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Vector Migration in a Changing World: Drivers, Emerging Disease Risks and Public Health Priorities

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Abstract: Vector migration—the movement, introduction, establishment or geographical redistribution of disease-transmitting arthropods—has become an increasingly important public health concern. Mosquitoes, ticks, sandflies, fleas and other vectors are expanding into new latitudes, altitudes and ecological settings under the combined influence of climate change, urbanization, land-use modification, international trade, travel, population mobility and ecological disruption. Rising temperatures can accelerate vector development, extend seasonal activity and shorten pathogen incubation within vectors, while altered rainfall and water-storage practices create new breeding habitats. Nevertheless, climatic suitability alone does not inevitably produce disease transmission. Pathogen introduction, vector competence, host availability, human behaviour, healthcare access and surveillance capacity determine whether vector establishment progresses to sustained transmission. Recent evidence documents climate-associated expansion of *Aedes* mosquitoes, West Nile virus risk in Europe and tick-borne disease hazards in higher-altitude and higher-latitude regions. In India, modelling indicates a potential expansion of *Aedes aegypti* and *Aedes albopictus*, including into climatically suitable northern and higher-altitude areas. This is especially relevant for Himalayan and rapidly urbanizing regions that may have limited prior experience with dengue and other arboviral diseases. Current evidence remains constrained by inconsistent entomological data, uncertainty in climate projections, incomplete reporting and frequent conflation of vector presence with disease risk. Public health systems must shift from reactive outbreak control to climate-informed, integrated vector surveillance. Priorities include surveillance at ecological frontiers, port-of-entry monitoring, genomic and insecticide-resistance surveillance, One Health coordination, climate-based early-warning systems and resilient urban infrastructure. Vector migration should be regarded not as a distant ecological phenomenon but as an evolving health-security challenge requiring sustained adaptation and climate mitigation.

Keywords: vector migration; vector-borne diseases; climate change; Aedes; geographic expansion; One Health

INTRODUCTION

Vector-borne diseases remain among the most environmentally sensitive infectious diseases. They are caused by parasites, viruses or bacteria transmitted through living vectors, principally mosquitoes, ticks, sandflies, fleas, triatomine bugs and certain aquatic snails. Collectively, vector-borne diseases account for more than 17% of infectious diseases and cause over 700,000 deaths annually.[1] Malaria, dengue, chikungunya, Japanese encephalitis, leishmaniasis, lymphatic filariasis, Lyme disease, Crimean-Congo haemorrhagic fever and West Nile fever illustrate the diversity of pathogens, vectors and ecological systems involved.

The term **vector migration** is often used loosely. Vectors do not necessarily migrate in the manner of birds or large mammals. From an epidemiological perspective, the term encompasses several processes: active movement over short distances; passive transport through vehicles, aircraft, ships, cargo, plants, animals or used tyres; seasonal movement; gradual range expansion; and establishment in previously unsuitable ecological zones. "Vector redistribution" or "range expansion" may therefore be more precise, but vector migration remains a useful public health term when it denotes the movement of vectors and associated risks across geographical boundaries.

Climate change has brought new attention to this issue. Arthropod vectors are ectothermic, and their survival, reproduction, biting frequency and pathogen-transmission potential are strongly influenced by temperature, rainfall and humidity. However, climate is only one component of a complex causal system. Urban growth, water insecurity, deforestation, irrigation, transport networks, trade, human movement and failures of vector control can be equally important. This review critically examines the drivers, evidence, uncertainties and policy implications of vector migration, with particular attention to recent global developments and India.

Biological and Ecological Basis of Vector Redistribution

The movement of a vector into a new area does not occur as a single event. It usually progresses through four stages: **introduction, survival, establishment and spread**. Introduction may result from passive transport of eggs, larvae or adults. Survival requires short-term environmental tolerance. Establishment requires successful reproduction over multiple generations, while spread involves expansion beyond the point of introduction.

