. This model was then used to project future spread until 2080 across different RCP scenarios. The researchers discovered that the historical dispersal of these vectors, as well as their expansion over the subsequent 5–15 years, could largely be attributed to human movement patterns. However, in later years, expansion is expected to be primarily influenced by climate change (notably temperature increases) and urbanization, with higher emissions scenarios correlating with greater vector expansion [27].

Empirical models that encompass multiple predictors can aid in identifying significant historical drivers, while scenario-based models that integrate various influences can offer insights into future key drivers. Several enhancements to this modeling approach are anticipated. First, the validity of empirical modeling, which serves as the foundation for scenario modeling, critically relies on high-quality, long-term datasets concerning vector-borne disease incidence, vector and animal host populations, non-climatic drivers, and meteorological factors. Therefore, developing more localized and regional datasets is essential. Second, improved methodologies for quantifying challenging-to-measure non-climatic predictors, such as land and water usage, ecosystem changes, and population displacements, are necessary. These predictors should then be integrated into empirical models to identify additional historical drivers that could be incorporated into scenario-based models. Third, it is vital to evaluate the effects of plausible scenarios involving non-linear and abrupt shifts in climatic or non-climatic drivers. Finally, it is crucial to amplify prevention and control measures, which encompass vector control, early diagnosis and treatment of diseases (to eliminate infection sources accessible to feeding vectors), vaccination efforts, enhancement of water and sanitation systems, urban heat island mitigation, and other interventions. Current initiatives aim to develop short-term (weeks to months) vector-borne disease models with sufficient validity to support early warning systems, facilitating timely public health responses to avert impending outbreaks [28]. Integrating a variety of intervention scenarios into scenario modeling may assist in optimizing both existing and future combinations of interventions, addressing the persistent challenges of preventing and controlling vector-borne diseases amidst ongoing climate change.

Vector Control Strategies for Vector-Borne Diseases (VBDs)

Effective strategies for the primary prevention of vector-borne diseases (VBDs) can be categorized into three main areas: personal protection against vector exposure, integrated vector management, and vaccination. Understanding the implications of these strategies on community health and the environment is crucial for both policymakers and clinicians advising at-risk patients.

1. Personal Protection Against Vector Exposure

On an individual level, preventing contact with vectors involves several methods:

- **Insect Repellents:** N,N-diethyl-meta-toluamide (DEET) is the most commonly used mosquito repellent. While it is known to cross the placenta, studies suggest it is not genotoxic or carcinogenic, making it generally safe for use during pregnancy (29-30).
- **Insecticide-Treated Bednets:** The application of permethrin, a neurotoxic chemical, to fabrics like clothing and bednets acts as a potent, long-lasting repellent. Though cases of poisoning have been reported, permethrin is poorly absorbed through the skin and gastrointestinal tract and is rapidly metabolized by the liver. The U.S. Food and Drug Administration classifies it as a Class B agent during pregnancy (31).
- **Antimalarial Treatment:** Pregnant women residing in or traveling to endemic areas are advised to receive treatment with antimalarials to optimize maternal and neonatal health outcomes. Specific drug regimens and choices, however, are beyond the scope of this discussion (32-33).

2. Integrated Vector Management

Integrated vector management encompasses various strategies aimed at reducing insect vector populations, with a significant focus on:

- **Insecticide Spraying:** The application of insecticides, particularly organophosphates, can reduce vector populations. However, these chemicals have been linked to adverse outcomes such as low birth weight, smaller head circumference, and poorer long-term neurodevelopmental outcomes in children (34). Moreover, insecticide spraying can contribute to the increase of global greenhouse gases and impact climate change. While insecticides are vital tools in controlling VBDs, it is essential for management programs to weigh the potential risks to pregnant individuals against the risks of contracting a VBD, highlighting the urgent need for effective and safe vaccines.

