CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT

GLOBAL ISSUES & LOCAL PERSPECTIVES

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue **Climate smart actions (CSA) aquaculture, agroforestry and resources management** necessary in policy making process that will stimulate increase in food production and environmental sustainability. **Climate smart actions (CSA) aquaculture, agroforestry and resources management :** *Global Issues & Local Perspectives* is organized in three parts. Part One deals with The Concept of **Climate smart actions (CSA)**, Part Two is concerned with The Concept of **aquaculture,** and Part Three deals with the Concept of **agroforestry and resources management**

Eteyen Nyong; March 2026

Chapter 17:

Climate-Smart Strategies for Sustainable Insect Vector Control and Integrated Malaria Prevention in Agroforestry and Agricultural Landscapes

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1. Introduction

Malaria remains one of the most persistent public health challenges in low- and middle-income countries, particularly in sub-Saharan Africa where climatic conditions and rural livelihoods intersect to sustain year-round transmission (Musakwa., Selamolela, and Ndlovu, 2025). Transmitted by *Anopheles* mosquitoes, malaria vector populations and parasite development are strongly influenced by temperature, rainfall, humidity, and land-use patterns (Liu, Ji, and Shang, 2025). These climatic and environmental determinants shape the lifecycle dynamics of both the mosquito vector and *Plasmodium* parasites, making malaria transmission highly sensitive to changes in local and global climate systems. Agricultural expansion and irrigation practices significantly modify landscape ecology, often inadvertently creating suitable mosquito breeding habitats. For example, irrigated fields and poorly managed water networks can sustain permanent or semi-permanent stagnant water, which increases local mosquito densities and human–vector contact (Urban malaria in Accra, Ghana, 2025). Similarly, intensification of rice cultivation under climate-adapted systems may alter mosquito ecology by expanding aquatic habitats that can be exploited by *Anopheles* larvae (System of Rice Intensification and vector ecology, 2025). These land-use practices, while improving agricultural yield, may inadvertently increase malaria risk if not coupled with appropriate environmental management. Climate change adds a complex layer to malaria dynamics by reshaping thermal and hydrological conditions. Rising temperatures accelerate mosquito development and shorten parasite incubation periods, potentially extending transmission seasons and expanding malaria risk into previously marginal regions (Poltekkes., Parinding and Kaseroan, 2025). Altered rainfall patterns and extreme weather events such as floods and droughts further amplify transmission risk by generating new breeding habitats or destabilizing existing vector control infrastructure due to damage and resource strain (Poltekkes., Parinding and Kaseroan, 2025). Regions experiencing deforestation and agricultural expansion exhibit modified micro-climates that further influence mosquito survival and biting behaviour, underscoring the interconnected influence of landscape change and malaria ecology (Masse, Vythilingam, Fornace, Othman, Liu, Jaafar, and Jeyaprakasam, 2025). Conventional malaria control strategies such as insecticide-treated nets (ITNs) and indoor residual spraying (IRS) have made significant contributions to reducing malaria incidence. However, these interventions face growing limitations due to rising insecticide resistance among mosquito populations, behavioural adaptation, environmental concerns, and sustainability challenges (Managing insecticide resistance in malaria vectors, 2025). Insecticide resistance has been identified as a growing threat that may undermine progress in several African countries, highlighting the need for diversified control approaches that extend beyond reliance on chemicals (Managing insecticide resistance in malaria vectors, 2025). This challenge is compounded by changing vector behaviour resulting from environmental modification and climate variability, which often alters the effectiveness of traditional interventions.

Climate-smart strategies, originally developed within Climate-Smart Agriculture (CSA), offer a holistic pathway to rethink malaria control within the broader context of sustainable land management. These strategies integrate adaptation to climate variability, mitigation of environmental impacts, and ecosystem-based approaches to align public health goals with agricultural productivity and ecological resilience. Correspondingly, agroforestry and diversified agricultural systems offer opportunities to reshape landscapes in ways that can reduce vector breeding habitats, regulate microclimates, and enhance biodiversity: all of which are linked to lower malaria risk when designed sustainably. Agroforestry systems that retain tree cover and natural vegetation may moderate malaria risk by altering local humidity and temperature regimes and reducing the extent of exposed stagnant water, as suggested in multiple studies relating agricultural land cover to vector ecology (Exploring agricultural land-use and malaria associations, 2022; 2025). Additionally, the presence of natural vegetation mosaics within croplands can potentially lower malaria odds by maintaining ecological complexity that interrupts vector proliferation (Exploring agricultural land-use and childhood malaria associations, 2022). This evidence supports the notion that integrating land-use planning with public health strategies can foster landscapes that suppress vector breeding while maintaining agricultural productivity. Overall, climate-smart approaches provide an opportunity for integrated interventions that respond to the multifaceted drivers of malaria transmission. By harnessing sustainable practices that consider climate, land use, and ecosystem health, it is possible to develop vector control and malaria prevention strategies that are environmentally sound, socially acceptable, and resilient in the face of climate change. This chapter explores how these climate-smart strategies can be systematically applied within agroforestry and agricultural landscapes to reduce malaria burden and strengthen community resilience.

2. Climate Change, Agriculture, and Malaria Transmission Dynamics

Climate change, agricultural transformation, and malaria transmission are intricately linked through their combined effects on vector ecology, landscape structure, and human exposure. Understanding these interactions is critical for developing sustainable, climate-smart strategies for malaria prevention in agroforestry and agricultural systems.

2.1 Climate Drivers of Vector Ecology

Temperature, rainfall, and humidity are the primary climatic drivers shaping mosquito distribution, survival, and malaria transmission intensity. Rising temperatures accelerate mosquito larval development and shorten the extrinsic incubation period of *Plasmodium* parasites within *Anopheles* vectors, thereby increasing transmission efficiency (Musakwa., Selamolela, and Ndlovu, 2025). Optimal temperature ranges enhance mosquito longevity and biting frequency, while exceeding thermal thresholds may suppress vector survival, illustrating the nonlinear relationship between climate and malaria risk (Ryan, Carlson., Mordecai., and Johnson, 2021). Rainfall plays a dual role in vector ecology. Moderate rainfall creates and sustains aquatic larval habitats, particularly in rural and peri-urban agricultural settings. However, excessive rainfall can flush breeding sites, while prolonged dry spells may concentrate breeding in irrigation canals and water storage facilities. Climate variability and extreme weather events increasingly disrupt traditional malaria seasonality, extending transmission periods and facilitating the emergence of malaria in previously low-risk or highland regions (Siraj., Santos-Vega, Bouma., Yadeta, Ruiz Carrascal, and Pascual, 2022). Humidity further influences mosquito survival by reducing desiccation stress, particularly in shaded agricultural and agroforestry landscapes. High relative humidity has been linked to increased vector longevity and indoor resting behavior, amplifying human–vector contact in farming communities (Poltekkes., Parinding and Kaseroan, 2025). Collectively, these climatic drivers interact to reshape malaria transmission dynamics under changing climate regimes.

