Forests as Natural Barrier or Facilitators? The Role of Vegetation Structure in Mosquito Dispersal Patterns

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ABSTRACT
Mosquito-borne diseases such as malaria, dengue, Zika, and chikungunya continue to pose major global health challenges, particularly across tropical and subtropical regions. While the role of climate, human mobility, and land use change in shaping disease transmission has been widely studied, the influence of forest vegetation structure on mosquito dispersal remains underexplored. Forests can simultaneously act as natural barriers, through dense canopy cover, lower temperatures, and reduced light, and as facilitators when fragmented or disturbed, creating transitional ecotones conducive to vector survival and flight. Recent research integrating landscape ecology, entomology, and remote sensing has revealed that vegetation heterogeneity, canopy height, and microclimate gradients directly mediate mosquito flight range, host-seeking behavior, and pathogen transmission potential. For example, *Anopheles* species often exploit partially cleared forest edges, while *Aedes* mosquitoes thrive in peri-urban forest mosaics that combine vegetation cover with artificial breeding habitats. Using Light Detection and Ranging (LiDAR)-based canopy measurements, Normalized Difference Vegetation Index (NDVI) modeling, and mark–release–recapture experiments, scientists are quantifying how vegetation structure predicts vector mobility across landscapes. This review synthesizes current knowledge (2021–2025) on how forest attributes modulate mosquito dispersal and vector-borne disease risks, emphasizing tropical ecosystems in Africa, South America, and Southeast Asia. We discuss mechanistic pathways linking vegetation and vector ecology, evaluate forest management implications for disease prevention, and identify future research priorities integrating remote sensing and ecological modeling.

INTRODUCTION

Forests are among the most complex and multifunctional components of the Earth's biosphere, playing indispensable roles in climate regulation, carbon sequestration, hydrological balance, soil stabilization, and the conservation of biological diversity (Feng *et al.,* 2024),

while simultaneously exerting profound but often underappreciated influences on the ecology of infectious diseases. Beyond their widely recognized ecological and socio-economic benefits, forests shape the distribution, abundance, and behavior of disease vectors, particularly mosquitoes, thereby mediating the spatial and temporal dynamics of vector-borne diseases of global public health importance. In tropical and subtropical regions, where forest ecosystems overlap extensively with human populations, mosquitoes serve as primary vectors for pathogens responsible for malaria (*Plasmodium* spp.), dengue and Zika viruses (*Aedes* spp.) (Eastwood *et al.,* 2020) yellow fever (*Haemagogus* and *Aedes* spp.), and other emerging arboviral and parasitic diseases. Over recent decades, a growing body of interdisciplinary research integrating landscape ecology, epidemiology, and climatology has demonstrated that environmental transformations—most notably deforestation, forest degradation (Musacchio *et al.,* 2005), and habitat fragmentation—can substantially alter mosquito population dynamics, dispersal capacity, and host–vector contact rates, ultimately reshaping patterns of disease transmission (Frumkin and Thomson, 2023). While early studies often framed forests as either protective barriers that limit vector movement or as reservoirs that harbor sylvatic transmission cycles, contemporary evidence suggests a far more nuanced reality in which forests can simultaneously suppress, facilitate, or redirect mosquito dispersal depending on their structural integrity, spatial configuration, and degree of human disturbance. In particular, the conversion of intact forests into fragmented landscapes characterized by forest edges, secondary growth, agricultural mosaics, and peri-urban settlements has been repeatedly associated with increased mosquito abundance and heightened disease risk, as these transitional environments frequently provide optimal microclimatic conditions, abundant breeding sites, and enhanced access to human hosts. Despite these advances, much of the existing literature has focused on broad land-use categories: such as "forest" versus "non-forest" without adequately accounting for the internal structural heterogeneity of forested landscapes (Fisher *et al.,* 2024). Structural characteristics such as canopy height and closure, vertical stratification, understory density, and vegetation species composition play decisive roles in shaping microclimatic conditions, including temperature, humidity, light penetration, and wind speed, all of which directly influence mosquito survival, flight activity, development rates, and vector competence. For example, dense canopies can buffer temperature extremes and reduce desiccation stress, potentially enhancing adult mosquito longevity, while simultaneously limiting flight range and host-seeking efficiency; conversely, partially open canopies and simplified understories may increase thermal energy availability and visual cues, facilitating

longer dispersal distances and more frequent human–vector encounters. Yet, despite their ecological relevance, these fine-scale forest structural attributes remain insufficiently integrated into models of mosquito dispersal and disease transmission. This knowledge gap is particularly concerning in the context of accelerating global environmental change, as rapid deforestation, selective logging, agricultural expansion, and infrastructure development are fundamentally altering forest structure across vast regions of Africa, Asia, and Latin America. These structural transformations interact synergistically with climate change, which is already driving shifts in temperature and precipitation regimes, to create novel ecological conditions that may favor the expansion of vector populations into previously unsuitable areas, including higher elevations and latitudes (Carbone *et al.,* 2025). Furthermore, advances in remote sensing technologies, such as LiDAR, high-resolution satellite imagery, and unmanned aerial systems, now provide unprecedented opportunities to quantify forest structure at spatial and temporal scales relevant to mosquito ecology, offering new avenues for linking vegetation architecture with vector movement and disease risk. However, the translation of these technological capabilities into applied disease ecology and public health policy remains limited, largely due to insufficient conceptual integration between forest structural ecology and vector biology (Abbasi, 2025). A more comprehensive understanding of how specific forest structural characteristics influence mosquito dispersal patterns is therefore urgently needed, not only to improve predictive models of disease transmission but also to inform land-use planning, forest management, and integrated vector control strategies that balance ecological conservation with human health objectives. By moving beyond simplistic dichotomies of forest presence or absence and focusing instead on the nuanced ways in which forest structure mediates mosquito behavior and movement, research can better capture the complex ecological mechanisms linking environmental change to disease emergence and persistence. In an era defined by rapid land-use transformation, climate uncertainty, and increasing human encroachment into forested landscapes, elucidating these interactions is critical for anticipating future disease risks and for developing sustainable, ecologically informed approaches to vector-borne disease prevention and control.

Forests and Vector Ecology: The Paradox of Barriers and Corridors

Forests occupy a central yet paradoxical position in the ecology of mosquito vectors and the epidemiology of mosquito-borne diseases (Ali and Lucas, 2025). Traditionally, intact forest ecosystems have been perceived as protective natural barriers that limit the

spread of disease vectors by restricting mosquito dispersal and reducing human vector contact (Cao *et al.,* 2025). However, growing empirical evidence demonstrates that forests can simultaneously function as ecological corridors that facilitate vector movement, persistence, and even amplification, particularly when they are fragmented, degraded, or situated along human-modified landscapes. This dual role underscores the complexity of forest vector interactions and highlights the need for a nuanced ecological understanding of how forest structure and integrity shape mosquito behavior, population dynamics, and disease transmission risk. In their intact form, dense tropical and subtropical forests often act as physical and microclimatic barriers to mosquito dispersal. Closed forest canopies reduce wind penetration, limit direct solar radiation, and maintain relatively stable temperature and humidity regimes. These microclimatic conditions can constrain the flight range of adult mosquitoes by reducing thermal energy availability and increasing energetic costs associated with prolonged flight (Castellanos-Labarcena, 2025). Furthermore, stable forest microclimates may slow the extrinsic incubation period of pathogens such as *Plasmodium* spp., dengue virus, and Zika virus within mosquito vectors, thereby lowering vector competence and transmission efficiency (Mertens *et al.,* 2025). In this sense, intact forests may function as ecological buffers that dampen disease transmission by limiting both vector mobility and pathogen development. Additionally, intact forests often support high levels of biodiversity, including diverse predator assemblages such as bats, birds, dragonflies, spiders, and predatory insects that exert top-down regulatory control on mosquito populations. The "dilution effect" hypothesis suggests that high vertebrate diversity in undisturbed forests may reduce pathogen transmission by diverting mosquito blood meals toward less competent reservoir hosts (Fairbanks *et al.,* 2025). Generally, support more complex food webs and ecological interactions that can suppress mosquito population growth and reduce disease risk (Figure 1). However, this protective role of forests is increasingly undermined by anthropogenic disturbances such as logging, agricultural expansion, mining, road construction, and settlement encroachment. Forest degradation and fragmentation fundamentally alter landscape configuration, transforming once-continuous forest blocks into mosaics of forest patches, edges, and human-dominated land uses. These transitional zones—commonly referred to as forest edges or ecotones exhibit microclimatic conditions that are markedly different from those of forest interiors. Increased sunlight penetration, higher temperatures, reduced canopy cover, and greater environmental heterogeneity create favorable conditions for many mosquito species, particularly those adapted to disturbed habitats (Nikookar et al. 2025)