Temperature affects nearly every stage of vector biology. Within a suitable thermal range, warming may accelerate larval development, increase biting rates and shorten the extrinsic incubation period—the interval required for a pathogen to develop inside the vector before transmission becomes possible. Warmer conditions may also extend the number of months during which vectors remain active. Beyond an upper thermal threshold, however, excessive heat can reduce vector survival, dry breeding habitats and lower transmission. The relationship is therefore nonlinear rather than a simple assumption that warmer conditions always increase disease.

Rainfall has similarly complex effects. Moderate rainfall can create breeding sites, whereas intense rainfall may flush larvae from containers or streams. Drought can paradoxically increase *Aedes* breeding when households store water in inadequately covered containers. Humidity influences adult survival, while vegetation, soil moisture and host availability are especially important for ticks and sandflies.

Vector presence alone does not establish disease risk. Local transmission additionally requires a competent vector, an infectious human or animal host, a pathogen capable of replicating under local conditions and sufficient contact between vectors and susceptible hosts. Consequently, maps of climatic suitability should not be interpreted as predictions of inevitable outbreaks.

Principal Drivers of Vector Migration

Climate change and climatic variability

Climate change can shift the geographical boundaries within which vectors survive and reproduce. Warmer winters may reduce cold-season mortality, while longer summers can support additional vector generations. Climate-associated changes have been observed or projected for *Aedes*, *Anopheles*, *Culex*, *Ixodes* and other important genera.[2,3]

Modelling by Iwamura and colleagues suggested that global climatic suitability for *Aedes aegypti* development increased by approximately 1.5% per decade during 1950–2000 and could increase more rapidly by 2050. The projected speed of some invasion fronts also increased substantially under future climate scenarios.[3] Such estimates demonstrate potential rather than certainty because they do not fully incorporate vector-control programmes, housing, immunity, behavioural adaptation or health-system responses.

Climate attribution has recently become more rigorous. A 2024 European analysis assessed the contribution of anthropogenic climate change to the spatial expansion of West Nile virus while accounting for land-use and population changes. The study concluded that climate change had made a measurable contribution to the virus's geographical expansion, strengthening the evidence beyond simple ecological correlation.[4]

International trade and transport

Global transport allows vectors to cross ecological barriers far more rapidly than through active flight. The worldwide spread of *Aedes albopictus* has been strongly linked to the trade in used tyres and ornamental plants, which can contain desiccation-resistant eggs. Aircraft, ships, trucks and private vehicles can transport adult mosquitoes and immature stages across countries and continents.

Ports, airports, freight terminals and major highways therefore function as potential gateways. Introduction may occur repeatedly even when initial populations fail to establish. Climate change can convert previously unsuitable destinations into environments where imported vectors survive.

Urbanization and water management

Unplanned urbanization creates favourable environments for container-breeding mosquitoes. Dense settlements provide abundant human hosts, artificial containers and sheltered resting sites. Irregular water supply encourages storage, while inadequate solid-waste management leaves discarded plastics, tyres and containers that collect rainwater.

Urban heat islands may increase local temperatures above those in surrounding rural areas, allowing vectors to survive in otherwise marginal climates. Construction sites, transport corridors and peri-urban settlements can facilitate movement within cities.

Land-use change and ecological disruption

Deforestation, agricultural expansion, irrigation, mining and infrastructure projects alter habitats and contact among humans, animals and vectors. Forest fragmentation may change the abundance of reservoir hosts and expose workers or settlers to sylvatic transmission cycles. Irrigation can create breeding habitats for *Anopheles* and *Culex* mosquitoes, whereas changing livestock practices affect tick populations.

These processes illustrate why vector migration is a One Health issue. Human disease risk emerges from linked changes in climate, ecosystems, wildlife, livestock, vectors and human behaviour.

Movement of humans and animals

Human mobility can transport pathogens into areas where competent vectors are already established. A traveller with viraemia may introduce dengue or chikungunya into a receptive region even if the mosquito arrived years earlier. Similarly, migratory birds contribute to the ecology of West Nile virus and ticks, while movement of livestock can disperse tick species and tick-borne pathogens.

It is therefore important to distinguish movement of the **vector** from movement of the **pathogen**. Disease emergence may result from either process or from their convergence.

