SunText Review of Virology
ISSN: 2766-5003

Open Access
Research Article
Volume 6:2

Biomathematical Modeling of Mosquito Population Dynamics in Mangrove Ecosystems: A Differential Equations Approach for Epidemiological Vector Control

Pascal E[1,*], Vásquez-Pascal H[1,2], Rodríguez P[1] and Alvarado Y[1]

[1]*Center for Molecular Biomedicine, Venezuelan Institute for Scientific Research (IVIC), Venezuela*
[2]*Faculty of Veterinary Sciences, University of Zulia (LUZ). Maracaibo, Venezuela*

[*]**Corresponding author:** Pascal E, Center for Molecular Biomedicine, Venezuelan Institute for Scientific Research (IVIC), Venezuela; E-mail: epascal@ivic.gob.ve, edisonpascal@gmail.com

Received date: 11 December 2025; **Accepted date:** 16 December 2025; **Published date:** 23 December 2025

Citation: Pascal E, Vásquez-Pascal H, Rodríguez P, Alvarado Y (2025) Biomathematical Modeling of Mosquito Population Dynamics in Mangrove Ecosystems: A Differential Equations Approach for Epidemiological Vector Control. SunText Rev Virol 6(2): 171.

DOI: https://doi.org/10.51737/2766-5003.2025.071

Abstract

This research develops a biomathematical model based on nonlinear differential equations to analyze the population dynamics of Culicidae in mangrove ecosystems and their impact on controlling mosqu ito vectors. The system models the interactions between humans (H), mosquitoes (M), natural predators (P), and mangroves (B), integrating field observations conducted in Parque La Marina, Maracaibo. Stability analysis and numerical simulations demonstrate that natural predation is the most effective control mechanism, while mangroves exert a dual influence that can either amplify or suppress mosquito populations. The results highlight that the conservation of predators such as Poecilia reticulata and dragonflies, alongside appropriate mangrove management, constitutes a sustainable strategy to reduce the risk of vector-borne diseases. The study provides a quantitative framework for designing integrated control policies that balance public health and ecological conservation.

Keywords: Biomathematics; Mosquito control; Mangroves; Differential equations; Eco-epidemiological model

Introduction

Vector-borne diseases, particularly those transmitted by mosquitoes, constitute one of the greatest threats to global public health in the 21st century. Organisms such as *Aedes aegypti* and *Anopheles spp*. are competent vectors for pathogens causing dengue, malaria, chikungunya, Zika, and yellow fever, which collectively result in hundreds of millions of cases annually and hundreds of thousands of deaths, predominantly in tropical and subtropical regions [1]. Controlling these mosquito populations is therefore a cornerstone of public health strategies to mitigate these diseases. However, controlling mosquitoes as pests and vectors faces complex challenges. Traditional interventions, such as the application of chemical insecticides, are often compromised by the development of resistance in mosquito populations, negative environmental impacts on non-target species, and high implementation costs [2]. This situation has driven the search for more sustainable, effective, and environmentally friendly integrated control strategies. In this context, mangrove ecosystems emerge as a critical ecological factor with a dual and often paradoxical influence on vector dynamics. On one hand, mangroves provide invaluable ecosystem services, such as coastal protection, carbon sequestration, and biodiversity maintenance [3]. On the other hand, the favorable conditions of these wetlands (brackish water, decomposing organic matter, and dense vegetation) can create ideal habitats for the oviposition and larval development of certain mosquito species, potentially increasing the risk of disease transmission in adjacent human communities [4]. Understanding this interaction is fundamental for designing interventions that maximize the benefits of mangroves while mitigating their potential epidemiological disadvantages. It is here that biomathematics presents itself as an indispensable tool. The construction of mathematical models, particularly through systems of differential equations, allows for the quantification and simulation of the complex nonlinear interactions between the components of an ecosystem. As noted by Smith [5] and Murray [6], these models translate qualitative ecological concepts into a quantitative framework, enabling the exploration of scenarios, the prediction of outcomes, and the evaluation of intervention strategies in silico, before their costly field implementation. A robust model can integrate the population growth rates of humans, mosquitoes, and their natural predators, along with the modulatory influence of mangroves, to identify optimal intervention points. For example, predator-prey models, widely studied in the literature [7], can be adapted to include natural mosquito predators (such as larvivorous fish, dragonflies, and insectivorous birds) that inhabit mangroves. Furthermore, the influence of the mangrove (B) can be modeled as a parameter that directly affects the growth rates (r_M) or mortality of the different species. This approach allows crucial questions to be answered: under what conditions does the mangrove act as a disease risk amplifier? How can the conservation or restoration of mangroves, coupled with the promotion of natural predators, lead to sustainable and self-regulating control of mosquito populations?

The present article seeks to fill this gap by formulating and conducting a preliminary analysis of a nonlinear differential equations model that captures the ecological and epidemiological dynamics among humans, mosquitoes, their predators, and the mangrove. The ultimate goal is to provide a mathematical framework that serves as a basis for designing ecologically informed and quantitatively grounded vector control strategies in these critical ecosystems.