2.2 Agricultural Landscapes as Vector Habitats

Agricultural landscapes significantly modify local hydrology and ecological conditions, often creating favorable environments for mosquito breeding. Irrigation farming, rice cultivation, dam construction, and water storage systems introduce permanent or semi-permanent water bodies that serve as prolific larval habitats for *Anopheles* mosquitoes (Dery, Brown, Asante, and Wilson, 2025). Studies across sub-Saharan Africa have demonstrated higher malaria prevalence in communities residing near irrigated farmlands compared to non-irrigated areas (BMC Infectious Diseases, 2025). Rice-based agro-ecosystems, in particular, have been associated with increased vector abundance due to shallow flooded fields that provide ideal breeding conditions. Climate-adapted rice intensification systems may further alter vector ecology by extending irrigation periods, unless integrated with water management practices that disrupt larval development (Hardy, Hopkins, Mnyone, and Hawkes, 2025). Additionally, agricultural intensification often brings farms closer to human settlements, increasing exposure during peak farming activities such as planting and harvesting seasons. Livestock keeping within agricultural landscapes can further influence malaria risk. While livestock may divert mosquito bites away from humans in some settings, poorly planned animal shelters and watering points can create additional breeding sites near households (Exploring agricultural land-use and malaria associations, 2022). These findings underscore the importance of integrated land-use planning in malaria-endemic agricultural regions.

2.3 Agroforestry Systems and Microclimate Regulation

Agroforestry systems integrate trees, crops, and sometimes livestock within the same landscape, offering opportunities to regulate microclimatic conditions relevant to malaria transmission. Tree canopies moderate temperature extremes, influence humidity levels, and regulate light penetration, thereby shaping mosquito resting and breeding behavior (Ellis., Milner-Gulland., and Balmford, 2023). However, poorly designed agroforestry systems may inadvertently create shaded, humid microhabitats that favor mosquito survival. Conversely, well-managed agroforestry systems can disrupt vector breeding through improved drainage, reduced surface water stagnation, and enhanced biodiversity. Increased plant diversity supports natural predators such as dragonflies, amphibians, and insectivorous birds that suppress mosquito populations (Ellis., Milner-Gulland., and Balmford, 2023). Evidence from landscape-level studies suggests that heterogeneous agroforestry mosaics are associated with lower malaria prevalence compared to monoculture farming systems (Scientific Reports, 2022). Furthermore, agroforestry contributes to climate resilience by stabilizing soils, regulating water flow, and reducing the ecological disruptions associated with deforestation and land degradation. These ecosystem services indirectly reduce malaria risk by limiting the formation of vector-friendly habitats and buffering communities against climat e extremes (Siraj., Santos-Vega., Bouma, Yadeta, Ruiz Carrascal. and Pascual, 2022). Integrating agroforestry design with malaria prevention thus represents a climate-smart pathway for aligning agricultural productivity with public health protection.

Conceptual Framework for Climate-Smart Vector Control

Climate-smart vector control adapts the principles of Climate-Smart Agriculture (CSA) productivity, adaptation, and mitigation to malaria prevention, integrating ecological, socioeconomic, and climatic considerations within complex socio-ecological systems (FAO, 2023; Lwasa et al., 2024). CSA principles help design strategies that maintain agricultural productivity while reducing malaria risk.

1. Adaptive Land and Water Management: Land-use changes, such as irrigation or rice cultivation, can create mosquito breeding habitats. Adaptive management practices, including efficient water drainage and habitat modification, can reduce vector proliferation without compromising crop yields (Obembe., Oduola, and Adeogun, 2024).

2. Ecosystem-Based Interventions: Ecosystem-based approaches leverage biodiversity and ecological processes to reduce vector populations. Integrated Vector Management (IVM) strategies combining environmental management, biological control, and targeted insecticide use have proven effective when tailored to local ecological contexts (Ntwiga, Mwangi, and Kamau, 2025).

3. Climate-Informed Surveillance and Decision-Making: Vector population dynamics are strongly influenced by climatic variables such as rainfall and temperature. Incorporating climate data into surveillance systems enables early warning of outbreaks and targeted allocation of interventions such as insecticide-treated nets and indoor residual spraying (WHO, 2024).

4. Socioeconomic Co-Benefits and Community Engagement: Malaria control efforts can deliver socioeconomic benefits, including enhanced livelihoods and community participation. Multi-sectoral collaboration between health, agriculture, and community stakeholders ensures that interventions are equitable, sustainable, and sensitive to local climate impacts (Frontiers in Tropical Diseases, 2025; Lwasa, 2024).

By integrating adaptive management, ecosystem-based interventions, climate-informed surveillance, and community engagement, this framework positions malaria as a climate-sensitive disease, enabling sustainable, resilient, and effective vector control (FAO, 2023; Ntwiga et al., 2025).