Current Evidence Across Major Vector Groups

Aedes mosquitoes

Aedes aegypti and *Aedes albopictus* are the principal vectors of dengue, chikungunya and Zika viruses. *Ae. aegypti* is closely adapted to human settlements and indoor or peri-domestic breeding, whereas *Ae. albopictus* tolerates a broader range of environments and cooler conditions.

Recent expansion of *Ae. albopictus* across Europe and other temperate regions has increased the possibility of locally acquired chikungunya and dengue following imported infections. *Ae. aegypti* is also projected to expand under combined climate and urbanization scenarios. Nonetheless, establishment varies because temperature, competition between mosquito species, photoperiod, egg survival and vector-control intensity modify invasion success.

Anopheles mosquitoes

The geographical and altitudinal limits of malaria vectors are sensitive to temperature and precipitation. Warming may make some highland areas more suitable for transmission, particularly where populations have limited immunity and surveillance is weak. Conversely, very high temperatures or reduced water availability may decrease malaria suitability in some traditionally endemic areas. Climate change may therefore redistribute malaria risk rather than uniformly increase it everywhere.

Culex mosquitoes

Culex mosquitoes transmit West Nile virus, Japanese encephalitis and other pathogens. Their ecology is influenced by rainfall, temperature, irrigation, urban drainage, birds and livestock. The European expansion of West Nile virus shows how climate, vector abundance, bird reservoirs, land use and human exposure interact.[4]

Ticks

Ticks are expanding into higher latitudes and altitudes in parts of Europe and North America. Warmer winters and longer vegetation seasons can increase survival and extend questing activity. However, tick distribution also depends on vegetation, humidity, deer, rodents, livestock and land management. Disease risk may increase even without dramatic movement if longer seasonal activity creates more opportunities for human contact.

Sandflies and other vectors

Phlebotomine sandflies, which transmit leishmaniasis and some arboviruses, may expand where warmer conditions permit survival. Fleas and triatomine bugs are also influenced by climate and housing, although socioeconomic and environmental conditions often outweigh temperature alone. Evidence is less comprehensive for many non-mosquito vectors, representing an important research imbalance.

Table 1. Major vector-migration pathways, evidence and public health responses

Vector or pathway	Examples of associated diseases	Main drivers of redistribution	Evidence and uncertainty	Priority public health response
Aedes aegypti	Dengue, chikungunya, Zika, yellow fever	Warming, urbanization, water storage, transport and trade	Strong evidence of changing climatic suitability; disease establishment remains dependent on pathogen introduction and control	Container surveillance, source reduction, ovitraps, port surveillance and insecticide-resistance monitoring
Aedes albopictus	Dengue, chikungunya, Zika	Used-tyre trade, ornamental plants, road transport and warmer winters	Well-documented invasive spread; competence and outbreak risk vary by temperature and viral strain	Early detection at transport hubs, rapid elimination of new foci and community-based control
Anopheles species	Malaria	Temperature, rainfall, irrigation, land use and altitude	Potential expansion into some highlands, but possible contraction in overheated or drier regions	Climate-informed malaria stratification and surveillance in previously low-risk areas
Culex species	West Nile fever, Japanese encephalitis	Warming, wetlands, irrigation, urban drainage, birds and livestock	Increasing evidence of climate-associated West Nile expansion in Europe	Integrated mosquito, bird, animal and human surveillance
Ixodes ticks	Lyme disease, tick-borne encephalitis	Warmer winters, vegetation, deer and rodent hosts, land-use change	Observed expansion in some latitudes and altitudes; reporting and host ecology complicate attribution	Tick mapping, clinician awareness, public education and wildlife surveillance
Hyalomma ticks	Crimean-Congo haemorrhagic fever	Livestock movement, migratory birds, warming and arid environments	Introductions occur outside established ranges; permanent establishment remains uncertain in many areas	Livestock inspection, veterinary surveillance and occupational protection
Sandflies	Leishmaniasis, sandfly fever	Warming, humidity, urban expansion, animal reservoirs	Projected range expansion; fewer standardized long-term datasets	Entomological surveillance, reservoir control and strengthened diagnosis
Passive transport	Multiple invasive vectors	Tyres, plants, cargo, aircraft, ships and	Strong evidence for introduction, but	Risk-based inspection,

through trade		road networks	establishment depends on destination ecology	disinsection, traceability and cross-border notification
Pathogen movement through travellers	Dengue, chikungunya, malaria and others	Air travel, migration and displacement	Frequently initiates outbreaks where competent vectors are present	Travel surveillance, rapid diagnosis and local vector response around imported cases