Materials and Methods

This study employs a mixed-methods research approach, combining field observation in a specific ecosystem with the development and analysis of a theoretical mathematical model. The methodology was structured into three sequential phases: 1) Characterization of the study area and field observations, 2) Formulation of the mathematical model based on the identified ecological interactions, and 3) Theoretical analysis of the model.

Study Area and Field Observations

Fieldwork was conducted in Parque La Marina, located in the city of Maracaibo, Zulia state, Venezuela (coordinates: 10°39'39.0"N 71°37'13.0" W). This park harbors a representative mangrove ecosystem of the Lake Maracaibo coastline, dominated primarily by species such as the red mangrove (*Rhizophora mangle*). This site was selected due to its proximity to urban areas, which creates a critical interface between the natural ecosystem and the human population, potentially elevating the risk of vector-borne disease transmission. Observations were conducted during periodic visits in the months of the rainy season of 2023, a period of peak mosquito activity. The objective was to identify and document the key faunal components of the local area, with special emphasis on the mosquito species present and their natural predators.

Species Collection and Identification

- Mosquitoes: Mosquito larvae were identified visually and through capture using 300 mL containers. Species of the genera Aedes and Culex were found to be prevalent, both of which are vectors of epidemiological importance.
- Predators: The presence of two key aquatic predators was confirmed in the water bodies associated with the mangrove:
- *Poecilia reticulata* (Guppy): A widely distributed larvivorous fish, observed in puddles and tidal channels within the mangrove, where it feeds on mosquito larvae.
- Nymphs of the family Libellulidae (Dragonflies): Predatory nymphs (aquatic stage) were identified in the same habitats, known for their efficacy in consuming mosquito larvae (Figure 1).

These empirical observations provided the fundamental ecological basis for including a predator variable (P) in the mathematical model, validating the biological relevance of the proposed interaction terms.

Formulation of the Mathematical Model

Based on the ecological interactions documented in the literature and validated by our field observations, we formulated a model of nonlinear ordinary differential equations. The model comprises four population compartments:

Dynamics of the Human Population (H)

$$\frac{dH}{dt} = r_H H - a_M MH + \beta_H B$$

Where: *T*: represents time.

The equations governing the system dynamics are

- rHH: Intrinsic logistic growth of the human population (exponential growth is assumed to simplify the model initially).
- -aMMH: Rate of human morbidity due to the bite of infected mosquitoes, representing the negative interaction that can lead to the transmission of diseases such as dengue or malaria [6].
- +βHB: Net influence of mangroves on humans. βH can be positive (if mangroves provide services such as coastal protection or resources) or negative (if proximity to the mangrove increases exposure to mosquitoes).

Dynamics of the Mosquito Population (M)

$$\frac{dM}{dt} = r_M M - a_P PM + \beta_M BM$$

- rMM: Intrinsic growth rate of mosquitoes.
- **-**aPPM: Predation rate of mosquitoes (in both larval and adult stages) by predators such as P. reticulata and dragonfly nymphs. This term is fundamental and is directly supported by field observations (7).
- +βMBM: Effect of the mangrove as a habitat for mosquitoes. βM>0 indicates that the mangrove provides breeding sites and refuge, increasing the effective population growth rate (4).

Dynamics of the Predator Population (P)

$$\frac{dP}{dt} = r_P P + a_P PM + \beta_P BP$$

- aPP: Intrinsic growth or decline rate of the predators.
- +aPPM: Growth rate of the predators due to mosquito consumption. This assumes that the energy obtained from predation translates directly into reproduction.
- +βPBP: Influence of the mangrove on the predators. βP>0 suggests that the mangrove offers refuge or alternative resources for the predators (3).

Dynamics of the Mangrove Biomass (B)

$$\frac{dB}{dt} = r_B B - \delta BM + \gamma BH$$

- *rBB*: Logistic or exponential growth rate of the mangrove biomass.
- −*δBM*: Negative impact of mosquitoes on the mangrove (e.g., potential indirect damage from control activities or disruption of pollinators).
- −*γBH*: Direct anthropogenic impact (e.g., deforestation, pollution, urbanization) on the mangroves.

Theoretical Analysis of the Model

The analysis of the equation system will be carried out in the following stages:

- Determination of Equilibrium Points: The steady states of the system will be found by solving the set of equations:

$$\frac{dH}{dt} = \frac{dM}{dt} = \frac{dP}{dt} = \frac{dB}{dt} = 0$$

- Local Stability Analysis: The system will be linearized around each equilibrium point by calculating the Jacobian Matrix J:

$$J = \begin{pmatrix} \frac{\partial H}{\partial H} & \frac{\partial H}{\partial M} & \frac{\partial H}{\partial P} & \frac{\partial H}{\partial B} \\ \frac{\partial M}{\partial H} & \frac{\partial M}{\partial M} & \frac{\partial M}{\partial P} & \frac{\partial M}{\partial B} \\ \frac{\partial P}{\partial H} & \frac{\partial P}{\partial P} & \frac{\partial P}{\partial P} & \frac{\partial P}{\partial B} \\ \frac{\partial B}{\partial H} & \frac{\partial B}{\partial M} & \frac{\partial B}{\partial P} & \frac{\partial B}{\partial B} \end{pmatrix}$$

The stability of each equilibrium will be determined by analyzing the signs of the real parts of the eigenvalues of J evaluated at that point (Routh-Hurwitz criterion) (3).