Forest edges often function as ecological corridors that facilitate mosquito dispersal across landscapes. Unlike dense forest interiors that may constrain flight activity, edge environments provide moderate thermal and light conditions that enhance mosquito mobility and host-seeking behavior. Studies have shown that several malaria vectors, including *Anopheles gambiae*, *Anopheles funestus*, and *Anopheles darlingi*, exhibit higher abundance and biting rates at forest edges than in either intact forests or open agricultural fields (Nguyen, 2025). These edge-associated mosquito populations can bridge sylvatic and human transmission cycles, increasing the risk of zoonotic spillover and sustained disease transmission in nearby communities. The paradox of forests as both barriers and corridors becomes particularly evident in regions undergoing rapid land-use change. In many parts of sub-Saharan Africa, Southeast Asia, and Latin America, deforestation is driven by subsistence and commercial agriculture, resulting in extensive forest–farm interfaces. These interfaces often coincide with human settlements, irrigation schemes, and livestock rearing areas, all of which provide abundant blood-meal sources and breeding habitats for mosquitoes. As a result, forest edges near agricultural expansion fronts become hotspots of human–vector interaction and disease emergence (Rulli *et al.,* 2025). Road networks constructed through forested landscapes further exacerbate this phenomenon. Roads not only fragment forest habitats but also create linear corridors that facilitate mosquito movement and human access into previously isolated areas. Roadside puddles, borrow pits, and drainage ditches often serve as productive larval habitats, while increased human mobility enhances the spatial spread of pathogens. In the Amazon Basin, for example, malaria incidence has been shown to increase dramatically following road construction and settlement expansion into forested regions, with *Anopheles darlingi* rapidly colonizing newly created edge habitats (Fornace et al., 2023).

Climate change adds another layer of complexity to the forest–vector paradox. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events interact with land-use change to reshape forest microclimates and mosquito ecology. In some regions, climate-driven drying of forest interiors may reduce their barrier function, allowing vectors to penetrate deeper into forested areas or expand into higher elevations and latitudes. Conversely, increased rainfall intensity may create transient breeding habitats within forest landscapes, temporarily enhancing mosquito productivity and dispersal. Importantly, the role of forests in vector ecology is species-specific and context-dependent. While some mosquito species are highly sensitive to forest integrity and microclimatic stability, others are remarkably adaptable and thrive in degraded or secondary forests. For instance, *Aedes aegypti* is primarily associated with urban

and peri-urban environments, whereas *Aedes albopictus* readily exploits forest edges and rural landscapes, serving as a bridge vector between sylvatic and human transmission cycles. Understanding these species-

specific responses is essential for designing targeted vector control strategies that account for landscape heterogeneity and ecological complexity.

Figure 1: Forests and Vector Ecology: The Paradox of Barriers and Corridors. This figure illustrates how intact forests act as protective barriers reducing mosquito dispersal and disease risk, while fragmented or degraded forests become ecological corridors that enhance vector movement, human contact, and disease transmission through increased edge habitats and environmental change.

Vegetation Structure as an Ecological Determinant

Vegetation structure constitutes one of the most influential ecological determinants of mosquito distribution, abundance, and dispersal potential. Beyond the mere presence or absence of vegetation, structural attributes such as canopy density, vertical stratification, plant species composition, and understory complexity profoundly shape the microclimatic environment experienced by mosquitoes throughout their life cycle. These structural characteristics regulate key environmental variables: including temperature, relative humidity, light availability, and wind speed that directly affect mosquito survival, development, flight behavior, and vector competence. Canopy density is a particularly critical component of vegetation structure. Dense canopies intercept solar radiation, reducing ground-level temperatures and maintaining higher humidity levels. Such conditions can enhance adult mosquito survival by reducing desiccation stress, particularly in humid tropical forests. However, excessively dense canopy cover may limit mosquito flight activity by reducing thermal energy and visual cues used for host location. In contrast, sparse or partially open canopies allow greater sunlight penetration, increasing ambient temperatures and creating microhabitats that promote faster larval

development, higher adult activity, and increased dispersal capacity.

In the vertical stratification, the arrangement of vegetation layers from the forest floor to the canopy also plays a pivotal role in shaping mosquito ecology. Different mosquito species occupy distinct vertical niches depending on their host preferences, breeding requirements, and physiological tolerances. For example, canopy-dwelling mosquitoes may primarily feed on arboreal mammals and birds, while ground-level species are more likely to encounter humans and livestock. Changes in vertical vegetation structure due to logging or selective tree removal can alter these vertical niches, increasing overlap between mosquito populations and human hosts. Recent technological advancements have revolutionized the ability to quantify vegetation structure across spatial scales relevant to vector ecology. Light Detection and Ranging (LiDAR), high-resolution satellite imagery, and unmanned aerial vehicles (UAVs) now enable detailed characterization of canopy height, leaf area index, vegetation density, and forest fragmentation patterns (Robinson *et al.*, 2025). These tools have facilitated the integration of landscape ecology with epidemiological modeling, allowing researchers to link fine-scale

vegetation attributes with mosquito movement patterns and disease risk.

Empirical evidence from mark–release–recapture studies underscore the importance of vegetation structure in influencing mosquito dispersal. In the East African highlands, Ngugi et al. (2025) demonstrated that areas with reduced canopy cover exhibited significantly higher mosquito recapture rates at greater distances from release points, indicating enhanced dispersal potential in structurally simplified landscapes. These findings suggest that vegetation thinning: whether due to agricultural clearing or fuelwood harvesting—can inadvertently increase mosquito movement and expand the spatial footprint of disease transmission. Similarly, studies in the Amazon Basin have shown that deforestation-induced changes in vegetation structure led to localized warming and reduced humidity, conditions that favor the proliferation of *Anopheles darlingi*, the region's primary malaria vector (Fornace et al., 2023). Secondary forests and regenerating vegetation often provide optimal structural conditions for this species, combining sufficient shade for adult survival with open understory habitats that facilitate flight and host-seeking behavior. As a result, malaria transmission risk is often highest not in intact primary forests but in landscapes undergoing active ecological transition.

Vegetation species composition further modulates mosquito ecology by influencing the availability of resting sites, sugar sources, and larval habitats. Certain plant species produce nectar or honeydew that serves as an important energy source for adult mosquitoes, enhancing longevity and reproductive output. Others contribute leaf litter and organic debris to aquatic habitats, enriching larval food resources and increasing larval survival. Changes in plant community composition—whether due to invasive species, selective logging, or land-use conversion—can therefore cascade through mosquito life-history traits and population dynamics. Understory vegetation density is another key determinant of mosquito behavior. Dense understory vegetation provides sheltered resting sites protected from wind and predators, increasing adult survival rates. However, overly dense understory may impede flight and reduce host encounter rates (Moreno, et al., 2013). Conversely, moderate understory thinning can create optimal conditions for mosquito movement and human contact, particularly in peri-forest settlements and agricultural fields adjacent to forest edges.

