Vector-borne Diseases and Climate Change:
North Carolina's Policy Should Promote Regional Resilience

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Emerging and endemic vector-borne diseases remain significant causes of morbidity and economic burden in North Carolina. Effective policies must promote climate change resilience through public health preparedness at local and regional scales to proactively address the diverse environmental, climatic, and demographic factors amplifying vector-borne disease risk.

Overview

Vector-borne diseases (VBDs) are caused by pathogens (e.g., bacteria, viruses, and protozoans) transmitted (vectored) from one host to another via an infectious arthropod (e.g., tick, mosquito, flea, etc.). They impact both veterinary and public health. Many VBDs are increasing in incidence and distribution within the United States and globally [1]. In North Carolina, tick-borne diseases are responsible for the largest burden of VBDs, while endemic mosquito-borne diseases also pose significant public health risks [1, 2]. Human malaria and dengue cases arrive annually in North Carolina via international travel [2, 3]. Similarly, emerging anthroponotic arboviral pathogens (e.g., Zika and chikungunya viruses) have been imported into the state with the potential to initiate local outbreaks [2]. Public health scientists, mosquito control personnel, and academic researchers increasingly discover invasive/exotic mosquito and tick species in North Carolina, while some native species have expanded their geographic ranges [4, 5]. Factors influencing VBD risk are complex, involving vector-human interactions influenced by biological and environmental factors that promote pathogen transmission. Emerging and endemic VBDs may have discrete or overlapping geographic risk. Thus, VBD risk should be assessed as a regional geographic phenomenon influenced by climate and other related factors such as urbanization, travel, biodiversity loss, and socioeconomic inequities.

Within the three major geographic regions of North Carolina (Coastal Plain, Central Piedmont, and Mountain), there is great variability in vector and host diversity and abundance, enzootic and endemic disease prevalence, entomologic and human/veterinary surveillance capacity, vector control resources and practices, land-use patterns, and human population density [6, 7]. Factors influencing VBD prevalence and emergence must be assessed as part of a larger climate change action plan with an "all hands on deck" approach to engaging public health and preparedness stakeholders, emergency management agencies (federal, state, local), vector control experts, health professionals, climate scientists, ecologists, resource managers, urban planning managers, citizen-scientists, and community action groups to influence policies. Regional risk assessments should inform and shape policy recommendations that promote regional resilience to mitigate the direct and indirect effects of climate change that will likely increase VBD risk and other public health issues [8].

Endemic and Emerging Vector-borne Diseases in North Carolina

During the 1800s, North Carolina experienced both endemic malaria transmission and outbreaks of yellow fever transmitted by mosquitoes. Currently, the state has regionally diverse endemic VBDs with ongoing threats of travel-associated and emerging VBDs (Table 1). Vector-borne diseases in North Carolina are primarily caused by tick- or mosquito-transmitted pathogens and can impact public and/or veterinary health. During 2004-2018, tick-borne pathogens were responsible for more than 90% of reportable human VBD cases in North Carolina (Figure 1). Spotted Fever Group Rickettsioses (SFGR) are caused by tick-transmitted bacteria in the genus *Rickettsia*, including *R. rickettsia*, the etiologic agent of Rocky Mountain spotted fever (RMSF). The SFGR are responsible for the largest burden of tick-borne disease across the state, with SFGR clusters frequently recognized in Central and Eastern North Carolina. Lyme disease, the second most common tick-borne disease in North Carolina, is caused by the bacterium *Borrelia burgdorferi* and is emerging in the northwestern part of the state (Figure 2), likely from areas of increasing prevalence in southwestern Virginia. Both RMSF and Lyme disease are named based on geography outside of North Carolina; the name Lyme disease is attributed to clusters of the disease in