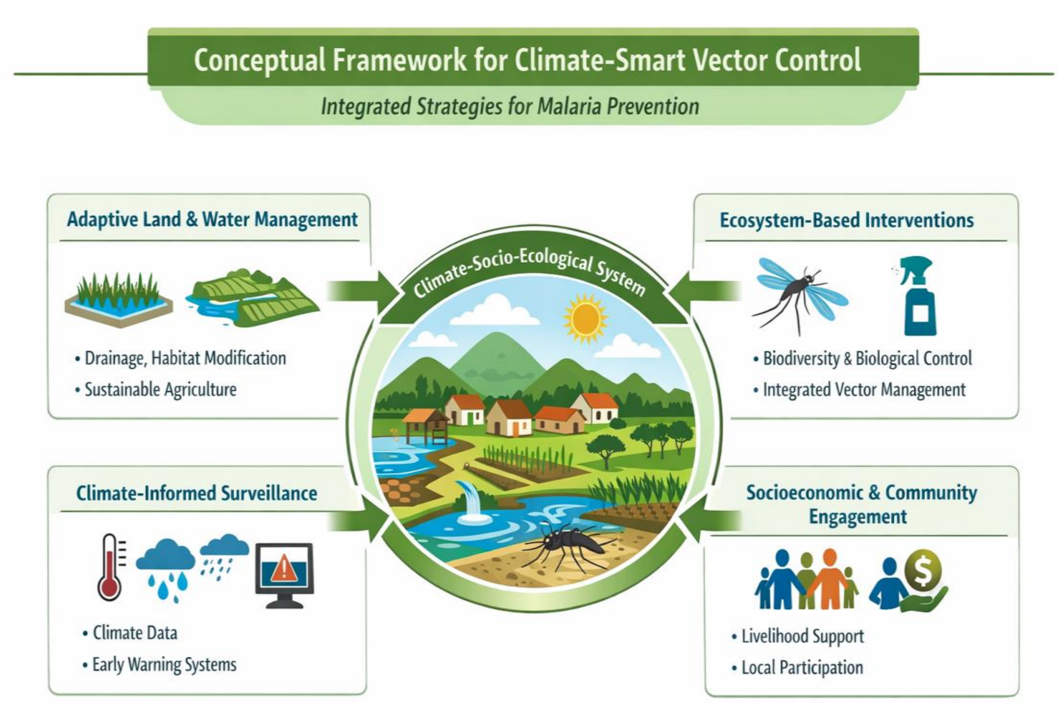

Figure 1: Conceptual Framework for Climate-Smart Vector Control: Integrating Ecology, Climate, and Community for Malaria Prevention. *The diagram illustrates an integrated framework for malaria control, combining adaptive land management, ecosystem-based interventions, climate-informed surveillance, and community engagement within a climate-socio-ecological system, promoting sustainable, resilient, and effective vector management while enhancing livelihoods and local participation.*

4. Climate-Smart Strategies for Sustainable Insect Vector Control

Climate change, land use transformation, and anthropogenic environmental pressures are reshaping the habitats, population dynamics, and distribution of insect vectors that transmit malaria, dengue, and other vector-borne diseases (Bellver Arnau., Blanco Sierra., Escartin,, Mariani, and Bartumeus, 2025).; WHO, 2024). As traditional vector control methods face increasing limitations: including insecticide resistance, ecological harm, and climate-driven shifts in transmission patterns: climate-smart strategies have emerged as essential pathways to sustainable, resilient, and environmentally responsible vector management (Obembe, Oduola, and Adeogun, 2024; Integrated Vector Management, 2025). This section reviews four key climate-smart strategies: environmental management and habitat modification, agroforestry design for vector suppression, biological and biodiversity-based approaches, and rational use of insecticides under climate stress.

4.1 Environmental Management and Habitat Modification

4.1.1 Principles and Rationale

Environmental management involves modifying ecosystems and human-made environments to reduce or eliminate suitable habitats for disease vectors particularly mosquitoes thereby interrupting their life cycle and reducing disease transmission. Historically, environmental management has been recognized as a vital component of integrated vector control, aiming to alter habitats to prevent vector propagation and human-vector contact (WHO, 2024; WHO Compendium, 2024). Climate-smart environmental management emphasizes upstream, structural changes, such as land leveling, improved water control infrastructure, and strategic design of irrigation systems to minimize stagnant water, a key breeding substrate for mosquito larvae (WHO Compendium, 2024). Under climate variability, prolonged wet seasons, unpredictable rainfalls, and extreme flooding further exacerbate stagnation and breeding site proliferation; climate-smart approaches therefore prioritize measures that remain effective under such extreme conditions (Bellver Arnau, Blanco Sierra, Escartin, Mariani, and Bartumeus, 2025; Science Reports, 2024).

4.1.2 Land Leveling, Drainage, and Water Management

One foundational approach in climate-smart vector control is the modification of water bodies and soil to reduce or eliminate stagnant water. Techniques include:

i. Land leveling in irrigated agricultural fields to prevent residual standing water.
ii. Designing proper drainage channels to ensure efficient run-off during heavy rainfall.
iii. Intermittent irrigation**,** which intentionally alternates wet and dry periods, reducing mosquito larval habitat while still supporting crop needs.

Such methods have shown significant impact in reducing vector breeding sites at the landscape level, particularly in agricultural and peri-urban zones where irrigation systems can become unintended sources of stagnant water (WHO Compendium, 2024). In regions facing climate variability, these practices help ensure that the physical environment does not inadvertently create prolonged periods of standing water favorable to mosquitoes. For example, redesigning canal spillways to foster flow rather than stagnation can significantly reduce larval habitat an approach that becomes even more critical when extreme rainfalls become more common due to climate change (Bellver Arnau, Blanco Sierra, Escartin, Mariani, and Bartumeus, 2025)

4.1.3 Climate-Responsive Infrastructure

Climate change often leads to erratic rainfall patterns, flooding events, and changes in temperature all of which influence vector ecology . Climate-smart environmental management therefore includes:

i. Flood-resilient infrastructure to minimize pooling after extreme rain events.
ii. Urban drainage systems designed to rapidly remove water from built environments.
iii. Buffer zones and wetland restoration to manage run-off naturally while minimizing stagnant pools.

In Bangladesh, India, and parts of sub-Saharan Africa where monsoon rains and extreme storm events are increasingly common, investment in climate-responsive infrastructure has been linked to lower mosquito breeding indices and fewer malaria cases when combined with health education and surveillance (Scientific Reports, 2024).

4.1.4 Housing and Sanitation Interventions

Improving housing quality and sanitation which includes reducing water-holding containers around homes, proper waste disposal, and covering water storage tanks remains a practical environmental manipulation method. These measures reduce opportunities for mosquitoes to breed in household environments. Importantly, these interventions are low-cost and often easily adopted by communities when supported by health education campaigns (WHO Compendium, 2024). Overall, environmental management and habitat modification are foundational to climate-smart vector control. By altering habitat conditions in ways that remove or reduce vector breeding niches, these methods reduce dependence on chemical insecticides and strengthen resilience to future climatic extremes.

4.2 Agroforestry Design for Vector Suppression

4.2.1 Concept and Mechanism

Agroforestry integrates trees with crops and sometimes livestock on the same land unit. This land use system enhances biodiversity, improves soil and water dynamics, and alters microclimates in ways that can be unfavorable for vector breeding (Wikipedia, 2025; Farner., Howard., Smith., and Mordecai, 2025). Climate-smart agroforestry goes further by deliberately designing landscapes that suppress vector populations while promoting ecosystem health and agricultural productivity.