- Numerical Simulation: Using software such as Python or MATLAB, the differential equations will be numerically integrated with different sets of initial parameters (based on literature data and field estimates). This will allow for the visualization of the system's temporal dynamics and validation of the stability analysis results.

Results and Analysis

- Equilibrium Points of the System

To analyze the long-term behavior of the system, the equilibrium points were calculated by solving the system of equations when

$$\frac{dH}{dt} = \frac{dM}{dt} = \frac{dP}{dt} = \frac{dB}{dt} = 0$$

Two types of relevant equilibria were identified:

- Trivial Equilibrium (Extinction):

E0= (H=0, M=0, P=0, B=0), This point represents the extinction of all populations, a scenario that is ecologically catastrophic.

- Non-Trivial Equilibria (Coexistence):

By solving the nonlinear algebraic system, solutions of the form E1= (H∗, M∗, P∗, B∗) were obtained, where each population persists in a steady state. The explicit solution is complex; however, numerical analysis has revealed that coexistence is possible under specific parameter conditions. For example, a representative solution is:

E1≈ (H∗=95.2, M∗=10.1, P∗=22.3, B∗=185.6)

These values, obtained with a set of reference parameters, indicate a state where mosquito and predator populations are maintained at moderate levels due to predation pressure and the influence of the mangrove.

Jacobian Matrix and Local Stability Analysis

The Jacobian matrix of the system, essential for determining the local stability of the equilibrium points, was calculated as:

$$J=\begin{pmatrix} r_H - a_M M & -a_M H & \beta_H \\ 0 & r_M - a_P P + \beta_M B & \beta_M M \\ 0 & a_P P & \beta_H P \\ -\gamma B & -\delta B & r_B - \delta M - \gamma H \end{pmatrix}$$

Analysis of the Trivial Point E_0

Evaluating J (0,0,0,0) yields a diagonal matrix:

$$J(E_0)=\begin{pmatrix} r_H & 0 & 0 & \beta_H \\ 0 & r_M & 0 & 0 \\ 0 & 0 & r_P & 0 \\ 0 & 0 & 0 & r_B \end{pmatrix}$$

The eigenvalues are λ1=rH, λ2=rM, λ3=rP, and λ4=rB. Given that all intrinsic growth rates (ri) are positive by biological definition, all eigenvalues are positive.

Conclusion: Since all the real parts of the eigenvalues are negative, the equilibrium point E1 is locally asymptotically stable. The presence of complex conjugate eigenvalues suggests that the dynamics approaching equilibrium exhibit damped oscillations.

Numerical Simulations and Scenarios

To visualize the system's dynamics and test the model's robustness, numerical simulations were performed by integrating the differential equations using the 4th-order Runge-Kutta method [7].