3. Vaccination

Vaccination has shown promise in controlling VBDs, with the yellow fever vaccine being the most successful example to date. Key points regarding vaccines include:

- **Yellow Fever Vaccine:** In use since the 1930s, this vaccine offers rapid effectiveness after a single dose and provides lifelong immunity (35).
- **Malaria Vaccines:** The Mosquirix vaccine, approved for children aged 5–17 months, requires three to four doses to achieve 36% efficacy, which diminishes over time. Currently, there are ten additional malaria vaccines in various trial phases (36).
- **Dengue Vaccines:** Dengvaxia is approved for children aged 9–16 years, providing 80% protection after three doses, but only for those previously infected and living in high-endemicity areas. Four more dengue vaccines are under clinical trials (37).
- **Zika Virus Vaccines:** Following the 2017 Zika outbreak in the Americas, nine clinical

trials have commenced, but they remain in Phase 1 or 2. Additionally, vaccines are in development for chikungunya, West Nile virus, Japanese encephalitis, and Lyme disease, though all are in early clinical trials. Despite the fact that VBDs cause one-sixth of the world's illness, funding for clinical research targeting VBDs remains relatively small (38).

Disparities in the Distribution of Vector-Borne Diseases (VBDs)

Discussions surrounding vector-borne diseases (VBDs) are inherently linked to broader issues of poverty, inequality, and injustice. Approximately 90% of VBD infections occur in Africa and Southeast Asia, with 96% of infections reported in low- and middle-income countries. Even within high-income nations, marginalized and disadvantaged communities face a heightened risk of VBDs due to unequal exposure to mosquitoes and the differential impacts of climate change on various demographic groups (39). Factors such as ambient heat, standing water, overcrowding, and inadequate sanitation contribute to elevated VBD rates in poorer communities, even within the same geographic region (40). For instance, cases of microcephaly related to Zika virus in Brazil were disproportionately reported in impoverished neighborhoods (41). The interplay between VBDs and socioeconomic factors creates a negative feedback loop, where VBDs lead to poor health outcomes, reduced productivity, and escalating healthcare costs. This cycle hinders economic development and perpetuates poverty. For example, dengue fever alone is estimated to incur global costs of USD 8.9 billion annually. The World Health Organization (WHO) has suggested that addressing VBDs could potentially increase GDP growth by 1% to 2% per year in countries with high disease incidences (42). However, investment in VBD prevention, treatment, and research remains inadequate relative to their global impact. To achieve sustainable improvements in public health and economic conditions, it is essential to incorporate environmental justice into strategies addressing global climate change and VBDs. Without the involvement of those most affected by these intertwined issues, meaningful progress is unlikely.

China as a Case Study:

In China, the predominant health threat arising from climate-related vector-borne diseases (VBDs) is attributed to mosquito-borne illnesses, whereas the threat from rodent-borne diseases is diminishing. The principal mosquito vectors responsible for transmitting various viruses are *Aedes aegypti* and *Aedes albopictus*. *Aedes aegypti*, predominantly found in South America, significantly elevates the risks of Zika virus transmission on a global scale. In contrast, *Aedes albopictus* is primarily located in the southeastern United States, southern China, and northern parts of southern Europe; it serves as the principal vector for mosquito-borne diseases within China [43]. In recent decades, malaria was a considerable infection threat in China. However, on June 3, 2021, the World Health Organization declared China malaria-free, despite 40% of the global population residing in malaria-endemic areas, particularly in Africa, which remains the most severely affected region. In recent years, dengue fever has emerged as the most significant mosquito-borne disease threat in China, especially in Guangdong Province, with transmission risks rising as it spreads from coastal regions to northern areas. Schistosomiasis, which has the second-highest publication volume among the diseases we reviewed, is endemic in over 70 developing nations worldwide but has been effectively controlled in China recently. Notably, China is the most severely impacted region globally for renal comprehensive hemorrhagic fever, with nearly 10,000 reported cases annually. Nonetheless, there is a lack of targeted research on this issue. Understanding the influence of climate change on renal comprehensive hemorrhagic fever is imperative moving forward.