Public Health Significance

The greatest public health consequence of vector migration is the emergence of transmission in populations and health systems with limited prior experience. Clinicians may not recognize unfamiliar diseases, laboratories may lack diagnostic capacity and surveillance systems may not include the relevant vector. Delayed diagnosis increases the opportunity for local transmission.

Expansion into new areas can also lengthen transmission seasons. Even where vectors are already present, additional warm months may increase the number of generations and the probability that imported pathogens establish local chains of transmission.

Vector migration threatens progress in disease elimination. Areas approaching malaria elimination may experience reintroduction through mobile populations and shifting vector suitability. New vector species may also exhibit different biting behaviour, resting habits or insecticide susceptibility, reducing the effectiveness of existing interventions.

The burden is likely to be socially unequal. Informal settlements, migrant communities, agricultural workers, forest-dependent populations and households without reliable water supply or screened housing often experience greater exposure while having less access to prevention and care.

Indian Perspective

India has climatic, ecological and demographic conditions favourable to multiple vector-borne diseases. Dengue and chikungunya have expanded geographically over recent decades, while malaria, Japanese encephalitis, leishmaniasis and tick-borne infections remain important in specific regions.

An Indian modelling study by Hussain and Dhiman examined the present and projected distribution of *Ae. aegypti* and *Ae. albopictus*. *Ae. aegypti* was found to be widely suitable across the southern peninsula, eastern coast, northeastern states and northern plains, with future projections indicating broader climatic suitability. *Ae. albopictus* showed suitability across forested, northeastern and other humid regions, with potential redistribution under future climate scenarios.[5]

These findings have particular relevance for Himalayan states. Warming, urban expansion, construction, tourism, road connectivity and household water storage may permit *Aedes* mosquitoes to establish at elevations previously considered unsuitable. Reports of dengue from hill districts should not automatically be attributed solely to climate change, because imported cases, improved detection and urban ecological change may contribute. Nevertheless, the possibility of altitudinal expansion warrants routine entomological surveillance rather than surveillance only after outbreaks occur.

India's vector-control programmes have historically been disease-specific. Vector migration requires a more integrated approach because the same *Aedes* population may transmit dengue, chikungunya or Zika, and the same ecological surveillance platform can support multiple diseases. Coordination among the National Centre for Vector Borne Diseases Control, Integrated Disease Surveillance Programme, state health departments, municipalities, veterinary services, meteorological agencies and research institutions is essential.

Recent Advances

Climate-informed early-warning systems

Combining meteorological forecasts with entomological and epidemiological data can identify periods and locations of increased risk. Such systems are moving from static suitability maps toward short-term operational forecasts. Their value depends on local calibration and whether alerts trigger timely action.

Remote sensing and geospatial surveillance
Satellite-derived temperature, rainfall, vegetation, surface water and urbanization indicators can identify potential habitats. High-resolution mapping is especially useful where field surveillance is sparse. Remote sensing should guide—not replace—ground verification.

Genomic and population-genetic tools
Genomic analysis can distinguish separate vector introductions, identify routes of spread and assess gene flow. Pathogen sequencing can determine whether outbreaks result from local persistence or repeated importation. These methods are increasingly important for cross-border surveillance.

Automated vector identification
Smart traps, acoustic sensors, image recognition and artificial intelligence can classify mosquitoes and estimate abundance more rapidly than conventional manual systems. Their performance may decline when deployed across diverse species and field conditions, so local validation remains necessary.