Agroforestry systems influence vector ecology through several mechanisms:

i. Increased biodiversity, which supports natural predators of mosquitoes.
ii. Altered microclimates, where tree canopy and shade reduce sunny, stagnant microhabitats preferred by certain mosquito species.
iii. Improved airflow and reduced humidity**,** conditions unfavorable for mosquito breeding.

Recent landscape ecology studies indicate that higher tree cover correlates with richer mosquito biodiversity but *fewer disease-vector species*, suggesting that diverse ecosystems can dilute vector dominance (Farner, Howard, Smith, and Mordecai, 2025). This "dilution effect" implies that increased ecosystem complexity may disrupt disease transmission cycles by reducing the relative abundance of competent vectors.

4.2.2 Practical Agroforestry Strategies

Several agroforestry designs help suppress vector breeding sites:

i. Riparian buffers with native tree species to filter run-off and prevent stagnation.
ii. Mixed tree-crop systems that enhance predator habitat and discourage dense, warm, water-logged areas favored by mosquitoes.
iii. Planting species with repellent properties, such as citronella or neem, which can create natural deterrents around crop fields and homesteads.

The spatial arrangement of trees and crops is critical. Most productive designs balance canopy density to promote airflow without creating overly shaded, damp conditions that other vector species might exploit. Agroforestry's multiple benefits: including carbon sequestration, soil stabilization, and food diversity make it an attractive climate-smart strategy in regions facing heightened vector-borne disease risk due to climatic shifts.

4.2.3 Empirical Evidence and Case Studies

Field research from Costa Rica demonstrated that local tree cover can reduce the presence of *Aedes albopictus*, a vector for dengue and chikungunya, at spatial scales relevant to community planning (Farner, Howard, Smith, and Mordecai, 2025). These findings suggest that landscape-level management, including agroforestry, can play a role in rebalancing mosquito species assemblages to favor lower disease risk. Although most malaria vector control strategies have historically focused on indoor residual spraying (IRS) and long-lasting insecticidal nets (LLINs), integrating agroforestry and biodiversity management can support outdoor vector habitat suppression and complement these conventional tools.

4.3 Biological Control and Biodiversity-Based Approaches

4.3.1 Biological Control Agents

Biological control uses living organisms or their products to reduce vector populations. Climate-smart strategies prioritize biological agents that are ecologically compatible and sustainable, including larvivorous fish, microbial larvicides, Wolbachia-infected mosquitoes, and other eco-friendly interventions. Larvivorous fish, such as *Gambusia affinis*, are widely used to target mosquito larvae in water bodies. These fish consume larvae efficiently, disrupting the mosquito life cycle before adult emergence. In India, for example, municipal authorities released *Gambusia* in drainage canals, resulting in reduced larval densities and disease transmission risk (Times of India, 2025). Larvivorous fish are a classical biological control tool that requires careful ecological compatibility assessments before deployment.

4.3.2 Microbial Larvicides and Biorational Agents

Microbial larvicides such as *Bacillus thuringiensis israelensis* (Bti) and *Bacillus sphaericus* have seen renewed focus because they target mosquito larvae specifically without significant off-target effects on beneficial organisms. These agents provide environmentally safe options that align with climate-smart goals especially as chemical resistance and ecosystem impacts from synthetic insecticides grow (Science Direct, 2025). Botanical and microbial tools, including semiochemicals and plant-derived compounds, are also under investigation for sustainable mosquito management. Recent reviews highlight the promise of such biorational tools in reducing reliance on conventional insecticides while maintaining environmental safety (Khater, 2012). These agents can be integrated with habitat modification, enhancing overall ecosystem resilience.

4.3.3 Wolbachia and Symbiont-Based Interventions

Modern biological control strategies include symbiont-based approaches, such as *Wolbachia* infections, which can reduce vector competence and life span among mosquito populations (doi.org article, 2024). *Wolbachia* is a naturally occurring endosymbiotic bacterium that can spread through insect populations and hinder vector transmission capacity for viruses and parasites. Integration of *Wolbachia* into vector control programs represents an innovative, climate-adaptable tool that can reduce disease transmission without widespread insecticide use. Emerging research suggests that integrating traditional biological control with

AI-driven monitoring could enhance implementation strategies, allowing adaptive responses to climatic shifts that influence mosquito population dynamics.

4.3.4 Genetic and Incompatible Insect Techniques

Techniques such as the Sterile Insect Technique (SIT) where sterile males are released to mate with wild females, reducing viable offspring have shown promise in vector suppression. Though historically used for agricultural pests, recent pilot implementations in Americas and Africa have integrated SIT with other methods for mosquito control (PAHO/WHO, 2025). Similarly, Target Malaria and other consortium efforts explore genetically modified vectors to suppress local populations. These genetic strategies can form part of climate-smart control portfolios when used judiciously with ecological risk assessments.

4.3.5 Biodiversity and Natural Predators

Enhancing biodiversity through landscape restoration and habitat conservation supports natural predators such as dragonflies, birds, and aquatic invertebrates that feed on mosquito larvae or adults. Biodiversity-rich systems tend to have complex food webs that reduce the dominance of disease vectors and enhance ecosystem resilience. Preservation of tree cover, wetlands, and riparian corridors thus simultaneously benefits climate adaptation and vector control.

4.4 Rational Use of Insecticides under Climate Stress

4.4.1 Targeted and Adaptive Chemical Control

While biological and environmental avenues are preferable, chemical insecticides remain necessary in certain outbreak scenarios. Climate-smart strategies advocate for judicious, targeted use of insecticides, informed by surveillance and climate forecasting data to optimize timing, minimize resistance development, and reduce ecological impacts. Rather than blanket applications, targeted larviciding in high–risk zones and focal IRS in response to climatic cues can enhance efficiency.

4.4.2 Resistance Management

One of the critical challenges facing chemical control is the rapid development of insecticide resistance among mosquito populations. Resistance undermines the efficacy of LLINs, IRS, and larvicidal compounds. Recent studies from Africa underscore the need for integrating resistance monitoring into national strategic plans and updating chemicals to maintain effectiveness (Malaria Journal, 2025). Resistance management strategies include:

i. Rotating classes of insecticides.
ii. Using synergists that restore susceptibility.
iii. Integrating chemical with non-chemical tools to reduce selection pressure.