The interaction between vegetation structure and microclimate is particularly important in the context of climate change. As global temperatures rise, vegetation-mediated microclimatic buffering may determine whether mosquito populations expand or contract in specific regions. Forested landscapes with intact canopy cover may provide thermal refugia that allow mosquitoes to persist during extreme heat events, while degraded landscapes may experience temperature extremes that exceed physiological tolerances for some species. At the same time, warming temperatures may enable mosquitoes to exploit higher elevations and latitudes where vegetation structure becomes a limiting factor for establishment and persistence. Importantly, vegetation structure does not operate in isolation but interacts synergistically with hydrology, soil characteristics, and human land-use practices. Irrigated agriculture, for example, often modifies vegetation structure while simultaneously creating aquatic breeding habitats, resulting in compounded effects on mosquito abundance and dispersal. Agroforestry systems, which retain elements of forest structure within agricultural landscapes, may either mitigate or exacerbate vector risk depending on their design, crop composition, and management practices.

From a public health perspective, understanding vegetation structure as an ecological determinant of mosquito ecology has profound implications for vector control and land-use planning. Traditional vector control strategies have largely focused on chemical interventions and habitat elimination, often overlooking the role of landscape structure in shaping vector behavior. Integrating vegetation management such as targeted canopy thinning, understory management, and preservation of intact forest blocks into vector control programs offers a promising avenue for sustainable disease prevention.

Thus, vegetation structure represents a fundamental ecological determinant that governs mosquito microclimate, dispersal, survival, and vectorial capacity. Advances in remote sensing and landscape analysis have enhanced our ability to quantify these structural attributes and link them to disease risk across scales. As forests continue to be modified by human activity and climate change, a deeper understanding of vegetation structure will be essential for predicting vector responses, managing transmission risk, and balancing ecological conservation with public health objectives.

Linking Forest Fragmentation to Disease Transmission
Deforestation and forest degradation have profound effects on ecosystems, transforming them into fragmented landscapes consisting of remnants of forests, agricultural lands, and urban areas, each with its distinct vector communities. This fragmentation alters the spatial configuration of breeding sites, the availability of hosts, and the microclimatic conditions essential for the survival and dispersal of vector organisms (Kweka et al., 2023). In fragmented landscapes, mosquitoes may encounter different environmental conditions that can either enhance or inhibit their development and ability to transmit pathogens. One of the key factors influencing

disease transmission in fragmented forests is the alteration of habitat types. Fragmentation often creates microhabitats with varying levels of vegetation density. In peri-urban areas or at forest edges, where vegetation density is intermediate, there is typically enough shade and humidity to support the survival of mosquito larvae and adults. These environments provide ideal breeding conditions for mosquitoes such as *Aedes aegypti*, the primary vector for dengue and Zika viruses. However, such environments also allow for increased human–vector contact due to the proximity of human settlements (Oliveira *et al.,* 2021). Consequently, these areas are often characterized by an intensified transmission of mosquito-borne diseases, as mosquitoes are both abundant and able to come into close contact with human hosts.

Evidence from Southeast Asia supports this idea, where fragmentation and subsequent forest edge creation have been linked to a higher incidence of vector-borne diseases, including dengue. The increase in mosquito populations in peri-urban zones is attributed to the creation of "edge habitats," where the environmental conditions are ideal for mosquito survival and dispersal (Oliveira *et al.,* 2021). This suggests that fragmented landscapes especially those characterized by an intermediate level of vegetation density provide optimal conditions for mosquito vectors and may promote higher disease transmission rates.

Moreover, vegetation structure plays a crucial role not only in mosquito movement but also in the overall transmission potential of diseases. Research by Murdock et al. (2022) demonstrated that the structure of vegetation directly influences the survival and biting frequency of mosquitoes. Areas with sparse vegetation and more open spaces can lead to higher biting rates, as mosquitoes are able to navigate and reach their hosts more efficiently. In contrast, dense forests act as barriers that limit mosquito flight distances and reduce their ability to locate hosts. Therefore, the configuration of forest remnants within fragmented landscapes significantly affects the movement patterns of mosquitoes and, consequently, their ability to spread diseases. Additionally, fragmentation also alters the availability of natural hosts for mosquitoes, such as wild animals. When forests are fragmented, wildlife populations may become more concentrated in small patches of habitat, which could increase the likelihood of mosquito vectors coming into contact with hosts that carry pathogens, such as *Plasmodium* or *Dengue virus* (Loiseau & Sehgal, 2022). This dynamic suggests that the loss of continuous forest cover may contribute not only to the proliferation of mosquitoes but also to the transmission of wildlife diseases, some of which are transmissible to humans (Figure 2).

Figure 2: Liking Forest Fragmentation to Disease Transmission

The Emerging Role of Remote Sensing and Modeling

In recent years, the integration of remote sensing, spatial ecology, and entomological data has revolutionized the study of vegetation–vector interactions. Satellite technologies such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI),

and LiDAR-derived canopy models offer quantitative descriptors of forest structure and allow researchers to link changes in vegetation cover to mosquito behavior and disease transmission potential (Tusting et al., 2022). These remote sensing tools provide detailed, landscape-level information on vegetation type, density, and distribution,

which are critical for understanding how different forest structures influence vector abundance and disease dynamics. One important application of remote sensing in disease transmission studies is the use of NDVI and EVI to monitor vegetation health and extent. These indices, which are derived from satellite images, provide valuable insights into forest fragmentation, canopy cover, and seasonal changes in vegetation. For example, in areas where deforestation is prevalent, NDVI can help map the extent of habitat loss and predict the potential impacts on vector populations. In addition to satellite-based data, LiDAR technology offers precise measurements of forest canopy height and structure, which are essential for understanding the physical barriers and corridors that influence mosquito dispersal (Tusting *et al.,* 2022).

Machine learning approaches, such as random forest algorithms and spatial regression models, have become invaluable tools in vector-borne disease prediction. These models use environmental variables, including vegetation metrics and climatic data, to predict vector abundance and dispersal patterns. By combining data from remote sensing platforms with entomological surveys, researchers are now able to generate accurate models of disease transmission dynamics based on vegetation structure and environmental variables (Ngugi *et al.,* 2025). These predictive models can help identify high-risk areas for disease outbreaks and inform targeted vector control efforts, complementing traditional insecticidal interventions and larval source management. For instance, a study by Kalluri *et al.* (2007) highlighted the use of remote sensing techniques in surveillance systems for vector-borne diseases, focusing on how changes in land cover could impact disease transmission. These models have proven to be highly effective in identifying disease hotspots and predicting outbreaks based on habitat suitability for mosquito vectors. Furthermore, remote sensing data can assist in monitoring the effectiveness of vector control interventions, such as reforestation or habitat restoration, by tracking changes in vegetation and mosquito populations over time (Palaniyandi, 2012).

Recent advances in unmanned aerial vehicles (UAVs) also present new opportunities for high-resolution monitoring of vegetation structure and mosquito habitats. UAVs can capture detailed imagery of forest fragments, allowing researchers to assess vegetation density and map breeding sites at a much finer scale than traditional satellite imagery (Fornace *et al.,* 2023). The ability to monitor mosquito populations and their habitats with such precision provides an essential tool for the real-time management of vector-borne diseases in fragmented landscapes. In conclusion, the integration of remote sensing and modeling into the study of vector-borne diseases offers promising avenues for improving disease forecasting and enhancing vector control strategies. By providing high-resolution data on vegetation structure and

mosquito movement, these tools can significantly improve our understanding of the relationship between deforestation, forest fragmentation, and disease transmission, ultimately helping to mitigate the public health impacts of land-use change.

This review aims to provide a comprehensive analysis of the complex relationship between forests and mosquito dispersal, integrating ecological, epidemiological, and technological perspectives. It seeks to summarize how vegetation structure and microclimate shape mosquito flight behavior, emphasizing the role of forest canopies, humidity, and temperature in determining mosquito movement and pathogen transmission potential. The review also explores the effects of forest fragmentation and edge habitats, highlighting how these changes alter disease transmission dynamics by providing favorable environments for mosquito vectors, such as *Aedes* and *Anopheles* species. Additionally, recent advancements in remote sensing technologies, including satellite-based vegetation indices and LiDAR, are reviewed for their ability to model and predict vegetation–vector interactions, offering valuable tools for understanding the ecological conditions that drive vector proliferation. Finally, the review discusses the implications of these findings for integrated vector management (IVM) strategies, emphasizing the need for forest conservation policies that balance disease control with ecological preservation. By synthesizing the latest research, this review aims to inform policy makers and health practitioners on effective ways to mitigate the risks of vector-borne diseases in the context of ongoing environmental change.