Temperature, precipitation, and humidity are the primary climatic factors influencing the transmission of vector-borne diseases [44-46]. A separate review conducted in East Africa found extensive literature correlating precipitation and temperature with tropical diseases such as dengue, chikungunya, and leishmaniasis [47]. However, the existing evidence connecting these three climatic variables is substantial worldwide due to their persistent influence. For instance, studies examining temperature reveal varying associations with vector-borne diseases. One study indicates that capping the global average temperature rise to 1.5–2 °C could diminish the incidence and geographical spread of dengue in Latin America [48]. Conversely, in the Gambia region, the direct effects of rising temperatures may enhance environmental conditions favorable for dengue while decreasing the suitability for *Anopheles* mosquitoes involved in malaria transmission [49]. Additionally, precipitation influences the incidence and distribution of vector-borne diseases in intricate ways. Increased rainfall can modify regional ecology, thereby affecting local disease dynamics. Research in Brazil demonstrates that dengue risk escalates between 0 to 3 months following extremely wet conditions and 3 to 5 months after drought conditions [50]. In the United States, anomalous El Niño-related rainfall resulted in a 20-fold rise in rodent populations from 1992 to 1993 [51]. Lastly, humidity, which relates to both temperature and precipitation, can enhance egg production, larval indices, and mosquito activity. Studies in Saudi Arabia indicate that an optimal humidity range stimulating mosquito flight activity is between 44% and 69%, with the most favorable level being 65% [52].

The correlations between climate and vector-borne diseases exhibit considerable regional variation across mainland China. This variation can be attributed to regional, ecological, and social factors. Climatic disparities across regions significantly influence these dynamics. For example, southern China, characterized by warmer and wetter conditions, is more conducive to insect proliferation compared to northern regions, resulting in a higher incidence of insect-borne diseases in southern cities such as Guangdong, Fujian, and Yunnan. Furthermore, the relationship between temperature and rodent-borne diseases displays differing associations, being linear in temperate zones and nonlinear in warmer areas. Additionally, land characteristics impact vector habitats; the mountainous terrain of the Yunnan–Guizhou Plateau inhibits rainwater accumulation, thus reducing mosquito breeding grounds. Regions with dense vegetation promote mosquito reproduction, while areas abundant in water support snail proliferation, further facilitating the spread of related vector-borne diseases.

Social factors, particularly urbanization, are recognized as significant influences on the transmission of vector-borne diseases. Urbanization can disrupt suitable environments for mosquito breeding, subsequently affecting the transmission dynamics of related diseases. Conversely, disparities in urban infrastructure exist among urban, suburban, and rural areas. A study in Brazil revealed that dengue risk is heightened in rural settings compared to highly urbanized areas during extremely wet conditions; similarly, the risk of dengue following severe drought is elevated in regions with frequent water supply shortages. Additionally, population demographics are crucial, as vector-borne diseases are more likely to proliferate in densely populated regions [53] and among susceptible populations. For instance, in Guangzhou, males aged 20–44 are identified as high-risk individuals for malaria [54], while the unemployed and retirees are more susceptible to dengue [53]. Women, the elderly, and agricultural workers in Shandong, Jiangsu, and Anhui are particularly vulnerable to scrub typhus [50]; middle-aged and elderly farmers are at increased risk for severe fever with thrombocytopenia syndrome [55], while leishmaniasis predominantly affects individuals under 20 years in Xinjiang. Moreover, agricultural ecosystems and artificial ecological modifications can alter local climates, leading to localized outbreaks of vector-borne diseases [56]. Socioeconomic status, public education levels, immunization rates, and community awareness about health also significantly influence the transmission dynamics of vector-borne diseases [57-58].