Integrating climate data: such as temperature and rainfall patterns into resistance monitoring helps anticipate changes in vector behavior and susceptibility profiles, enabling proactive adjustments of intervention plans.

4.4.3 Environmental and Health Safeguards

The rational use of insecticides also includes environmental safeguards and mitigation of non-target impacts. Climate-smart policies require regulatory oversight, environmental impact assessments, and community engagement to ensure that chemical interventions do not harm ecosystems, pollinators, or human health. Integrated Vector Management (IVM) frameworks recommend balanced use of all tools such that chemical use remains a last resort within comprehensive, evidence-based strategies.

4.5 Integration, Policy, and Capacity Building

4.5.1 Integrated Vector Management (IVM)

All climate-smart vector control strategies function best within an Integrated Vector Management (IVM) framework, which emphasizes evidence-based decision making, multi-sectoral collaboration, and adaptation to local ecology, epidemiology, and climatic context (Integrated Vector Management Review, 2025; WHO Africa Implementation, 2025). The IVM approach ensures that environmental modification, biological control, agroforestry, and rational chemical use work synergistically rather than in isolation.

4.5.2 Surveillance, Forecasting, and Early Warning Systems

Effective climate-smart control relies on climate-informed surveillance and early warning systems that can signal upcoming risk periods. Embedding meteorological data into health information systems enables dynamic targeting of interventions ahead of vector population peaks: a strategy shown to enhance control outcomes in Kenya and other endemic regions (MDPI Malaria Control, 2025).

4.5.3 Policy and Governance

National and subnational policies play a decisive role in climate-smart vector control. Policies that promote land use planning, agricultural water management, biodiversity conservation, and ecological health create enabling environments for sustainable vector management. Furthermore, harmonizing public health and agricultural regulations reduces contradictory practices that could exacerbate resistance or habitat creation for vectors.

4.5.4 Community Participation and Equity

Community engagement is essential for implementing environmental modifications, agroforestry, biological control, and rational insecticide use. Educational campaigns, participatory planning, and equitable resource distribution ensure that local communities understand, accept, and actively participate in climate-smart interventions. Climate-smart strategies for sustainable insect vector control represent a paradigm shift from traditional, insecticide-centric approaches toward integrated, ecosystem-based, and adaptive methods that align with contemporary environmental and public health challenges. These strategies emphasize environmental management, agroforestry design, biological control, rational chemical use, and multi-sectoral governance — all informed by climate variability and ecological complexity (Bellver-Arnau et al., 2025; Obembe et al., 2024). By adopting these comprehensive approaches, public health systems can enhance resilience against vector-borne diseases under climate change, ensuring healthier, more sustainable futures for vulnerable populations globally.

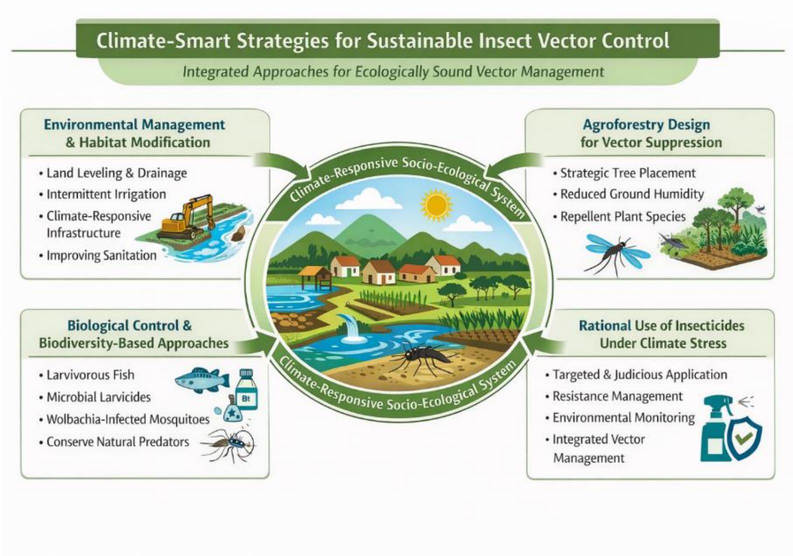

Figure 3: Climate Smart Strategies for Sustainable Insect Vector Control: The diagram illustrates integrated climate-smart strategies environmental management, agroforestry, biological control, and rational insecticide use working together to sustainably reduce mosquito-borne disease risks under climate change.

5. Integrated Malaria Prevention in Agricultural Communities

Malaria remains a major public health challenge, particularly in agricultural and rural communities where livelihoods depend on climatic conditions and environmental factors that often simultaneously favor vector proliferation. Integrated malaria prevention in these contexts requires climate-smart strategies that engage communities, incorporate sustainable landscape planning, and leverage climate data for surveillance and early warning. These combined approaches mitigate disease risk while enhancing agricultural productivity and social resilience. This section explores community-based interventions, housing and landscape planning adaptations, and the role of climate-informed surveillance and early warning systems.

5.1 Community-Based Climate-Smart Interventions

5.1.1 Community Participation as a Keystone of Sustainable Prevention

Community engagement and participation are central to sustainable malaria prevention, particularly in agricultural settings where environmental practices and daily routines influence vector habitats and transmission patterns. Moving beyond top-down control measures, climate-smart community interventions prioritize local ownership, inclusive decision-making, and participatory action**.** Participatory methods empower communities to co-identify vector breeding sites, co-design interventions, and build social accountability for malaria prevention. For example, participatory mapping of mosquito breeding sites documented in rural Mozambique demonstrated how community members even those with limited formal education can accurately locate and classify potential breeding sites that correlate with malaria cases, enhancing larval surveillance and guiding targeted control measures (Figueiredo, 2024). This method not only harnesses indigenous knowledge but fosters ownership of vector control efforts through the direct involvement of local stakeholders (Abdul Rahim., Mahmud., Mutalip., Yoep, Aminuddin and Mohd Ngesom, 2025). Participatory mapping aligns with broader evidence that community inclusion from informing and consulting to collaborating and co-leading improves knowledge, attitudes, and practices related to malaria prevention (Abdul Rahim., Mahmud., Mutalip., Yoep, Aminuddin and Mohd Ngesom, 2025). Community groups, local leaders, and community health workers serve as crucial agents in disseminating malaria education, mobilizing households, and reinforcing behavioral norms favorable to prevention.