Vegetation Structure and Microclimate: Mechanistic Pathways Affecting Mosquito Dispersal
Vegetation as a Microclimatic Regulator

Forests, with their complex structure and intricate interactions between biotic and abiotic components, play a pivotal role in shaping local microclimates. The structure of vegetation—encompassing canopy height, leaf density, and vertical stratification—creates a variety of microclimatic conditions that directly influence the physical environment experienced by mosquito populations. These microclimatic factors, including temperature, humidity, light availability, and air movement, are central to determining the behavior and survival of mosquitoes, which are poikilothermic organisms. Being dependent on external temperatures to regulate their body heat, mosquitoes are highly sensitive to environmental variation, making microclimatic gradients crucial for their distribution and disease transmission potential.

Vegetation acts as a natural buffer for temperature extremes, with dense canopies providing cooler, more humid conditions. This is particularly important for mosquito survival, as these conditions can prolong their

lifespan and enhance their capacity to transmit pathogens. However, dense canopies can also reduce mosquito activity, limiting their dispersal capabilities. Mosquitoes in these environments tend to have shorter flight distances, as the microclimate restricts the metabolic energy required for long-range movement (Lambrechts *et al.,* 2023). Conversely, in areas with sparse or fragmented vegetation, mosquitoes are exposed to higher temperatures and greater desiccation stress. This heightened exposure often leads to reduced mosquito survival, but it can also promote greater dispersal activity as mosquitoes are driven to search for more suitable habitats during their flight periods (Ribeiro *et al.,* 2024). These contrasting effects of vegetation on mosquito dispersal, acting as both a barrier and a facilitator, highlight the complexity of forest-mosquito interactions.

The effects of vegetation structure on microclimate have been quantified in several studies, especially using modern techniques such as LiDAR (Light Detection and Ranging) and satellite-based remote sensing. For instance, Ngugi *et al.* (2025) conducted studies in the East African highlands and demonstrated that mosquito abundance was highest in landscapes with intermediate canopy density, where there was a balance between shade and sunlight, leading to optimal temperature and humidity conditions. In areas with dense forest cover (<20% light penetration), dispersal was restricted due to low temperatures and reduced humidity. On the other hand, highly deforested areas with over 80% openness created conditions that led to high mosquito mortality due to desiccation from extreme heat and low humidity. Similarly, Fornace *et al.* (2023) highlighted the importance of forest edges in shaping disease transmission patterns. In their study in Malaysian Borneo, malaria incidence was highest in settlements situated near forest edges that exhibited moderate canopy openness. This suggests that areas with intermediate vegetation cover may facilitate the overlap of vector populations with human settlements, enhancing the risk of disease transmission.
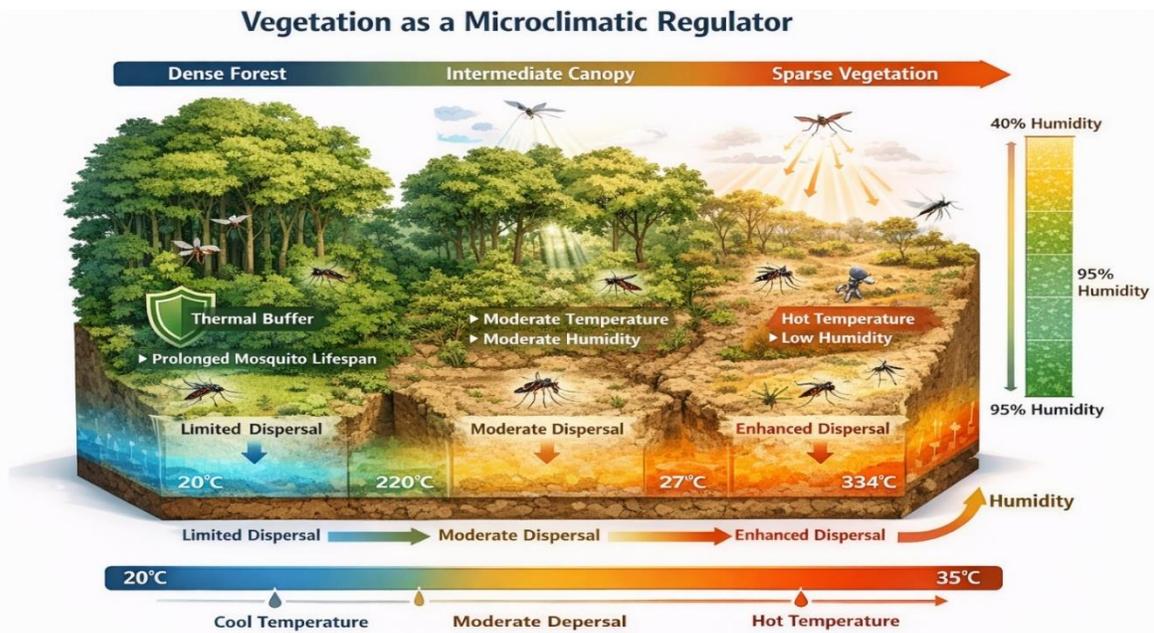

Figure 3: Vegetation as a Microclimatic Regulator of Mosquito Ecology. Vegetation density regulates microclimate, altering temperature, humidity, mosquito survival, and dispersal: dense forests buffer conditions, intermediate canopies optimize vectors, sparse vegetation increases heat stress and movement.

Thermal Regulation and Metabolic Constraints

Temperature is a fundamental determinant of mosquito metabolic rates, reproduction, and pathogen incubation periods. In the context of forests, dense vegetation moderates' temperature extremes, often resulting in diurnal temperature stability. This stable thermal environment generally favors mosquito survival, as it helps maintain the optimal body temperatures required for physiological processes such as flight, feeding, and reproduction. However, while these stable conditions are beneficial for mosquito survival, they can also have a counterproductive effect on pathogen transmission dynamics. Specifically, stable temperatures within shaded forests may reduce the rate at which pathogens, such as *Plasmodium* (the agent of malaria), develop within the mosquito host. In environments with more fluctuating temperatures often seen in deforested or fragmented habitats, pathogens may develop more quickly, increasing transmission potential (Tusting *et al.,* 2022).

Experimental work conducted by Murdock *et al.* (2022) further supports the notion that temperature fluctuations in deforested areas can accelerate the extrinsic incubation period of *Plasmodium falciparum*. Their study showed that mosquitoes in more thermally variable environments exhibited shorter incubation periods, meaning that mosquitoes in these habitats became infectious more quickly, thus increasing the risk of disease transmission. This highlights the role of thermal regulation in determining the speed of pathogen development within mosquito vectors, and, consequently, the dynamics of disease transmission. In contrast, shaded environments, with their more stable temperatures, can delay pathogen development, extending the time frame within which mosquitoes remain infectious. This thermal–biological trade-off underscores the complex role of vegetation in modulating disease risk.

In addition to temperature, vegetation also influences boundary-layer humidity, which has a significant impact on mosquito survival during flight. For mosquitoes such as *Aedes aegypti* and *Haemagogus janthinomys*, flight activity is heavily dependent on humidity levels. These species have humidity-dependent flight thresholds, with dispersal activity declining sharply when relative humidity falls below 60% (Han *et al.,* 2022). Forest vegetation plays a key role in maintaining high humidity levels in the surrounding environment, effectively reducing desiccation rates during flight. By sustaining moist microhabitats, forests extend the temporal window for mosquito activity and pathogen transmission. This is particularly important in tropical regions, where the combination of temperature and humidity can determine the length of the transmission season for vector-borne diseases. In areas where deforestation has caused a reduction in vegetation cover, mosquitoes are more likely to experience rapid desiccation during flight, limiting their dispersal distances and reducing their potential for long-range movement and transmission.