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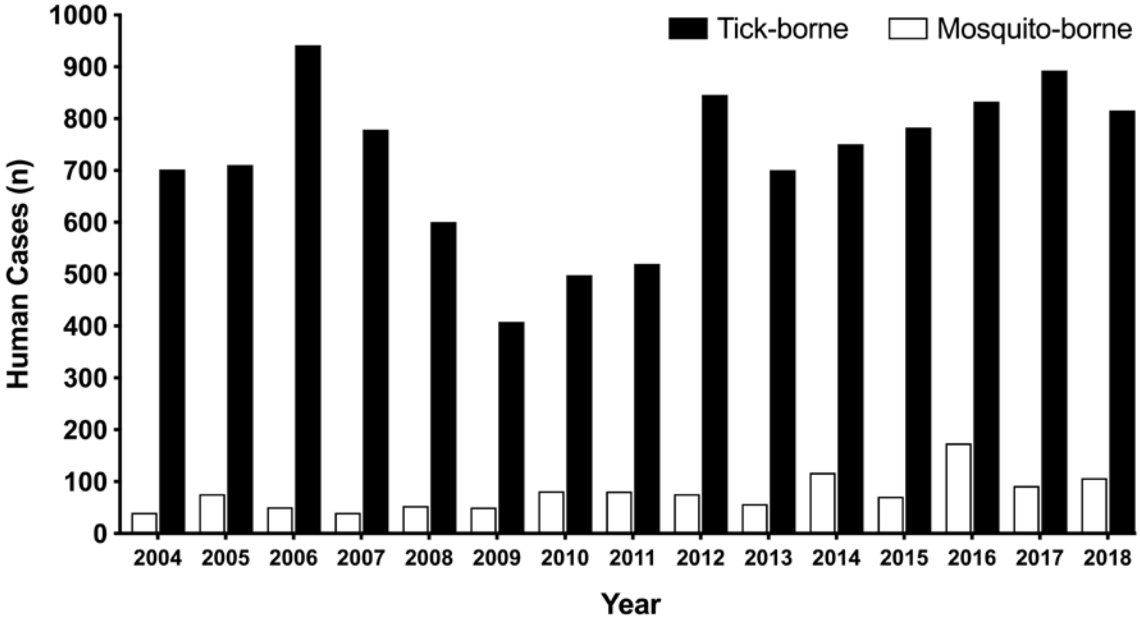
adults and children initially recognized in Lyme, Connecticut, while RMSF originated in the Rocky Mountain states. In previous years, North Carolina has reported human RMSF infection rates higher than any other state. The names of these VBDs may perpetuate an incorrect assumption that these diseases are uncommon in North Carolina. However, these tick-borne diseases account for the vast majority of the VBD burden in the state. Clinicians increasingly recognize other human tick-borne diseases, including those caused by *Ehrlichia* and *Anaplasma* bacteria. The prevalence of

TABLE 1.
Vector-borne Diseases of Public Health Significance in North Carolina

Disease (Pathogen/Etiologic Agent)	Primary Vector(s) of Concern in NC	Distribution in US (NC Distribution)	Epidemiological Significance in NC	Reservoir or Amplifying Host(s) in NC
Tick-borne Disease				
Ehrlichiosis (*Ehrlichia* spp.)	*Amblyomma americanum*	southeastern and south-central US (all NC regions, most prevalent in central NC)	0.62 confirmed and probable cases per 100,000 residents (2013-2017)	deer, wild and domestic dogs, domestic ruminants, rodents
Lyme Borreliosis (*Borrelia burgdorferi*)	*Ixodes scapularis*	mid-Atlantic and north-central US (all NC regions, increasing incidence in western NC)	1.97 confirmed and probable cases per 100,000 (2012-2016)	rodents, some birds (e.g., robins)
Rocky Mountain Spotted Fever [Spotted Fever Group Rickettsiosis] (*Rickettsia rickettsia, Rickettsia* spp.)	*Dermacentor variabilis Amblyomma maculatum*	central and eastern US; most cases in "tick belt" Arkansas, Missouri, NC, Oklahoma, and Tennessee (central and eastern NC)	4.76 confirmed and probable cases per 100,000 residents (2013-2017)	rodents
Southern Tick-Associated Rash Illness (undetermined)	*Amblyomma americanum*	south-central and eastern US (unknown NC distribution)	unknown	unknown
Alpha-gal Syndrome/ Meat Allergy (carbohydrate galactose-1,3-galactose)	*Amblyomma americanum Ixodes scapularis*	southeastern and midwestern US (unknown NC distribution; likely state-wide)	unknown	n/a
Mosquito-borne Disease				
Disease (Pathogen)	**Primary Vector(s) of Concern in NC**	**Distribution in US (NC Distribution)**	**Epidemiological Significance in NC**	**Reservoir or Amplifying Host(s) in NC**
Chikungunya* (chikungunya virus)	*Aedes albopictus*	all US regions (all NC regions)	0.03 confirmed and probable cases per 100,000 residents (2016-2018)	human
Eastern Equine Encephalitis (Eastern equine encephalitis virus)	*Culex, Aedes, Coquillettidia* spp.	eastern US (eastern NC)	0.01 confirmed and probable cases per 100,000 residents (2016-2018)	bird
La Crosse Encephalitis (La Crosse virus)	*Aedes triseriatus Aedes albopictus*	upper midwestern, mid-Atlantic and southeastern US (western NC)	2.28 confirmed and probable cases per 100,000 residents (2009-2018)	chipmunk, squirrel
West Nile Encephalitis** (West Nile virus)	*Culex, Aedes, Coquillettidia* spp.	all US regions; primarily central US (all NC regions)	0.06 confirmed and probable cases per 100,000 residents (2016-2018)	bird
Zika* (Zika virus)	*Aedes albopictus*	all US regions; locally transmitted in Florida (all NC regions)	0.34 confirmed and probable cases per 100,000 residents (2016-2018)	human
Dengue* (dengue virus)	*Aedes albopictus*	all US regions; locally transmitted in Florida, Hawaii, and Texas (all NC regions)	0.10 confirmed and probable cases per 100,000 residents (2016-2018)	human
Malaria* (*Plasmodium* spp.)	*Anopheles* spp.	(all NC regions)	0.48 confirmed and probable cases per 100,000 residents (2016-2018)	human