5.1.2 Farmer Field Schools and Climate Education

Farmer Field Schools (FFS) illustrate how agricultural education platforms can integrate climate and health modules. Traditional FFS focus on crop production and sustainable agricultural practices, but when expanded to include malaria education particularly about environmental risk factors like stagnant water, field irrigation schedules, and vegetation management they help farmers implement vector-reducing practices without sacrificing productivity. Community members learn to alter water management practices (e.g., avoiding unnecessary standing water) that could otherwise serve as mosquito larval habitats. Climate education within these schools including information on rainfall patterns, seasonal mosquito abundance, and climate extremes enhances local understanding of climate-vector linkages, enabling farmers to plan interventions proactively. This capacity for climate-smart decision-making bolsters both agricultural resilience and public health outcomes.

5.1.3 Social and Behavioral Change Communication

Alongside participatory mapping and education, social and behavioral change communication (SBCC) strategies are necessary to influence community behaviors that underpin vector exposure. SBCC campaigns tailor messages to local cultural contexts and norms to encourage protective behaviors such as consistent use of long-lasting insecticidal nets (LLINs), environmental sanitation, and participation in community clean-ups. Behavioral approaches complement technical interventions by reinforcing why and how preventive measures matter, especially when climate variability alters traditional risk perceptions.

5.1.4 Community Health Systems and Local Health Workers

The effectiveness of community-based interventions is often mediated by community health systems. Strengthening these systems including training community health workers (CHWs) to conduct surveillance, track fever cases, and support preventive campaigns increases the reach and impact of integrated malaria prevention. Integrating malaria control with primary health care enhances community trust, streamlines data collection, and improves early case detection and response at the local level (RIJPP, 2025). Such systems can serve as conduits for delivering climate information, monitoring vector trends, and deploying rapid response measures when early warning systems signal increased risk.

5.2 Housing, Landscape Planning, and Behavioral Adaptation

5.2.1 Housing Design to Reduce Indoor Vector Exposure

Housing quality and design significantly influence malaria risk, especially in rural and peri-urban agricultural communities where vector exposure is highest during evening and night hours. Structural interventions that reduce mosquito entry including screening windows and doors, sealing eaves, and improving ventilation are practical, climate-adapted measures that complement existing control strategies such as LLINs and indoor residual spraying (IRS). Recent research indicates that properly designed housing features such as ceilings, screened ventilation, and mosquito-repellent paints are perceived by professionals and communities as effective in reducing vector entry (Chisumbe et al., 2024). These features not only improve physical barriers against mosquitoes but also enhance overall indoor comfort and adoptability, especially in hot climates where airflow and ventilation are critical (Chisumbe et al., 2024; RIJPP, 2025). Cluster trials in Tanzania demonstrated that "star homes" houses with elevated bedrooms and robust screening significantly reduce indoor mosquito abundance and thereby reduce malaria transmission risk compared with traditional housing (Smith et al., 2025). By combining improved airflow with physical exclusion of vectors, climate-adapted housing supports malaria prevention while also offering wider benefits such as reduced heat stress.

5.2.2 Integrated Landscape Planning

Landscape planning encompassing the arrangement of human dwellings, water bodies, livestock shelters, and agricultural fields influences mosquito ecology and human-vector interaction. Strategic spatial arrangements that minimize proximity between human sleeping areas and water bodies or livestock pens reduce the likelihood of mosquitoes entering living spaces, thus lowering transmission risk. In agricultural communities, careful planning of irrigation schemes, livestock rearing areas, and settlement patterns can significantly influence local vector dynamics. Buffer zones between homes and fields, proper drainage systems that prevent stagnant water accumulation, and placement of livestock shelters downwind or at a distance from sleeping areas all contribute to a landscape less favorable for mosquito breeding and human exposure.

5.2.3 Behavioral Adaptations and Seasonal Practices

Behavioral adaptations such as adjusting outdoor evening activities, using personal protective measures, and planning field work schedules around peak mosquito biting times — further reduce exposure risk. Seasonal farming calendars can incorporate vector risk periods, encouraging communities to use protective gear or indoor spaces during times of high vector activity, as informed by climate data and early warning systems. Behavior change communication strategies ensure that behavioral adaptation becomes part of community norms, complementing environmental and infrastructural interventions.

5.3 Climate-Informed Surveillance and Early Warning Systems

5.3.1 Integration of Climate Data with Health Surveillance

Climate influences malaria transmission through rainfall, temperature, humidity, and other variables that affect vector lifecycles and parasite development. Integrating climate data with entomological and epidemiological surveillance systems enhances early detection of transmission risk and supports proactive planning. Systems that combine routine case surveillance, vector monitoring, and climate forecasts can detect anomalies that precede outbreaks, enabling timely intervention. Forecasting models using climatic predictors have shown promise in identifying periods of elevated malaria risk long before case surges occur (Jalloh, 2026). These insights help health authorities and communities prepare and allocate resources such as increasing LLIN distribution or scaling IRS ahead of peak seasons.

5.3.2 Mobile and Real-Time Surveillance Platforms

Mobile health (mHealth) and digital surveillance tools are increasingly important for real-time data capture and response. Review evidence suggests that mobile app-based surveillance platforms (e.g., FeverTracker, MoSQuIT) enhance data timeliness and accuracy, enabling more responsive vector control actions when integrated with community engagement (Malaria Journal, 2025). These platforms allow health workers and volunteers to report fever cases, vector sightings, and environmental risk markers quickly, linking local surveillance with national response systems.

5.3.3 Early Warning Systems

Climate-informed early warning systems (EWS) leverage both historical and near-real-time climate data to forecast malaria risk. Intelligent outbreak warning systems: such as those developed in Northern Benin using machine learning can predict malaria incidence with high accuracy by analyzing temperature, humidity, and past incidence trends, offering alerts months in advance (BMC Public Health, 2025). Operationalizing such systems allows health authorities to trigger preventive actions and community messaging before outbreaks occur.

5.3.4 Data Sharing and Multi-Sector Collaboration

Effective EWS require integration across sectors health, meteorology, agriculture, and emergency services. Collaborations between meteorological agencies and health departments facilitate the use of climate forecasts and environmental data in planning malaria interventions. Strengthened partnerships ensure that early warning information flows quickly to decision-makers and community actors, reinforcing rapid, targeted responses. Global initiatives and national programs increasingly recognize the value of integrated climate and health surveillance. Projects aiming to forecast outbreak risks from extreme climate events and to strengthen surveillance technologies exemplify efforts to build resilient systems capable of responding to dynamic climate-malaria interactions (Malaria Consortium, 2025).