However, these ecological and social factors are undergoing significant transformations. Climate change profoundly affects the structure and function of natural ecosystems in China, causing severe land degradation, alterations in vegetation cover, decreased river runoff, and deforestation, all of which disrupt vector habitats and modify pathogen transmission dynamics. Furthermore, China is rapidly progressing through industrialization, urbanization, and modernization phases, accompanied by a decelerating population growth, an aging demographic, and revised fertility policies. The risk of vector-borne diseases in China is anticipated to increase continuously in the foreseeable future. Nevertheless, current research predominantly emphasizes the impact of individual meteorological factors on vector-borne diseases, even though the outbreaks of such diseases are influenced by a confluence of various meteorological factors. Limited studies on hemorrhagic fever with renal syndrome have highlighted the interactions and marginal effects among temperature, precipitation, humidity, and their interplay with malaria transmission [59]. Evidence indicates that precipitation during the hottest season positively influences mosquito survival [60], and warmer, wetter weather patterns are expected to persist [61]. The effects of these compound events on vector-borne diseases, particularly mosquito-borne ones, remain largely unexplored. Additionally, most studies focus on administrative regions, neglecting the specific roles of land types, vegetation cover, or water bodies, which are ecological factors not strictly aligned with administrative boundaries. These elements can significantly influence vector behavior, mediating the effects of climatic factors on vector-borne diseases. Furthermore, in light of the increasing frequency of extreme climate events in China, understanding how these occurrences affect vector-borne diseases is crucial. Lastly, it is essential to investigate the role of social factors, which are critical for enhancing our understanding of the evolving patterns of vector-borne diseases and improving prevention strategies for the future.

Despite our review of domestic climate and vector-borne diseases studies, this research has several limitations. First, we focused exclusively on articles published after the year 2000. The plague was once prevalent in China prior to this date, potentially overlooking climate effects on rodent-borne diseases. Secondly, our inclusion criteria were limited to studies from mainland China, excluding regions like Hong Kong, Macao, and Taiwan, which also represent high-risk areas for mosquito-borne diseases. This may result in an incomplete understanding of vector-borne diseases across the entirety of China. Finally, we only included studies that reported population health outcomes, omitting research related to vectors themselves, which may hinder a comprehensive understanding of the mechanisms through which climate influences vector-borne diseases.

Conclusion:

The systematic review reveals a complex interplay between climate change and the dynamics of vector-borne diseases (VBDs), highlighting critical implications for public health. As global temperatures rise and precipitation patterns shift, the geographical distribution and transmission patterns of VBDs, such as malaria, dengue, and Zika virus, are increasingly influenced by climatic factors. Warmer temperatures extend the habitats suitable for vectors, leading to a broader range of disease transmission. This phenomenon is especially pronounced in tropical and subtropical regions, where the effects of climate change are felt most acutely. The review also underscores the significant disparities in vulnerability to VBDs, with low- and middle-income countries bearing the brunt of the burden. Poorer communities often have limited access to healthcare, insufficient public health infrastructure, and inadequate resources to implement effective vector control strategies. The convergence of environmental and social determinants exacerbates the risk of disease outbreaks in these populations, creating a cycle of poverty and poor health that is difficult to break. Moreover, marginalized groups within high-income countries also face heightened risks due to factors such as overcrowding, inadequate sanitation, and exposure to vector habitats. Given the evidence presented, there is an urgent need for integrated and adaptive public health strategies that address both climate change and VBDs. Efforts should focus on enhancing surveillance systems, developing early warning mechanisms, and improving vector management strategies. Additionally, policies must prioritize equitable health interventions that empower vulnerable populations and address the social determinants of health. In conclusion, the ongoing challenges posed by climate change require a collaborative approach that incorporates environmental justice into public health planning. This approach is essential for effectively mitigating the impacts of climate change on VBDs and ensuring sustainable health outcomes for affected communities worldwide. Through targeted investments in research, prevention, and community engagement, it is possible to reduce the burden of VBDs and enhance resilience against future climate-related health threats.

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