*Travel associated disease with no endemic (local) transmission in NC; vectors of these diseases are implicated by natural history studies and epidemiological evidence.
**Only human neuroinvasive disease cases are reported in NC.
Incidence Data. NCDHHS Communicable Disease Branch (https://epi.dph.ncdhhs.gov/cd/)

FIGURE 1.
Mosquito-borne and Tick-borne Human Disease Cases in North Carolina (2004-2018)



Source. Centers for Disease Control and Prevention. National Notifiable Diseases Surveillance Systems, Annual Tables of Infectious Disease Data. CDC Division of Health Informatics and Surveillance.

tick-borne arboviruses, including Powassan, Heartland, and Bourbon viruses, is not yet known in North Carolina [1].

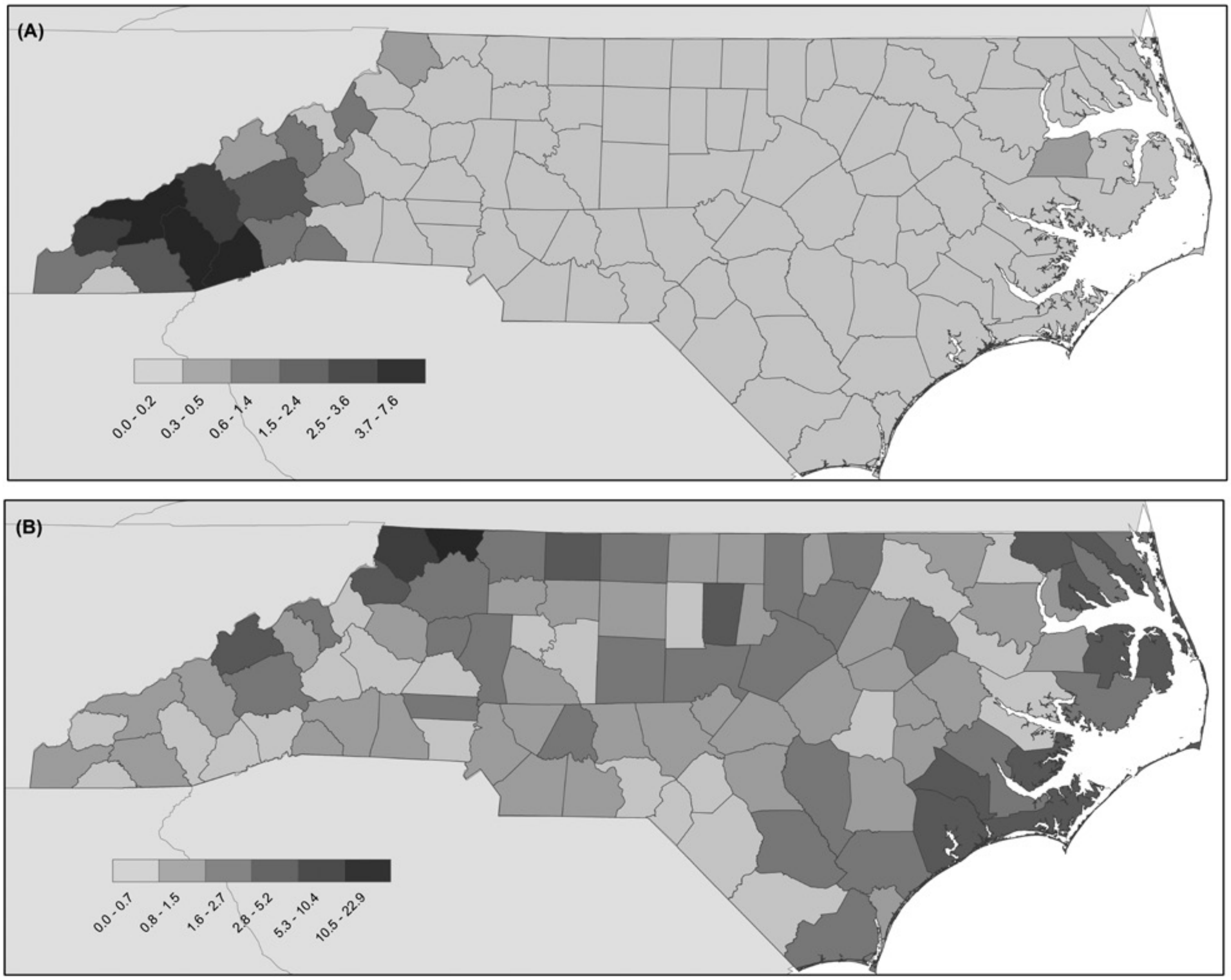
In North Carolina, clinicians report endemic zoonotic arboviral diseases such as La Crosse encephalitis (LACE), West Nile neuroinvasive disease (WNND or WNV), and Eastern equine encephalitis (EEE) annually to local and state public health authorities [1, 2]. The state's most common endemic mosquito-borne disease, LACE (Figure 2), largely impacts children under age 16 and occurs primarily in Western North Carolina [9]. Reported human WNND and EEE cases occur sporadically throughout the state, with most occurring in Central/Eastern North Carolina. Travel-associated anthroponotic mosquito-borne diseases such as malaria (protozoan) and dengue (virus) have been reported annually in North Carolina for decades, while emerging anthroponotic mosquito-borne diseases caused by chikungunya and Zika viruses became more prevalent in the state after Pan-American epidemics in 2014-2015 and 2015-2016 [2, 3].

Climate Change and Vector-borne Diseases in North Carolina