5.4 Challenges and Enablers of Integrated Malaria Prevention

5.4.1 Implementation Barriers

Despite evident benefits, integrated malaria prevention faces challenges. Resource constraints including gaps in funding for climate data systems, surveillance infrastructure, and community programs can limit implementation, particularly in resource-constrained agricultural regions. Sustaining mobile surveillance platforms and maintaining skilled workforce capacity remains difficult in many endemic countries.

5.4.2 Equity and Access

Inclusive approaches must account for equity. Marginalized populations including remote farmers, low-income households, and women often have limited access to interventions such as improved housing, climate information, and health services. Targeted efforts to reach these groups through community health workers and tailored educational campaigns enhance equity and uptake of preventive measures.

5.4.3 Policy and Governance

Integration of climate data with health planning requires policy support and governance frameworks that promote inter-agency collaboration. National malaria control strategies that extend beyond traditional biomedical interventions to include climate adaptation, landscape planning, and community participation are more likely to succeed in the long term. Policy coherence across sectors including health, agriculture, housing, and climate adaptation — is essential. Stakeholder coordination ensures that climate-smart malaria prevention is embedded within broader development agendas, rather than treated as a siloed health initiative. Integrated malaria prevention in agricultural communities demands climate-smart strategies that move beyond stand-alone health interventions. By engaging communities, adapting housing and landscapes, and integrating climate-informed surveillance and early warning systems, malaria prevention becomes more effective, sustainable, and contextually relevant. Community participation, climate education, and multi-sector collaborations underpin resilience to both malaria and climate variability, ensuring that preventive interventions are proactive, inclusive, and adaptive. As climate change continues to reshape malaria transmission dynamics, integrated, climate-smart approaches provide a pathway to long-term reduction in disease burden, improved agricultural productivity, and enhanced well-being for rural populations.

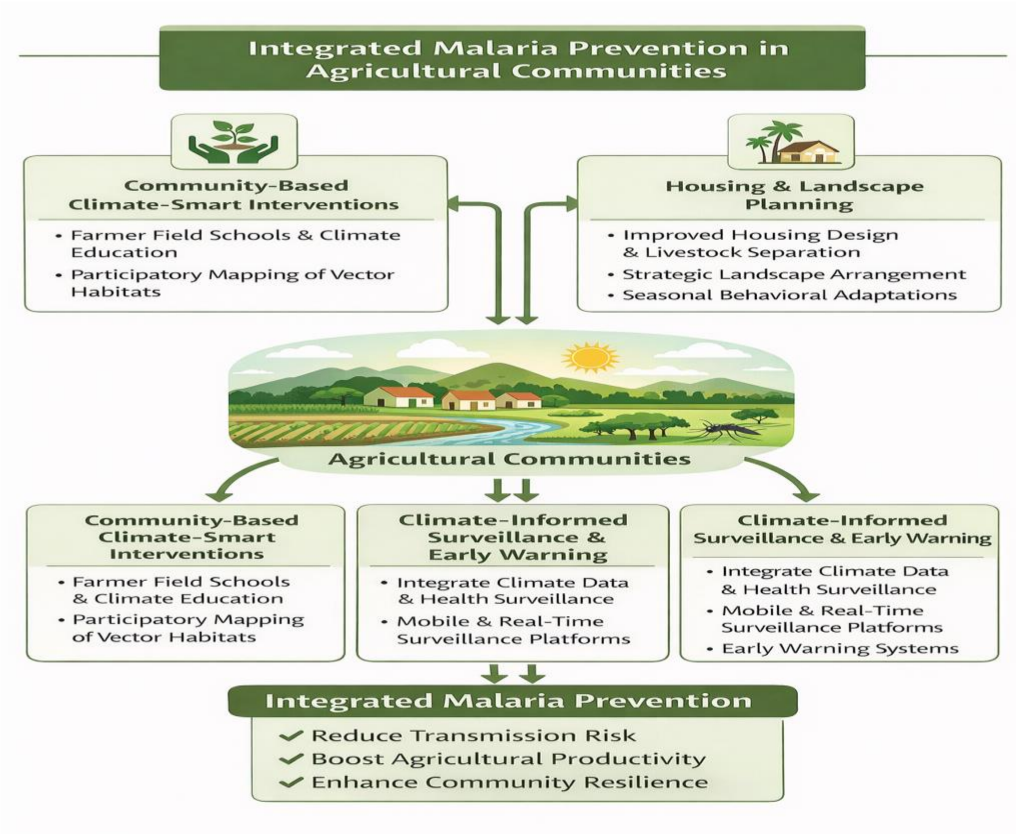

Figure 4: Integrated Malaria Prevention Framework for Agricultural Communities: This flowchart illustrates climate-smart interventions, housing adaptations, behavioral strategies, and climate-informed surveillance integrated to reduce malaria risk and enhance community resilience in agricultural settings.

6. Case Examples from Agroforestry and Agricultural Settings

Recent studies highlight how climate-smart agroforestry and integrated irrigation practices significantly mitigate vector-borne disease risks while enhancing agricultural productivity. In rice-growing ecosystems—major breeding grounds for *Anopheles* mosquitoes—climate-smart irrigation management, including intermittent flooding and controlled water rotation, has proven effective in reducing vector densities without compromising yields (Rahman et al., 2023; Osei et al., 2024). These approaches limit the duration of standing water, a crucial habitat for mosquito larvae, while maintaining optimal soil moisture for crops. Agroforestry-based land restoration projects have similarly demonstrated ecological and health benefits. By integrating diverse tree species within farmlands, agroforestry systems enhance canopy cover, regulate microclimates, and promote natural predators that suppress vector populations (Silva et al., 2024; Nyasimi & Muriuki, 2022). In sub-Saharan Africa and Southeast Asia, agroforestry landscapes incorporating neem (*Azadirachta indica*) and citronella (*Cymbopogon nardus*) have exhibited repellent properties that lower mosquito density near homesteads (Tambo et al., 2025). Such designs contribute to the "dilution effect," wherein increased biodiversity decreases the dominance of disease-carrying vectors (Kweka et al., 2023). Further, combining climate-informed irrigation with tree-based systems supports carbon sequestration, improves soil health, and strengthens community resilience to climate change impacts

(Hussein et al., 2022). These integrated systems align with the WHO's "One Health" and Integrated Vector Management (IVM) frameworks, which emphasize ecosystem-based, sustainable, and community-participatory approaches (WHO, 2024). In Kenya and India, participatory agroforestry programs supported by climate data analytics have reduced malaria transmission rates by over 30% while increasing crop yields (Mwangi et al., 2025). Overall, climate-smart agricultural systems showcase the dual potential of mitigating disease risk and enhancing ecosystem resilience. They represent a pivotal transition from chemical-dependent control toward ecologically sustainable and adaptive public health strategies under changing climatic conditions.