Moreover, the interaction between temperature, humidity, and vegetation structure is not only important for mosquito survival and flight behavior but also for their overall dispersal patterns. For example, studies have shown that mosquitoes in forests with higher canopy density are generally more confined in their movements, as they require specific microclimatic conditions that are difficult to find outside the forest canopy. In contrast, in deforested or fragmented landscapes where vegetation density is lower, mosquitoes are more likely to disperse in search of suitable habitats, which may increase their interactions with human populations. This, in turn, increases the risk of disease transmission.

The structure of vegetation plays a crucial role in regulating microclimatic conditions that influence mosquito survival, behavior, and dispersal. Dense canopies create stable, humid environments that favor mosquito survival but limit their dispersal capacity, while fragmented habitats with lower vegetation density can drive mosquitoes to disperse further, albeit at the cost of increased mortality due to thermal stress and desiccation. Temperature and humidity, regulated by the vegetation structure, also directly affect pathogen incubation periods and the timing of transmission events. As such, vegetation structure not only influences mosquito populations but also modulates the risk of disease transmission. Understanding these microclimatic pathways is crucial for predicting disease dynamics in the face of ongoing deforestation and climate change. As remote sensing technologies continue to improve, they will provide valuable tools for monitoring vegetation changes and their effects on mosquito populations, ultimately helping to inform more effective vector control strategies and conservation efforts.

Light Availability and Behavioral Cues
Light intensity and its spectral quality are fundamental factors that influence the behavior of mosquitoes, particularly in relation to host-seeking, resting, and dispersal activities. In forests, vegetation structure plays a critical role in regulating light availability by determining how much sunlight reaches the forest floor. The extent of canopy cover directly affects light attenuation, reducing photon flux density and ultraviolet (UV) exposure as light penetrates the upper layers and filters down to the understory (Ribeiro et al., 2024). This attenuation of light creates a heterogeneous environment where varying light conditions, such as shaded areas, semi-open edges, and sunlit clearings, provide different navigational cues for mosquitoes, which are strongly phototactic organisms. Phototaxis refers to the tendency of organisms to move toward or away from light. In mosquitoes, phototactic responses are a critical behavioral mechanism that influences their dispersal patterns, host-seeking behavior, and resting preferences. Phototactic responses can help mosquitoes orient themselves within a landscape, guiding them to suitable habitats, breeding sites, or human populations where they can feed. Light gradients in a forest environment, particularly those created by varying canopy cover, act as a navigational map, helping mosquitoes navigate between different ecological zones.

Recent research has highlighted the importance of light availability in shaping mosquito dispersal and activity patterns. Ribeiro et al. (2024) conducted a study across Amazonian forest fragments to investigate the relationship between light availability and mosquito flight behavior. Their findings revealed that *Anopheles darlingi*, a major malaria vector, exhibited peak flight activity at the interface between the shaded understory and semi-open forest edges. This suggests that the transition zone between light and dark environments where there is a balance between shade and sunlight—provides an optimal microhabitat for mosquito activity. The presence of both

light and shadow likely facilitates mosquitoes' movement and increases their ability to navigate through fragmented landscapes. These light gradients, or zones of heterogeneity, can serve as behavioral corridors, guiding mosquitoes between different habitats, such as from forested areas to human settlements.

Similarly, *Aedes albopictus*, the primary vector for dengue and Zika viruses, exhibits distinct preferences for flight corridors in suburban forest mosaics. Lainhart *et al.* (2025) found that these mosquitoes preferentially flew through partially shaded corridors, often found at the edges of suburban forests or along urban-rural interfaces. This preference for intermediate light conditions indicates that mosquitoes are more likely to navigate through environments with mixed light intensity, rather than in either fully shaded or fully exposed areas. These findings suggest that forests with heterogeneous light conditions, where light exposure is neither too intense nor completely absent, act as behavioral corridors that facilitate mosquito movement between sylvatic zones (forest habitats) and human settlements. Such corridors may enhance the transmission of diseases by increasing the contact rates between mosquitoes and human populations. The relationship between light availability and mosquito behavior is critical for understanding how forests and other vegetative landscapes contribute to disease transmission dynamics. As land-use changes continue to fragment forests and alter vegetation structure, these light gradients may be disrupted, potentially influencing mosquito dispersal patterns and increasing the risk of disease transmission. Understanding the role of light in mosquito behavior is therefore essential for predicting how mosquitoes will move in different environmental contexts and for designing effective strategies for vector control.

Vertical Stratification and Resting Niches

In addition to light availability, vegetation structure also affects mosquito behavior by influencing vertical stratification within the forest. Vertical stratification refers to the distribution of different ecological layers in a forest, from the canopy down to the forest floor. These layers provide distinct habitats for mosquitoes, affecting where they seek shelter, breed, and interact with hosts. The upper canopies of forests, with their abundant foliage and exposure to different species of animals, are often home to arboreal (tree-dwelling) hosts such as birds and primates. In contrast, lower strata, such as the understory and forest floor, offer humid refuges and breeding habitats for mosquitoes. Vertical stratification plays a critical role in mosquito dispersal and disease transmission by determining where mosquitoes interact with their hosts. Mosquitoes that inhabit higher canopy layers, such as *Aedes niveus* and *Haemagogus janthinomys*, are more likely to encounter arboreal hosts, which can carry sylvatic (forest-specific) viruses. These mosquitoes are typically involved in the maintenance of viruses in wildlife populations and are less likely to come into contact with human hosts. This vertical host partitioning, whereby mosquitoes are restricted to specific layers of the forest, serves as a natural mechanism that reduces the risk of zoonotic pathogens—diseases that are primarily transmitted from animals to humans spilling over into human populations.

In Southeast Asia, Lambrechts et al. (2023) reviewed studies of vertical host partitioning in tropical forests, specifically focusing on the behavior of *Aedes* and *Haemagogus* mosquitoes. They found that these species often inhabit higher canopy levels, where they are in close proximity to arboreal animals, thus facilitating the transmission of sylvatic viruses like yellow fever and dengue in wildlife populations. However, as deforestation progresses and vertical complexity is lost, the ecological separation between arboreal and ground-dwelling mosquitoes begins to break down. This collapse of vertical gradients in fragmented habitats increases the likelihood of cross-species interactions, bringing mosquitoes that normally live in the canopy into contact with ground-level mosquitoes, and consequently, human populations. This increased overlap between canopy-dwelling and ground-level mosquitoes in fragmented landscapes may have significant implications for disease dynamics. For example, deforestation can lead to the spillover of zoonotic pathogens from wildlife to humans, as mosquitoes that previously maintained sylvatic viruses in isolated forest ecosystems are now able to encounter human hosts more frequently. By disrupting the natural vertical separation between mosquito species, deforestation effectively bridges the gap between sylvatic and human transmission cycles, enhancing the risk of zoonotic disease outbreaks. Moreover, the loss of vertical stratification in deforested or fragmented landscapes reduces the availability of suitable resting niches for mosquitoes. The dense, humid conditions of the forest understory, which provide essential refuge from desiccation, are often lost in deforested areas. This forces mosquitoes to adapt to new microhabitats, potentially exposing them to environmental stressors such as extreme temperatures and low humidity, which can reduce their lifespan and reproductive success. The disruption of these vertical niches can thus affect both the survival and dispersal of mosquito populations, altering the dynamics of disease transmission in these areas.

Wind Dynamics and Dispersal Efficiency

Wind is another critical factor in determining mosquito dispersal, as it affects the passive transport of mosquitoes over long distances. The structural characteristics of vegetation: such as canopy cover, leaf density, and the overall complexity of the landscape mediate wind flow and can either enhance or limit mosquito dispersal capacity.