Climate change and weather variability affect vector biology, distribution, and abundance, as well as the transmission potential of VBDs [10, 11]. North Carolina is already experiencing important changes in climate variability [12]. A recent North Carolina Climate Science Report provides a summary of both observed and projected changes in temperature and precipitation, hurricanes, and other extreme events for the state [13]. Future VBD burden will continue to be impacted by unprecedented warming and the potential intensification of the hydrologic cycle with increases in hurricane activity and the time periods between rain events.

Researchers have identified increasing temperatures, changing precipitation patterns, and extreme weather events as the predominant climate stressors influencing VBD outbreaks [10]. Climate sensitivities have been detected in the seasonal activity and distribution of vectors, the number and availability of susceptible hosts, and pathogen replication rates [10, 14]. Temperatures across North Carolina have warmed about 1°F since record-keeping began, and the most recent decade has been the warmest on record [12]. Climate projection models show that this warming trend will continue. Climate experts expect historically unprecedented warming for the state to continue, with climate projections indicating an increase of 2°-5°F (lower scenario: 2°-4°F, higher scenario: 2°-5°F) by mid-century compared to baseline annual average temperature trends for 1996-2015 [13]. Similarly, mid-century projections for the annual hottest temperatures forecast a 2°-3°F increase in the Coastal Plain, and a 3°-4°F increase for the Piedmont and Mountain regions of North Carolina [13]. Long-term trends of warmer temperatures will likely increase the reproductive number and/or survivorship of vectors and shorten their developmental time, thereby extending seasonal vector activity [15, 16]. Ultimately, climate-driven changes in pathogen-vector-host interactions may result in more frequent contact between infectious vectors and susceptible hosts (such as humans), thereby increasing the risk of VBD outbreaks in North Carolina.