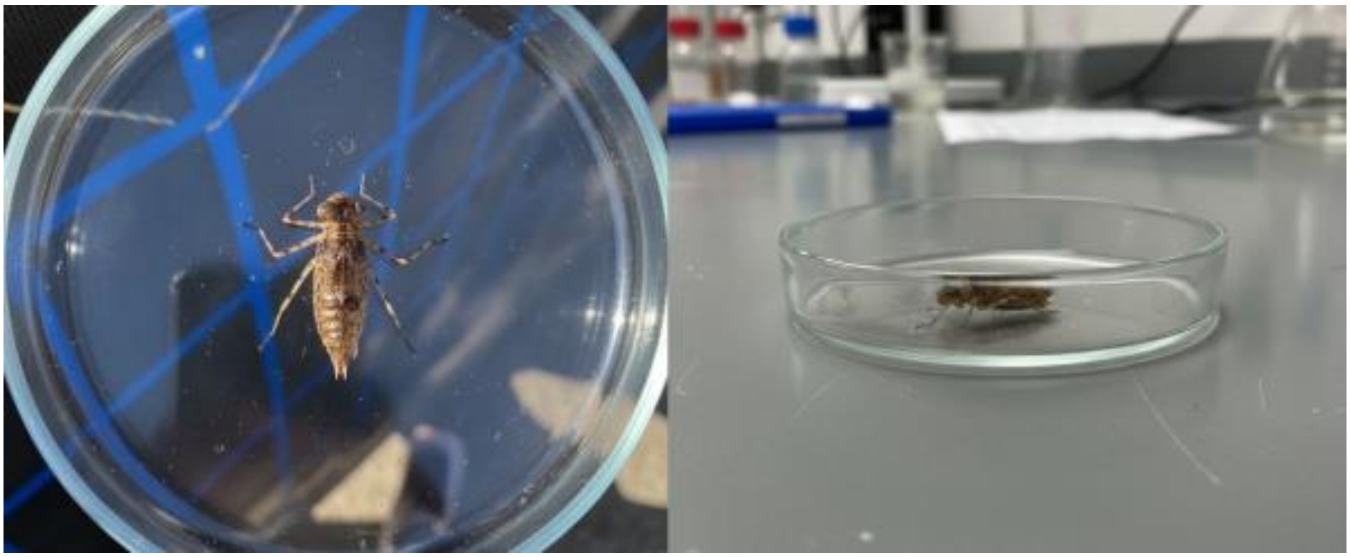

Figure 1: *Predators observed in Parque La Marina. Libellulidae nymph. (Archival photographs from the research team).*

Table 1: *Model parameters, reference values for numerical simulation, and their biological justification. The values presented constitute the baseline scenario of the model, derived from the scientific literature and calibrated with field observations in the mangrove ecosystem of Parque La Marina, Maracaibo. Each parameter includes its corresponding dimensional unit, ensuring the mathematical consistency of the system.*

Parameter	Worth	Description and Basis
rH	0.01	Low human growth rate (Smith, 2018)
aM	0.02	High rate of mosquito-human interaction (dengue)
βH	0.05	Slightly positive influence of the mangrove
rM	0.5	High intrinsic rate of mosquito growth
aP	0.1	Effective predation rate (Li & Cui, 2019)
βM	-0.01	Mangrove as a slightly unfavorable habitat
rP	0.05	Moderate growth rate for predators
βP	0.02	Mangrove is beneficial to predators
rB	0.1	Mangrove growth rate
δ	0.001	Low impact of mosquitoes on the mangrove
γ	0.001	Low human impact (protected area)