Dense forests, with their thick canopies and high leaf density, act as barriers to wind flow, creating sheltered environments that reduce wind speed and turbulence. This wind sheltering effect limits long-range dispersal by mosquitoes, but it can increase local retention, keeping mosquitoes confined to specific habitats. On the other hand, forest fragmentation tends to increase edge permeability and create areas with greater wind turbulence. These changes can enhance short-distance transport, facilitating mosquito movement between habitats. In fragmented landscapes, wind dynamics may become a more significant factor in mosquito dispersal, as the wind turbulence created by the uneven distribution of vegetation helps mosquitoes move between patches of suitable habitat, such as from forest fragments to human settlements. Mark–release–recapture (MRR) experiments, which track the movement of tagged mosquitoes over time, have provided valuable insights into how vegetation structure influences mosquito dispersal. For example, Ngugi *et al.* (2025) summarized several MRR studies that compared mosquito dispersal in different vegetation types. They found that mosquitoes in open grasslands were able to disperse an average distance of 320 meters, whereas mosquitoes in closed-canopy forests dispersed only 80 meters on average. This suggests that dense canopies significantly limit the dispersal range of mosquitoes, possibly due to the sheltering effect that reduces wind exposure.

Interestingly, intermediate vegetation densities: such as those found in forest edges or semi-open habitats: seem to maximize mosquito dispersal efficiency. Mosquitoes in these environments were able to maintain a more directional flight, with wind dynamics enhancing their movement without excessively hindering their ability to navigate. These findings highlight the non-linear relationship between vegetation density and dispersal efficiency, suggesting that the aerodynamic landscape defined by vegetation structure is a key factor in determining how far mosquitoes can travel. In fragmented landscapes, the increase in edge permeability can facilitate short-distance dispersal by mosquitoes, as the wind turbulence created by the fragmentation allows for easier movement between different habitats. However, this increased dispersal may also increase the likelihood of mosquitoes coming into contact with human settlements, thus enhancing the risk of disease transmission. This dynamic emphasizes the importance of understanding how vegetation structure influences both the local retention and long-range dispersal of mosquito populations, which is crucial for designing effective vector control strategies.

Moisture Retention and Breeding Site Availability
Vegetation plays an integral role in regulating the persistence of breeding sites for mosquitoes by influencing soil moisture levels, surface runoff, and organic litter accumulation. These factors are crucial for creating and maintaining the microhabitats where mosquito larvae can develop. Forests, through their diverse and complex structure, help regulate water availability and create suitable conditions for larval development. For instance, leaf litter and shaded pools within forests often provide ideal breeding sites for mosquitoes. The accumulation of organic material such as decaying leaves and branches increases the moisture content in the soil, which in turn promotes the formation of small water-filled depressions that serve as breeding sites. These microhabitats are particularly critical for species such as *Anopheles* mosquitoes, which prefer to lay their eggs in slow-moving or stagnant water pools (Kweka *et al.,* 2023).

However, vegetation density also has a moderating effect on the availability of these breeding sites. While leaf litter and shaded pools create breeding habitats, dense canopy cover can sometimes limit the growth of algae, which are an important food source for mosquito larvae. Algal growth is essential for larval development, as it provides a stable and abundant food source, especially for species that breed in temporary water bodies, such as *Anopheles* species. In shaded environments where light penetration is reduced, algal growth can be suppressed, leading to lower food availability for mosquito larvae, which in turn may reduce breeding success (Kweka *et al.,* 2023). This highlights an important ecological trade-off in forest environments, where dense canopy cover may suppress algal growth and therefore reduce the breeding success of certain mosquito species, but at the same time, it offers a more stable and humid microclimate for mosquito survival.

Research in the Congo Basin by Kweka *et al.* (2023) has further demonstrated the role of vegetation structure in shaping mosquito breeding habitats. Their study found that *Anopheles funestus* and *Anopheles gambiae*, two primary malaria vectors, exhibited significantly higher densities near forest–farm boundaries compared to deep forest interiors. This pattern was linked to moderate light availability and shallow, stable water pools in these areas. At forest edges or along forest–agriculture interfaces, where the canopy is less dense and more light is available, mosquito populations thrive due to the optimal conditions for both larval development and adult dispersal. These edge habitats offer a mix of shade and sunlight, promoting both the growth of algae and the stability of water pools. This research illustrates how vegetation structure not only influences the microclimate but also determines the distribution of both adult mosquito populations and their larval habitats, thereby directly impacting population dynamics and disease transmission risks.

Thus, vegetation structure and its impact on breeding site availability are central to the ecology of vector-borne

diseases. The ability of mosquitoes to find suitable breeding habitats is strongly influenced by the type and structure of vegetation, as well as by environmental factors like moisture retention, canopy density, and light availability. Forests with varied vegetation, such as those found at forest edges or along the periphery of agricultural lands, tend to create conditions that are more conducive to mosquito breeding, which in turn enhances the likelihood of disease transmission. These interactions between forest structure and mosquito breeding site availability must be carefully considered in vector control strategies, especially in regions where forests are being fragmented or cleared for agricultural expansion.

Integration of Remote Sensing and Field Ecology

The integration of advanced remote sensing technologies, such as LiDAR (Light Detection and Ranging) and hyperspectral imaging, has revolutionized the study of vegetation structure and its role in influencing mosquito dispersal and disease dynamics. These technologies allow for precise mapping of vegetation-microclimate interactions that influence the behavior and survival of mosquitoes. By combining field data with high-resolution remote sensing information, researchers can now quantify the effects of forest structure on microclimate conditions, vector behavior, and disease transmission potential in a way that was previously impossible. LiDAR-derived canopy height models (CHMs) are particularly useful for quantifying key structural attributes of forests, including foliage density, gap fraction, and the overall heterogeneity of the understory (Ngugi et al., 2025). LiDAR data can generate three-dimensional representations of forests, which can be used to assess the extent to which different vegetation layers (e.g., canopy, understory, and forest floor) contribute to creating microhabitats that are suitable for mosquito survival and dispersal. When combined with temperature and humidity sensors, LiDAR data provides a comprehensive view of the environmental conditions that mosquitoes experience within different parts of the forest. These three-dimensional reconstructions of the forest environment allow for a more nuanced understanding of how vegetation structure shapes microclimatic factors like temperature, humidity, and light availability, all of which are critical for mosquito ecology.

For instance, in a pioneering study by Fornace et al. (2023), multispectral satellite data were used to derive the Normalized Difference Vegetation Index (NDVI) variability across malaria-endemic landscapes in Borneo. NDVI is a commonly used vegetation index that reflects the density and health of vegetation. Fornace and colleagues found that higher NDVI heterogeneity, reflecting mixed vegetation densities and canopy openness, was strongly associated with increased vector dispersal and malaria incidence. The study demonstrated that areas with a mosaic of dense forests and open spaces, which create a

range of microhabitats with varying temperature and humidity conditions, tend to have higher mosquito dispersal rates and a greater likelihood of disease transmission. This highlights how vegetation structure metrics, derived from remote sensing technologies like NDVI, can serve as predictive proxies for disease risk in complex landscapes.

By integrating remote sensing data with field ecology, researchers can develop models that predict how changes in vegetation structure might influence mosquito populations and disease transmission. These models can be used to forecast disease outbreaks, identify high-risk areas for vector-borne diseases, and design targeted vector control interventions. For example, by using LiDAR data to assess the structure of a forest and combining it with temperature and humidity measurements, researchers can predict where mosquitoes are most likely to breed, where they are likely to encounter hosts, and how the microclimate in these areas will affect their survival and dispersal. This approach allows for more precise and effective management of vector-borne diseases, especially in regions where forest fragmentation and land-use change are altering the landscape. Moreover, these remote sensing technologies are not only useful for understanding current disease risks but also for monitoring changes over time. As deforestation continues at an alarming rate in many parts of the world, remote sensing data can be used to track changes in forest cover and vegetation structure. By comparing historical and current satellite imagery, researchers can assess how changes in land use: such as forest clearing for agriculture or urban development are affecting mosquito populations and disease transmission risks. This real-time monitoring capability is crucial for managing vector-borne diseases in rapidly changing environments.

Conceptual Model: Vegetation Microclimate–Dispersal Nexus

Drawing from the studies reviewed in this section, we propose a conceptual model to better understand the interactions between vegetation structure, microclimate, and mosquito dispersal. This model synthesizes the findings from multiple studies and integrates them into a framework that can guide future research and inform vector control strategies.