FIGURE 2.
(A) La Crosse Encephalitis (2000-2019) per 100,000 (crude rate) at the County Level for North Carolina
(B) Lyme Disease (2000-2018) per 100,000 people (crude rate) at the County Level for North Carolina



Source. Centers for Disease Control and Prevention and U.S. Census Bureau

While there is no clear historical trend in annual total precipitation for the state, there is an upward trend in the number of heavy precipitation events (days with ≥ 3 inches of rainfall), due in part to hurricanes (e.g., Hurricane Florence in 2018, during which some parts of North Carolina experienced >30 inches of total precipitation). Projected increases (3%-6%) in annual total precipitation for 2041-2060 are anticipated for much of the state [13]. As global warming is met with parallel increases in atmospheric water vapor, the risk of more frequent and extreme precipitation is *very likely* throughout the state [12]. Hurricane-associated heavy precipitation events are expected to increase, resulting in amplified potential for coastal and inland flooding. Hurricane-associated flooding events can impact VBD transmission dynamics in temperate areas due to increased vector abundance, declines in public health measures/mitigation strategies in the acute aftermath period, and increased risks of vector contact among responders and displaced populations [17]. Temperature and precipitation are well-established factors that affect vector life cycles, habitat availability and usage, and host-seeking patterns [15, 18]. In general, wetter conditions enhance mosquito abundance and reproductive rates by providing more suitable larval habitats, especially following extreme precipitation events.

Hotter temperatures will likely cause warmer, more intense droughts with diminished humidity [13]. Drier conditions may inhibit the range expansion of some vectors and, under longer-term drought conditions, may yield reductions in some vector populations [19, 20]. A warmer climate may also influence the emergence or reemergence of VBDs by increasing the abundance and/or infection rates of endemic and/or exotic vectors, subsequently increasing pathogen transmission intensity [14, 20]. For instance, research conducted in the Southeastern United States has shown that, during periods of drought, bird hosts and mosquito vectors come in closer proximity to humans, amplifying WNV transmission [21].

Mosquito- and tick-borne diseases will likely respond differently to the shorter- and longer-term impacts of a changing climate. The relatively short life (up to a few weeks) and pathogen transmission cycles (3-7 days) of mosquitoes make them more susceptible to short-term fluctuations in weather. Conversely, some tick-borne pathogen transmission cycles occur over a longer time frame (1-2 years), and as a result, tick-borne disease risks are more sensitive to longer-term (decadal) changes in climate. For instance, longer-term weather trends from teleconnections patterns (e.g., El Nino Southern Oscillation [ENSO], El Nino) or large-scale climate anomalies have preceded noted increases in tick-borne and rickettsial diseases in the Western United States and decreases in the Southern United States [22]. The varying effects of climatic stressors over the short and long term can work in opposing directions, increasing disease risk for one VBD while decreasing risk for another. Therefore, it is essential to monitor climate-induced changes in vectorial capacity and VBD risk at local and regional scales [23].

The Interplay of Climate, Environmental Stressors, and Social Determinants

A changing climate will likely increase the risk of VBD transmission by expanding the seasonal activity and geographic ranges of some vectors. However, this relationship is difficult to predict due to a myriad of confounding biological and environmental factors. Research shows that climate is necessary but not solely responsible for the spread, emergence, or persistence of vectors and VBDs [14]. A number of complex interactions between non-climate stressors should be considered, including land use, social and cultural factors, vector biology, vector control practices, public health infrastructure, and population health status. Climate change and weather extremes act as a threat multiplier through which existing social stressors (e.g., rising inequality, unemployment, poverty) work in combination with environmental stressors (e.g., urbanization, pollution, land cover changes) to amplify climate stressors (e.g., extreme heat, hurricane-associated flooding), particularly in vulnerable populations. Vulnerable populations may be at direct risk for VBDs after extreme weather events due to preexisting housing conditions (e.g., absence of air conditioning, screened doors, and screened windows) that may be exacerbated by storm damage. Furthermore, vulnerable populations may not have the resources to effectively evacuate or mitigate storm damage and may be at higher risk for VBDs due to increased exposures while being displaced or working outdoors. Recovery and vector control efforts may be delayed in rural areas, further exacerbating risk to some vulnerable populations.