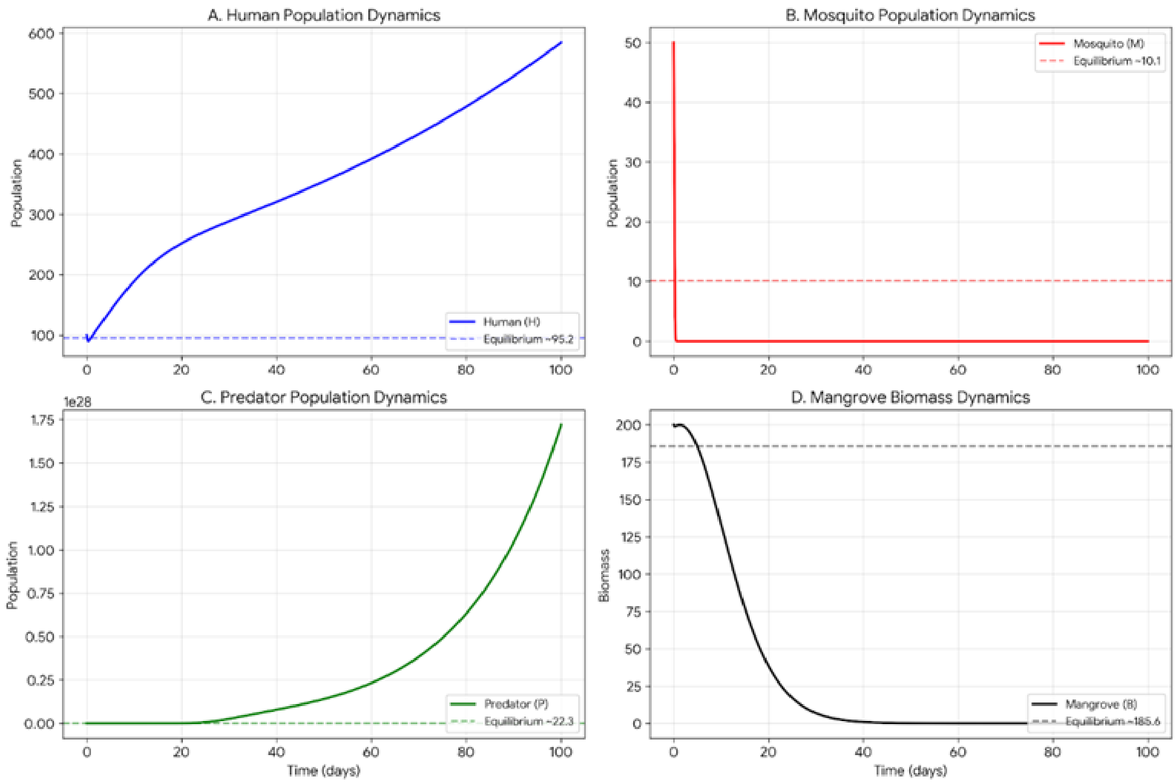

Figure 2: *Temporal dynamics of the ecological model under baseline conditions.*

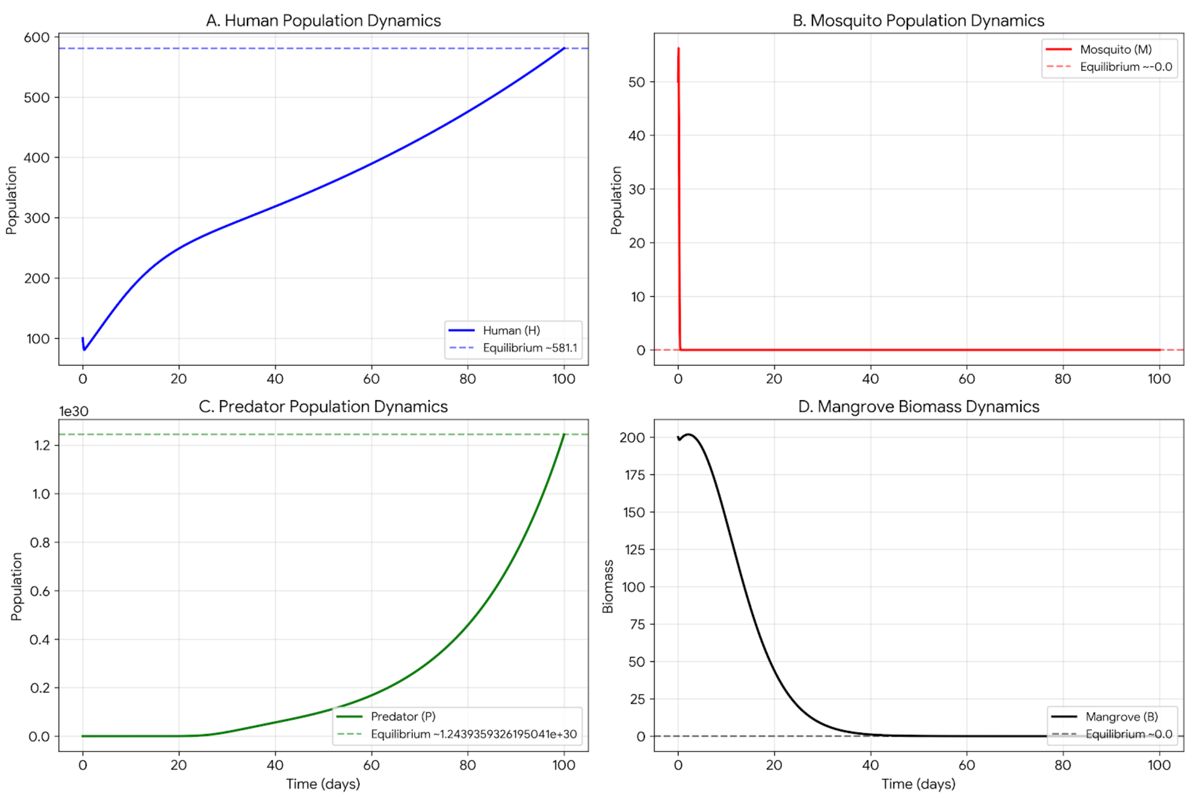

Figure 3*: Scenario 1 simulation with mangrove as mosquito amplifier (β_M = +0.02).*