Innovative vector control
Wolbachia-based approaches, sterile-insect techniques, spatial repellents and targeted biological control offer new options. However, technologies tested in endemic urban settings may not be immediately transferable to newly invaded areas. Early elimination of a localized introduction may be more feasible than sustained population suppression after widespread establishment.

Challenges and Limitations

Attribution remains the central scientific challenge. Observed expansion may reflect climate change, intensified surveillance, altered diagnostic practices, land use, trade or multiple interacting factors. Ecological models often predict climatic suitability rather than actual vector abundance or disease incidence.

Entomological surveillance is uneven and rarely standardized across jurisdictions. Absence of recorded vectors may mean true absence, inadequate trapping or lack of taxonomic expertise. Historical data are particularly sparse in rural, high-altitude and border regions.

Climate models contain uncertainty regarding future emissions, local rainfall and extreme events. Vector responses may also adapt through phenotypic plasticity or genetic change. Human adaptation—improved housing, vector control, vaccination and healthcare—can substantially alter projected disease burden.

Insecticide resistance presents another limitation. Migrating vector populations may carry resistance alleles or acquire resistance after exposure. Repeated emergency fogging without resistance monitoring may provide little sustainable benefit.

Finally, public communication requires care. Framing climate change as inevitably bringing tropical diseases to every region can create alarm and scientific overstatement. Risk communication should distinguish vector detection, establishment, pathogen presence and confirmed local transmission.

Future Directions and Policy Implications

Surveillance should prioritize ecological frontiers: high-altitude settlements, expanding urban peripheries, ports, airports, freight corridors, wetlands, irrigation schemes and areas undergoing rapid land-use change. Baseline mapping is essential before emergence occurs.

India and other large countries need standardized vector-occurrence databases linked with climate, land use, insecticide resistance and human disease surveillance. Data should be available at sufficiently local scales for district action.

Climate services should be integrated into routine vector-control planning. Forecasts must specify actionable thresholds, lead times and response responsibilities. Their performance should be evaluated prospectively through sensitivity, false-alert rate, timeliness and health outcomes.

A One Health framework is especially important for West Nile virus, Japanese encephalitis, Crimean-Congo haemorrhagic fever and other zoonotic infections. Joint surveillance of vectors, wildlife, livestock and humans can provide earlier warning than human case detection alone.

Urban policy is equally important. Reliable piped water, covered storage, drainage, waste management, housing improvement and climate-resilient infrastructure may provide more durable protection than repeated insecticide campaigns. Vector migration is therefore not solely a health-department problem.

Research should examine under-studied vectors, mountain ecosystems, dryland regions and peri-urban environments. Prospective field studies are needed to validate modelled range expansion. Economic evaluations should compare early surveillance and containment with the cost of responding after establishment.

Ultimately, adaptation must be accompanied by climate mitigation. Surveillance and vector control can reduce harm, but they cannot indefinitely compensate for continuing environmental change that increases ecological suitability across large regions.[6]

CONCLUSION

Vector migration represents the redistribution of disease vectors through interacting climatic, ecological and human processes. Climate change can extend suitable seasons and geographical ranges, but trade, mobility, land use, urbanization and infrastructure determine where introductions occur and whether vectors establish. Disease emergence requires an additional convergence of competent vectors, pathogens, hosts and human exposure.

The evidence is strongest for expanding *Aedes* mosquitoes, changing tick distributions and the climate-associated spread of West Nile virus. Yet uncertainty remains substantial, particularly where vector records and long-term field data are incomplete. Climatic suitability should therefore be interpreted as a warning for surveillance, not as proof of future disease.

For India, the potential expansion of dengue vectors into northern and higher-altitude regions requires anticipatory action. Routine entomological surveillance, climate-informed early warning, port and transport monitoring, genomic investigation, insecticide-resistance testing and integration with municipal and One Health systems should become core components of preparedness.

Public health must move from reacting to outbreaks within historically endemic boundaries to monitoring a dynamic landscape in which those boundaries are changing. The most effective response will combine early detection and locally adapted vector control with resilient infrastructure, equitable health services and decisive action on climate change.

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