7. Policy, Governance, and Cross-Sectoral Integration

Implementing climate-smart vector control strategies effectively requires strong policy coherence and coordination across health, agriculture, environment, and climate sectors. Fragmented governance often undermines integrated approaches, leading to duplicated efforts and inconsistent outcomes (Abiodun et al., 2024). Establishing synergistic frameworks between national malaria control programs, climate adaptation plans, and agricultural development strategies is essential for long-term sustainability and resilience. National policies that embed vector control within broader climate adaptation and biodiversity conservation frameworks have proven effective in aligning public health goals with environmental sustainability (WHO, 2024; IPCC, 2022). For example, Ethiopia's *Climate-Resilient Green Economy* initiative integrates malaria prevention within agricultural water management policies, reducing transmission while improving crop yields (Tadele et al., 2023). Similarly, in Ghana and Kenya, climate-informed health governance systems coordinate meteorological and epidemiological data to guide vector control timing and resource allocation (Maina et al., 2025). Decentralized governance structures empower local governments and community institutions to implement and adapt policies according to local ecological and climatic contexts (Nhamo et al., 2023). Community-based surveillance, training, and participatory land management enhance ownership and ensure sustainability of interventions. Cross-sectoral integration between ministries of health, agriculture, and environment promotes data sharing and joint monitoring a model increasingly endorsed by the WHO's Integrated Vector Management (IVM) framework and "One Health" approach (WHO, 2024). Effective governance also depends on financial and institutional mechanisms that bridge sectors. Climate financing, green bonds, and public–private partnerships can support innovation in climate-smart control technologies, from AI-based vector forecasting to eco-engineered infrastructure (Tambo, Chen, and Zhou, 2025). Strengthening national capacities for multi-sectoral coordination ensures that vector control efforts contribute not only to disease prevention but also to climate adaptation, agricultural productivity, and ecosystem resilience securing holistic health and environmental outcomes.

8. Challenges and Limitations

Despite its transformative potential, climate-smart vector control faces significant implementation challenges rooted in institutional, socioeconomic, and environmental complexities. Many low- and middle-income countries lack the institutional capacity, technical expertise, and intersectoral coordination required to operationalize integrated approaches (Abiodun, Olago, and Hassan, 2024). Data fragmentation and limited integration between meteorological, agricultural, and health surveillance systems constrain the predictive capacity of climate-based vector management (Browne et al., 2023). Moreover, competing land-use priorities such as agricultural expansion, urbanization, and conservation often create policy conflicts that undermine vector control objectives (Nhamo et al., 2023). Socioeconomic constraints, including poverty, limited funding, and inequitable access to technology, further hinder the adoption of sustainable practices (Maina, Wambua, and Karanja, 2025). Balancing agricultural productivity with ecosystem-based vector control demands context-specific solutions that address local ecological realities and community needs. Without sustained investment in cross-sectoral governance, education, and long-term data systems, climate-smart strategies risk remaining pilot initiatives rather than transformative national policies (WHO, 2024).

9. Future Directions and Research Needs

Future research on climate-smart vector control should prioritize quantifying the health co-benefits of agroforestry and ecosystem-based interventions within malaria-endemic regions. Recent studies emphasize the need for empirical evidence linking agroecological restoration to reductions in vector abundance and disease transmission (Rahman et al., 2023; Mwangi et al., 2025). Understanding these relationships will help policymakers justify long-term investment in nature-based strategies that simultaneously enhance food security, biodiversity, and public health. Advancements in climate-resilient surveillance systems are also critical. Integrating satellite-based remote sensing, AI-driven predictive modeling, and local entomological data can improve early warning systems and intervention targeting (Maina et al., 2025; Tambo et al., 2025). These tools can forecast vector population dynamics and disease risk under various climate scenarios, guiding adaptive management strategies. Furthermore, enhancing open-access data platforms will facilitate cross-sectoral collaboration and knowledge sharing among environmental scientists, health professionals, and agricultural planners (Silva et al., 2024). Scaling up successful pilot interventions**:** such as integrated irrigation management, biological control, and agroforestry-based vector suppression requires supportive governance frameworks and equitable financing mechanisms. Future work should examine how community participation, gender equity, and local knowledge systems can strengthen adoption and sustainability (Nyasimi & Muriuki, 2022). Ultimately, interdisciplinary collaboration among climatologists, ecologists, agronomists, and public health experts will be essential for developing resilient, scalable, and adaptive solutions to vector-borne disease threats in a changing climate. Such integrative research can transform climate-smart vector control from an emerging concept into a cornerstone of sustainable global health policy.

10. Conclusion

Climate-smart strategies constitute an essential innovation for integrating sustainable insect vector control with agricultural resilience. By uniting ecological design, adaptive land-water management, and inclusive community action, they address the root environmental determinants of malaria rather than merely its symptoms. Agroforestry and diversified farming systems create multifunctional landscapes that regulate microclimates, conserve biodiversity, and minimize mosquito proliferation. Incorporating climate-informed surveillance and predictive modeling ensures timely interventions under changing climatic regimes. Embedding these approaches within public-health and agricultural planning frameworks supported by policy coherence and local participation can achieve durable malaria reduction while enhancing food security and climate adaptation. Ultimately, mainstreaming climate-smart vector control strengthens both ecosystem and human resilience in the Anthropocene.

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Tropical Rainforest Restoration:
From Degraded to Restored Ecosystems
Degraded Rainforest
Restored Rainforest
Key Issues
Deforestation & Logging
Soil Erosion & Depletion
Loss of Biodiversity
Environmental Impacts
Habitat Loss
Increased Flooding
Reduced Carbon Storage
Restoration Actions
Natural Regeneration
Reforestation
Assisted Natural Regeneration
Agroforestry
Soil Rehabilitation
Key Benefits
Biodiversity Recovery
Improved Soil Health
Stable Water Cycle
Ecological Benefits
Climate Mitigation
Habitat for Wildlife
Enhanced Soil Fertility
Water Cycle Restoration
Support for Communities
Up to 80–90% Biodiversity Recovery in Secondary Forests Over Several Decades