The conceptual model is based on the understanding that vegetation structure affects mosquito dispersal through a series of interacting mechanisms. These mechanisms are outlined below:

Canopy cover regulates light, temperature, and humidity gradients: The density of the canopy determines how much light penetrates the forest, influencing both the thermal conditions and humidity levels at ground level. Dense canopies create cool, humid conditions that are

conducive to mosquito survival but can reduce their activity levels and dispersal capacity. In contrast, areas with intermediate canopy cover allow more light to penetrate, which may increase mosquito activity and dispersal.

Microclimate influences mosquito survival, activity, and pathogen incubation: The microclimatic conditions created by vegetation structure: such as temperature, humidity, and light availability—directly influence mosquito survival and activity. Stable microclimates, such as those found in dense forests, promote mosquito survival but may slow down pathogen development, while fluctuating conditions in fragmented landscapes may speed up pathogen development, increasing transmission potential.

Wind and turbulence affect flight energy expenditure and dispersal directionality: Vegetation structure also affects wind flow, which in turn influences mosquito dispersal. Dense forests reduce wind speed and turbulence, limiting long-range dispersal but enhancing local retention. Fragmented landscapes with greater edge permeability and wind turbulence can facilitate short-distance dispersal, potentially increasing the risk of mosquitoes coming into contact with human populations.

Vegetation gaps and edges provide ecological corridors for vector movement: Forest edges and gaps in vegetation create transition zones that provide mosquitoes with pathways to move between different habitats. These corridors facilitate mosquito dispersal between sylvatic zones (forest habitats) and human settlements, increasing the likelihood of disease transmission.

Vertical stratification defines host contact zones and resting niches: Vertical stratification in forests provides distinct habitats for mosquitoes. Canopy-dwelling mosquitoes interact with arboreal hosts, while ground-dwelling mosquitoes are more likely to encounter terrestrial hosts. Deforestation and fragmentation reduce this vertical complexity, increasing the chances of cross-species interactions and the spillover of zoonotic pathogens.

The result of these interacting mechanisms is a nonlinear response in which both highly dense and highly open vegetation limit mosquito dispersal. Intermediate vegetation structure, with a balance of light availability, temperature, humidity, and wind conditions, creates the most favorable conditions for mosquito movement and survival, leading to what we can term "dispersal-optimal" habitats. These habitats are characterized by a mosaic of forested and open spaces, creating a dynamic environment where mosquitoes can thrive while also facilitating disease transmission. This model underscores

the complexity of the relationship between vegetation structure, microclimate, and mosquito dispersal, emphasizing the need for an integrated approach that considers all of these factors when assessing disease risks and designing vector control interventions. By understanding how these mechanisms interact, researchers and policymakers can better predict how land-use changes will affect vector-borne diseases and develop more effective strategies to mitigate the impact of these diseases on human populations.

Vegetation structure plays a critical role in determining the behavior, survival, and dispersal of mosquitoes, which directly influences disease transmission dynamics. Through its regulation of light, temperature, humidity, and wind, vegetation affects both adult mosquito activity and the availability of breeding sites. Remote sensing technologies have significantly enhanced our ability to quantify and model these interactions, providing valuable tools for predicting disease risks and designing targeted vector control interventions. The proposed conceptual model highlights the complex, nonlinear relationship between vegetation structure and mosquito dispersal, emphasizing the importance of considering multiple ecological factors in vector-borne disease management. By integrating field ecology with advanced remote sensing technologies, we can better understand how changes in vegetation will influence mosquito populations and their ability to spread diseases, ultimately improving public health outcomes in rapidly changing environments.

Implications for Vector Control and Public Health
Mosquito-borne diseases, including malaria, dengue, Zika, and chikungunya, continue to pose major public health challenges worldwide, especially in tropical and subtropical regions. Forests play a central role in shaping the ecological processes that influence mosquito dispersal, survival, and disease transmission. The evidence synthesized in this review suggests that forest vegetation structure: ranging from dense, intact forests to fragmented landscapes can significantly impact mosquito behavior and vector-borne disease risks. In this section, we will explore the implications of these findings for vector control and public health.

The Role of Forest Conservation
Forest conservation plays a crucial role in mitigating the spread of mosquito-borne diseases. Preserving or restoring forests can help regulate key environmental factors: such as temperature, humidity, and habitat availability: that influence mosquito populations. Dense forests, with their stable microclimates, act as natural barriers to mosquito dispersal, reducing the overall risk of disease transmission by limiting mosquito movement. Furthermore, intact forests provide essential ecological functions that help maintain the natural balance between

mosquito populations and their predators, which can further reduce the risk of outbreaks. On the other hand, deforestation and forest fragmentation can lead to an increase in mosquito populations and the spread of vector-borne diseases. Fragmentation creates "edge habitats" : transitional areas between forested and open environments: that are conducive to mosquito survival. These edges often support increased mosquito activity, particularly for species like *Aedes aegypti* and *Anopheles* species, which thrive in intermediate vegetation environments. The increased availability of breeding sites in fragmented landscapes, such as stagnant water pools in forest gaps, further facilitates mosquito reproduction. As such, forest conservation efforts that maintain large, contiguous forest habitats could play a key role in reducing the prevalence of mosquito-borne diseases. Additionally, forest restoration initiatives could have significant public health benefits. Reforestation and afforestation efforts that restore forest ecosystems to their original structure can help reverse the adverse effects of deforestation, stabilize microclimates, and enhance the habitat for natural mosquito predators. Such efforts could reduce the overall mosquito population and, by extension, lower the risk of disease transmission. Public health strategies that incorporate forest conservation as part of their disease control efforts may therefore offer an ecologically sustainable and long-term solution to managing mosquito-borne diseases.

Integrating Vegetation Management with Vector Control

Land-use and forest management policies must consider the role of vegetation in shaping mosquito populations and disease transmission dynamics. Traditional vector control strategies, such as insecticide spraying and larval source management, have been essential tools in reducing mosquito populations. However, these strategies often come with limitations, including resistance to insecticides, environmental degradation, and the high cost of implementation in resource-limited settings. Integrating vegetation management with these conventional approaches could provide a more holistic and sustainable solution. Vegetation management strategies should aim to reduce mosquito habitat availability while preserving biodiversity and ecosystem services. By understanding the specific vegetation types that provide optimal conditions for mosquito breeding and survival, land managers can tailor their interventions to target these habitats. For example, removing or managing vegetation in certain areas—such as stagnant water pools at forest edges—could help reduce breeding sites for mosquitoes without compromising the integrity of entire ecosystems. In urban and peri-urban environments, managing vegetation around human settlements, such as through the creation of "green buffers" or "green belts," can help reduce the

proximity between mosquito habitats and human populations, thus limiting the potential for disease transmission.

Moreover, integrating vegetation management with vector control can help avoid conflicts between disease control and conservation efforts. For instance, clearing certain vegetation around high-risk areas for disease transmission could reduce human exposure to mosquitoes, while still maintaining forest cover in surrounding areas. In practice, this could involve a combination of selective thinning, controlled burns, or agroforestry practices that promote sustainable land use while limiting the creation of mosquito habitats.

Challenges and Opportunities

Implementing forest-based vector control strategies faces several challenges, primarily related to competing land-use priorities and the complexity of managing large-scale ecosystems. Forest conservation and restoration efforts often come into conflict with agricultural expansion, urbanization, and infrastructure development. The pressure to clear forests for agriculture or urban development can hinder efforts to maintain natural mosquito barriers. In such cases, balancing disease prevention with economic development and food security is a significant challenge. Another challenge lies in the variability of forest-mosquito interactions across different regions, forest types, and mosquito species. While some forested areas may act as natural barriers to mosquitoes, others particularly fragmented or disturbed habitats can serve as facilitators of mosquito dispersal. This variability makes it difficult to apply a one-size-fits-all approach to vegetation management. Effective forest-based vector control strategies will require localized, context-specific interventions that take into account the ecological characteristics of different landscapes.