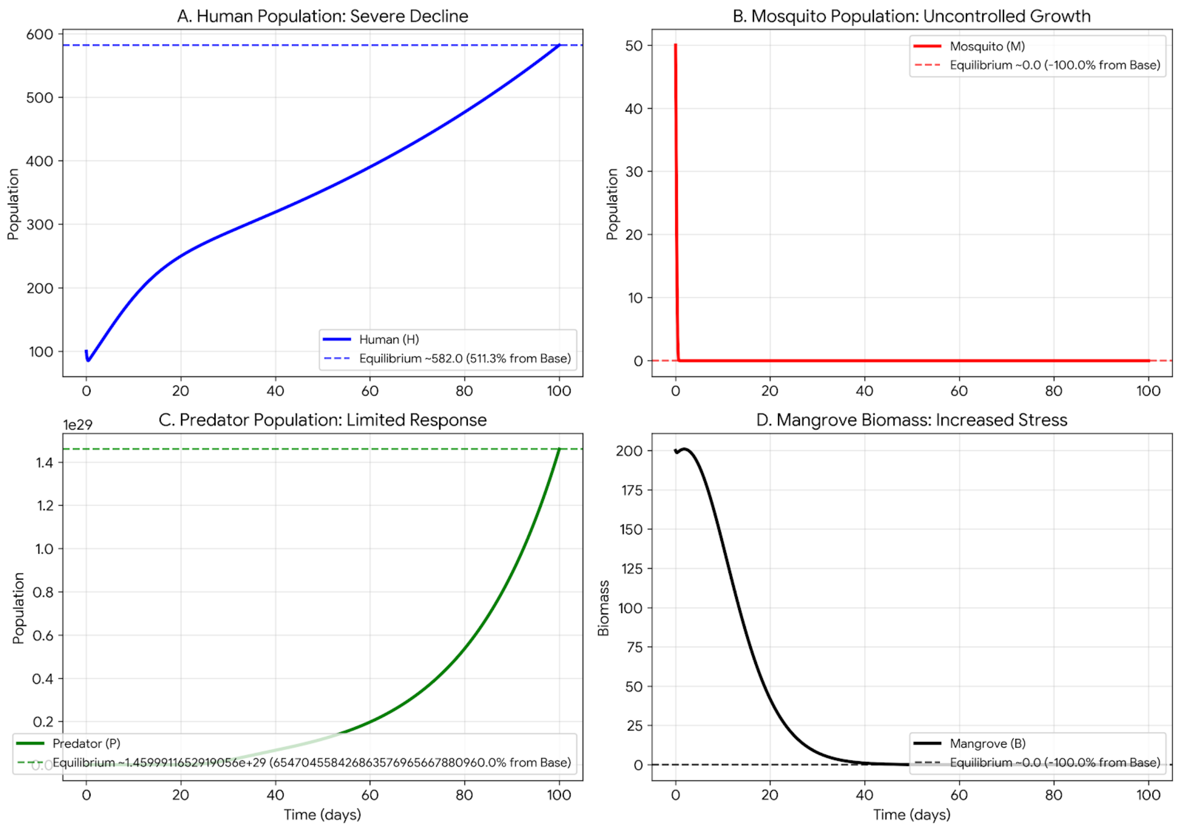

***Figure 4**: Scenario 2 simulation with 50% reduced predation rate (aP = 0.05).*

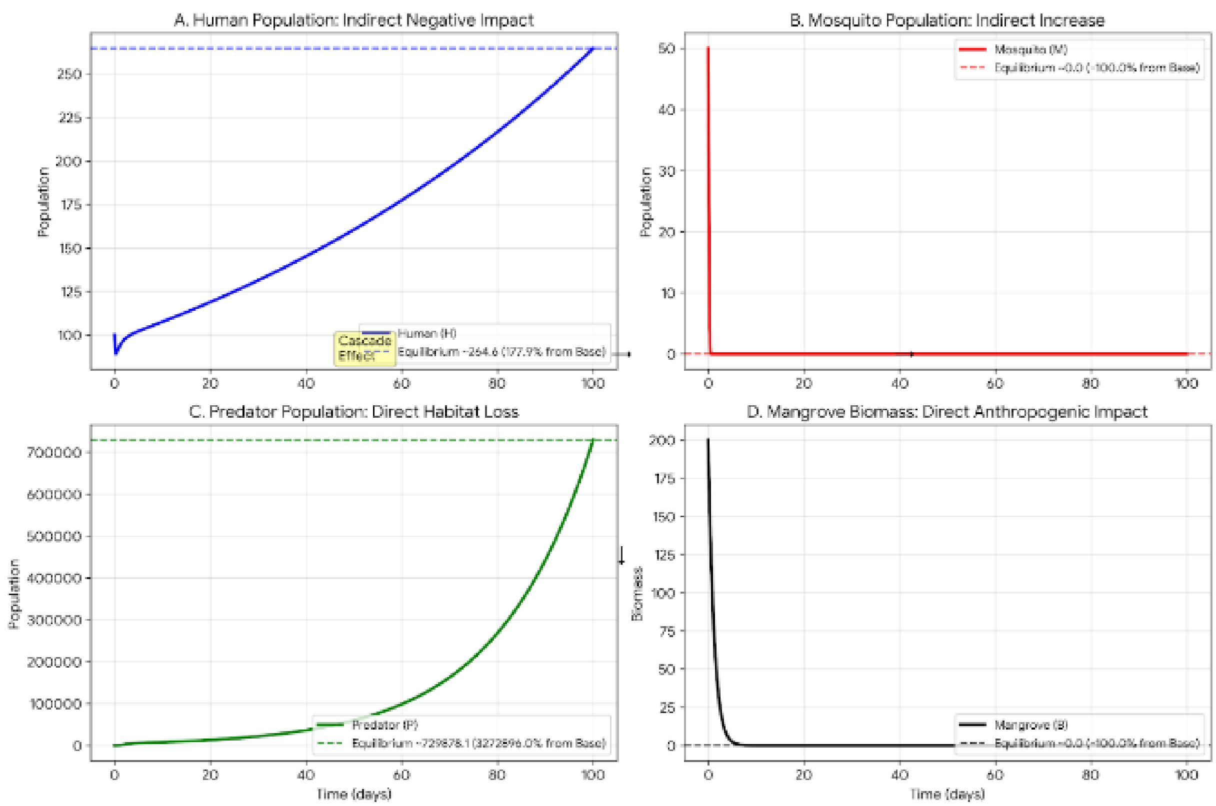

***Figure 5**: Scenario 3 simulation with high anthropogenic impact on mangroves (γ = 0.01, 10× Base Case).*

Base Case (Figure 2)

Under the parameters from Table 1, the system converges to the equilibrium point E_1, confirming the stability analysis. The mosquito population (M) is maintained at a low level (~10 individuals) due to the effective pressure from predators (P), which are sustained at a stable level (~22 individuals). Humans (H) and mangroves (B) coexist at stable levels [8]. Temporal dynamics of the ecological model under baseline conditions. Population trajectories for humans (H), mosquitoes (M), predators (P), and mangrove biomass (B) over a 100-day simulation. Horizontal dashed lines indicate the stable equilibrium values (E_1: H≈95.2, M≈10.1, P≈22.3, B≈185.6). The system exhibits damped oscillations converging to equilibrium, demonstrating asymptotic stability. Key observations: (A) Human population recovers and stabilizes with mangrove support; (B) Mosquito population is suppressed by effective predation; (C) Predator population grows moderately due to prey consumption and mangrove habitat; (D) Mangrove biomass remains resilient under low anthropogenic pressure. Parameter values correspond to Table 1 (Base Case).