The interplay between environmental and social stressors varies regionally. Efforts to conduct community climate health assessments are needed to determine which populations and geographic locations will be at increased risk for VBD outbreaks.

Climate Change Resilience

Climate change is expected to worsen the burden of VBDs in North Carolina. However, questions remain regarding the complex interactions of climate, environmental, and social factors that alter VBD risks. It is unclear how specific vectors, hosts, and pathogen reproduction rates respond to climate changes, especially within the context of interacting and synergistic factors at regional and local scales. The state is addressing climate change, deriving resilience-based solutions, and transitioning to clean energy, as evidenced by Executive Order 80 [24]. A broad approach is needed to ensure sustained, multi-institutional progress at local, state, and federal levels to address climate change and mitigate VBD risks [25]. Efforts to address climate change and VBDs need to complement current public health efforts to manage climate-related risks directly. As such, climate change resilience should be interwoven with community resilience and public health practice. Thus, we recommend five strategies that collectively will improve North Carolina's ability to respond to VBD threats broadly and within the context of climate change.

Resilience Strategy #1: Conduct Statewide and Regional Vulnerability Assessments

The interaction of climate and non-climate stressors on VBD burden and associated vector abundance and distribution will likely vary regionally in North Carolina. Disease risks and population vulnerabilities should be evaluated and mapped to assess the adaptive capacities (i.e., abilities to resist or respond to impacts) of communities from a regional perspective. Collaborative assessments with states surrounding North Carolina should also be considered in this analysis.

Resilience Strategy #2: Enhance Surveillance Efforts for Vectors and VBDs

Timely recognition of VBDs is dependent on continued financial, political, and public support for surveillance programs carried out by public health in coordination with vector control professionals. Effective entomologic (vector) surveillance requires an experienced cadre of regionally based professional personnel with intimate knowledge of local environmental conditions, known vectors and pathogens, and their natural habitats.

Resilience Strategy #3: Secure Sufficient Public Health Funding

Overreliance on episodic federal grant-based support, coupled with reductions in state funding for VBD surveillance and control capacity, grossly limits North Carolina's ability to respond to climate change. The lack of public health infrastructure for VBDs forces the state to respond reactively to emerging VBDs instead of fostering a more efficient proactive approach.

Resilience Strategy #4: Foster Multidisciplinary and Regional Partnerships

Partners from multiple disciplines (i.e., public health, academia, public sector [planners, emergency response], vector control professionals, community advocates, nonprofit organizations) must establish working groups to assess vulnerabilities and foster climate change resilience at a regional scale. Funding to support working groups should promote tangible outcomes (i.e., vulnerability assessments and recommendations) for their local communities as policymakers and public/environmental health professionals need practical knowledge and tools to build climate resiliency.

Resilience Strategy #5: Integrate Climate Resilience Solutions in Public Health and Health Education

Climate change will exacerbate many health and social inequalities, while the impacts of VBDs will be disproportionately borne by vulnerable communities. Public health and climate science communities must build climate resilience while planning VBD prevention and response activities at the community level. Local health providers and public health agencies are uniquely poised to promote resilience to climate-related stressors, recognizing that not all individuals and communities are impacted equally by climate change. By applying a health equity lens to the framing, understanding, and quantifying of the co-benefits of climate resilience action, public health professionals can help promote local and state policymaking that simultaneously improves health and reduces health inequities. Health and climate are linked and North Carolina could be on the forefront of health education in this regard with many environmental health, public health, and academic medical programs across the state.

Conclusion

As demonstrated by the COVID-19 pandemic, a robust public health infrastructure, clear understanding of socioeconomic and health determinants, and readily deployable emergency preparedness responses are critical factors in a community's ability to mitigate *unanticipated* infectious disease burden and reduce spread. An increase in VBDs due to climate change is *anticipated*. Immediate efforts to build regional climate change resilience are necessary to address the diversity of endemic VBDs, increasingly recognized travel-associated mosquito-borne diseases, and inevitable introductions and/or reintroductions of other pathogens and vectors. NCMJ

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