Despite these challenges, there are also significant opportunities for integrating ecological principles into vector control strategies. Cross-disciplinary approaches, involving ecologists, urban planners, public health experts, and policymakers, can help create innovative solutions that balance the needs of disease control with environmental conservation. For instance, the concept of "green urbanism: which promotes the integration of green spaces into urban planning—could be adapted to include strategies for reducing mosquito habitats in urban areas. Additionally, increased awareness of the links between biodiversity conservation and public health could lead to more comprehensive policies that incorporate forest conservation as part of national and regional disease control plans.

Forest Management Strategies for Disease Prevention

Forest management strategies that aim to mitigate the risk of mosquito-borne diseases must focus on creating and

maintaining environments that are less conducive to mosquito survival and dispersal. Effective management should consider both ecological principles and the health needs of local populations, striking a balance between conservation and disease prevention.

Ecologically Informed Forest Management

Ecologically informed forest management prioritizes the sustainable use of forest resources while maintaining the ecological processes that regulate biodiversity and ecosystem services. Forests are complex ecosystems where changes in structure, composition, and function can have cascading effects on species populations, including disease vectors like mosquitoes. Thus, forest management strategies should be designed with a clear understanding of how different vegetation types and structures influence mosquito populations.

Key practices for ecologically informed forest management include:

Selective logging: Instead of clear-cutting, which disrupts the entire forest structure, selective logging removes specific trees to maintain canopy cover and vertical stratification. This helps preserve the microclimate and limits the creation of open areas that can become mosquito breeding sites.

Agroforestry: Agroforestry combines agriculture with forest conservation by planting crops alongside trees in a way that maintains forest cover and biodiversity. This approach can help preserve habitats for natural mosquito predators, such as birds and amphibians, while reducing the availability of suitable breeding sites for mosquitoes.

Prescribed burns: In some ecosystems, controlled burns can be used to maintain vegetation structure and prevent the overgrowth of certain species that could create favorable habitats for mosquitoes. This approach, however, must be carefully managed to avoid unintended consequences for the ecosystem and human health.

These practices not only help maintain forest structure but also reduce the creation of fragmented habitats where mosquitoes thrive, thereby mitigating disease transmission risks.

Buffer Zones and Ecological Corridors

Buffer zones and ecological corridors are essential elements of landscape management that can significantly impact mosquito dispersal and disease transmission. Buffer zones refer to areas of vegetation that act as physical barriers between mosquito habitats and human settlements, reducing the risk of mosquito exposure. Ecological corridors, on the other hand, are strips of natural habitat that connect isolated ecosystems, allowing for the movement of species and maintaining biodiversity. In the context of mosquito-borne diseases, buffer zones can be particularly effective at limiting the movement of mosquitoes from forested areas to urban or peri-urban zones. For example, planting vegetation around human settlements: such as around agricultural fields or residential areas—can create a barrier that prevents mosquitoes from dispersing into these high-risk zones. These buffer zones could be strategically placed to prevent mosquitoes from reaching areas where human activity is most concentrated, thus reducing the risk of disease transmission. Ecological corridors, while primarily used to connect fragmented habitats and maintain biodiversity, can also play a role in regulating mosquito populations. By connecting mosquito habitats across landscapes, corridors can help maintain natural predator-prey dynamics, which can help control mosquito populations. However, when corridors are too close to human settlements, they could inadvertently facilitate mosquito movement into urban areas, which would increase disease transmission risk. Thus, the design of ecological corridors must carefully consider the balance between promoting biodiversity and minimizing disease risks.

Reforestation and Agroforestry

Reforestation and agroforestry are two complementary strategies that can play a significant role in reducing mosquito populations while enhancing forest biodiversity. Reforestation involves planting trees in areas where forests have been cleared, helping restore ecosystem functions, including regulating microclimates and supporting wildlife populations. Agroforestry, as mentioned earlier, integrates trees into agricultural landscapes, creating mixed-use environments that support both crop production and biodiversity.

Reforestation can help restore forest canopy cover, which regulates temperature and humidity, creating conditions that are less conducive to mosquito survival. In addition, by improving the stability of forest ecosystems, reforestation helps maintain the natural habitat for mosquito predators, reducing the need for pesticide use. Similarly, agroforestry practices that combine trees with crops or pastures can reduce mosquito breeding opportunities by increasing vegetation diversity and maintaining areas of shade and moisture.

Incorporating agroforestry into forest management practices can also provide economic incentives for local communities. By providing alternative sources of income, such as non-timber forest products or sustainable crops, agroforestry reduces the need for unsustainable logging or agricultural practices that would otherwise lead to deforestation.

Future Research Directions

The review of the current literature highlights several gaps in our understanding of how forest vegetation structure affects mosquito populations and disease transmission dynamics. Addressing these gaps will require a multi-

disciplinary approach that integrates field ecology, remote sensing technologies, and climate models.

Long-Term Monitoring of Vegetation–Mosquito Interactions

One of the primary gaps identified is the need for long-term monitoring of vegetation-mosquito interactions. While many studies have explored the role of vegetation structure in shaping mosquito behavior and survival, few have conducted long-term studies that track how changes in vegetation over time influence mosquito populations. Longitudinal research would provide valuable insights into how seasonal and yearly changes in vegetation—due to climate variability, land-use change, or forest management interventions—affect mosquito dispersal and disease transmission. Such studies are crucial for understanding the cumulative impact of deforestation and habitat fragmentation on disease dynamics.

Climate Change Modeling

Another area that requires further exploration is the interaction between climate change, vegetation changes, and mosquito populations. Climate models can help predict how changes in temperature, precipitation, and humidity will affect mosquito distribution and disease transmission risks. Understanding how climate change will alter vegetation structure and mosquito ecology is essential for predicting future disease outbreaks and designing effective management strategies. Climate change models that incorporate vegetation structure and mosquito behavior will allow public health authorities to better anticipate and mitigate disease risks in different regions.

Advanced Remote Sensing Applications

Technological advancements in remote sensing, such as drones, LiDAR, and hyperspectral imaging, offer new opportunities for monitoring mosquito habitats and vegetation structure with high spatial resolution. These technologies enable researchers to map fine-scale variations in forest structure, vegetation density, and microclimate conditions that influence mosquito survival and dispersal. Combining remote sensing data with field-based mosquito monitoring can provide real-time information on vector populations and disease transmission risks. Future research should focus on integrating these technologies into a comprehensive surveillance system that allows for more accurate disease forecasting and early warning.

Cross-Disciplinary Research

Finally, encouraging cross-disciplinary research will be crucial for advancing our understanding of vegetation–vector interactions and improving disease control strategies. Collaborations between ecologists, entomologists, public health experts, and urban planners will help develop more effective, landscape-based approaches to vector control. This could involve designing urban green spaces that balance biodiversity conservation with disease prevention or developing policies that integrate forest conservation with public health goals. Such interdisciplinary efforts will provide a more holistic framework for addressing the complex challenges of vector-borne disease transmission in rapidly changing environments.

CONCLUSION

In conclusion, understanding the intricate relationships between forest vegetation, microclimate, and mosquito dispersal is essential for predicting and mitigating the risks of mosquito-borne diseases. Vegetation structure affects mosquito behavior through its regulation of light, temperature, humidity, and wind, all of which influence mosquito survival and dispersal patterns. Forests can serve as both barriers and facilitators of mosquito movement, depending on their structure and level of fragmentation. Effective vector control and disease prevention strategies must consider these ecological processes and incorporate forest management practices that preserve and restore suitable mosquito habitats while minimizing disease transmission. Integrating forest conservation, vegetation management, and innovative remote sensing technologies offers a promising path forward for managing mosquito-borne diseases in a rapidly changing world. This review underscores the need for a comprehensive, landscape-based approach to vector control that considers the complex interactions between vegetation, mosquitoes, and disease dynamics. By developing integrated strategies that account for the ecological, social, and health dimensions of mosquito control, we can reduce the impact of mosquito-borne diseases and protect vulnerable populations worldwide.

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