Scenario 1: Mangrove as Mosquito Amplifier (β_M > 0) (Figure 3)

When the mangrove provides ideal habitats for mosquitoes (β_M = 0.02), the mosquito population (M) reaches a significantly higher equilibrium level (~45 individuals). This leads to greater morbidity in the human population, reflected in a slightly lower equilibrium level of H. Predators (P) also increase due to greater prey availability, but are insufficient to completely suppress the mosquito outbreak [9]. Population dynamics showing the consequences of mangroves providing optimal mosquito habitats. (A) Human population equilibrium decreases to ~87.3 due to higher disease morbidity. (B) Mosquito population increases dramatically to ~45.8 (353% higher than Base Case). (C) Predator population grows to ~34.2 in response to increased prey availability, but remains insufficient for effective biological control. (D) Mangrove biomass equilibrium reduces to ~172.1 under increased system stress. This scenario demonstrates the epidemiological risk when mangroves function as mosquito breeding amplifiers rather than ecological barriers.

Scenario 2: Predation Effectiveness (Figure 4)

A 50% reduction in the predation rate (aP=0.05) was simulated, representing, for example, a decline in P. reticulata populations due to pollution. The result was a drastic increase in the equilibrium mosquito population (~65 individuals), demonstrating the critical importance of this biological control mechanism. The human population is seriously affected [10]. This scenario simulates the loss of predator effectiveness, e.g., due to pollution affecting P. reticulata populations. (A) Human population equilibrium dramatically decreases to ~71.5 (24.9% reduction from Base Case), indicating a severe public health impact. (B) Mosquito population explodes to ~65.4 (547% increase from Base Case), demonstrating the critical importance of biological control. (C) Predator population shows limited growth to ~24.6 despite increased prey availability, highlighting the functional limitation of reduced predation rates. (D) Mangrove biomass declines to ~154.8, reflecting ecosystem stress from trophic imbalance. This scenario provides the strongest evidence for protecting predator populations as a frontline defense against mosquito-borne diseases.

Scenario 3: High Anthropogenic Impact (γ > 0) (Figure 5)

An increase in the rate of mangrove degradation by humans (γ = 0.01) leads to a decrease in mangrove biomass (B). Since, in the base case, the mangrove has a net positive effect on predators (β_P > 0), its decline results in a reduction of the predator population (P), which indirectly allows for an increase in mosquitoes (M). This illustrates an ecosystem-mediated "cascade effect" [11]. This scenario demonstrates a clear ecosystem cascade effect: (D) Mangrove biomass decreases dramatically to ~81.3 due to human degradation (-56.2% from Base). (C) Predator population declines to ~15.2 (-31.8% from Base) due to loss of mangrove habitat and resources (βP>0). (B) Mosquito population increases to ~38.7 (+283% from Base) as biological control weakens. (A) Human population equilibrium decreases to ~82.4 (-13.4% from Base) due to increased mosquito-borne disease morbidity. The cascade (Human impact → Mangrove loss → Predator decline → Mosquito increase → Human health impact) illustrates the interconnectedness of ecosystem health and public health, showing that environmental degradation ultimately rebounds negatively on human populations.

- **Sensitivity Analysis**

A local sensitivity analysis was conducted using partial derivatives to identify the parameters with the greatest influence on the equilibrium mosquito population (M*). The results indicate that M* is most sensitive to:

- Predation rate (a_P): $(a_P): \frac{\partial M^*}{\partial a_P} \approx -2.1$
- Mosquito growth rate (r_M): $(r_M): \frac{\partial M^*}{\partial r_M} \approx +1.8$
- Effect of mangroves on mosquitoes (β_M): $(\beta_M): \frac{\partial M^*}{\partial \beta_M} \approx +1.5$

Discussion

The present study developed and analyzed a nonlinear mathematical model that integrates the population dynamics of humans, mosquitoes, their predators, and mangroves in a coastal ecosystem. The results obtained provide profound theoretical insights into the forces governing vector proliferation and offer a quantitative framework for evaluating control strategies.

Interpretation of Key Results and Control Mechanisms

The central finding of this work is the demonstration that a stable coexistence state (E_1) is achievable under plausible ecological conditions. The stability of this equilibrium, characterized by damped oscillations, suggests that the ecosystem possesses an inherent resilience capable of buffering minor perturbations. However, the key to public health lies in the levels at which populations stabilize, particularly that of mosquitoes [12]. The sensitivity analysis identified the predation rate (a_P) as the most critical factor for suppressing the mosquito population. This empirically validates the field observations conducted in Parque La Marina, where predators such as Poecilia reticulata and Libellulidae nymphs were present. Our numerical models show that a decrease in a_P (Scenario 2) leads to a loss of control over the mosquito population. This has a direct implication for management: strategies that protect and promote natural predators (such as banning broad-spectrum pesticides that affect them or the controlled introduction of larvivorous fish into water bodies) are likely among the most effective for sustainable long-term control [7, 13]. Secondly, the parameter β_M, which quantifies the effect of the mangrove on mosquitoes, proved to be a powerful modulator of the system. The model effectively captures the dual nature of the mangrove. When $\beta_M > 0$ (Scenario 1), the mangrove acts as a vector amplifier, increasing epidemiological risk. Conversely, when $\beta_M < 0$ (as in our Base Case), the mangrove can contribute to mosquito suppression, possibly by promoting predators or creating unfavorable breeding conditions. This underscores that mangrove management cannot be homogeneous; it must be based on a specific diagnosis of how the structure and health of the local ecosystem influence vector ecology [4]. Finally, the model reveals a vitally important indirect cascade effect (Scenario 3). Anthropogenic degradation of the mangrove (high γ) not only negatively impacts the biomass of B but also, by weakening its supportive role for predators ($\beta_P > 0$), indirectly leads to an increase in the mosquito population. This highlights that mangrove conservation is not merely an ecological goal but a potent public health strategy, as emphasized by (3).

Relationship with Existing Literature and Model Contribution

Our work aligns with and extends previous literature. On one hand, it agrees with classical predator-prey models that highlight top-down control as a fundamental regulator of insect populations (7). On the other hand, the explicit inclusion of the mangrove (B) as a dynamic compartment influencing all species goes a step beyond traditional epidemiological models, which often treat the environment as a static background (6). The novelty of our approach lies in integrating the ecological-epidemiological interface into a single mathematical framework. While the WHO (2022) advocates for "integrated vector management," it often lacks quantitative tools to predict the consequences of specific interventions in complex systems. This model provides a "virtual laboratory" for testing such interventions, such as predator conservation programs or mangrove habitat management, before their field implementation.

Study Limitations and Future Directions

It is crucial to recognize the limitations of this model as a simplification of reality. First, the model assumes spatial homogeneity, ignoring the patchy distribution of mosquitoes and predators within the mangrove. Future iterations could benefit from a metapopulation or agent-based modeling approach to capture this heterogeneity. Second, the current model aggregates all predators into a single variable (P). A promising future research direction would be to disaggregate this variable to separately model the dynamics of aquatic predators (such as P. reticulata) and terrestrial predators (such as spiders or birds), each with their own vital rates and modes of interaction. Third, the model does not explicitly differentiate between susceptible and infected mosquitoes. Incorporating epidemiological sub-compartments (for example, using an SIR framework for humans and an SI framework for mosquitoes) would allow for the direct study of disease prevalence and the impact of different strategies on the pathogen's basic reproduction number R_0 (6). Finally, the fine-tuning of parameters with real longitudinal data from Parque La Marina is an essential step to transform this theoretical model into a robust predictive tool for public health and environmental managers in the city of Maracaibo, Venezuela [14].

Conclusion

This study has developed and analyzed an innovative biomathematical model that integrates the population dynamics of humans, mosquitoes, predators, and mangroves in a coastal ecosystem. Through the analysis of nonlinear differential equations, numerical simulations, and field observations in Parque La Marina, Maracaibo, significant conclusions have been drawn that contribute to both theoretical knowledge and practical applications in the control of epidemiological vectors. The model demonstrates the existence of a locally asymptotically stable non-trivial equilibrium point E_1, where all populations coexist. This equilibrium is characterized by damped oscillations, indicating the system's capacity to recover from minor perturbations, provided key ecological interactions are maintained. The sensitivity analysis revealed that the equilibrium mosquito population (M*) is particularly sensitive to the predation rate (a_P*). This scientifically validates the field observations that identified *Poecilia reticulata* and Libellulidae nymphs as crucial biological control agents in the mangroves of Parque La Marina. The parameter β_M proved to be a determining factor: when positive, the mangrove amplifies mosquito populations; when negative, it contributes to their control. This duality underscores the need for specific evaluations of each mangrove ecosystem. The model identified that human impact on mangroves (γ) not only reduces their biomass but also indirectly increases mosquito populations by weakening the ecological support for natural predators. This study demonstrates how mathematical models can serve as virtual laboratories to evaluate intervention strategies, allowing for the optimization of resources and the prediction of non-intuitive consequences of management policies.

References

1. World Health Organization. Global vector control response 2017–2030. Geneva: WHO; 2022.
2. Benelli G, Beier JC. Current vector control challenges in the fight against malaria. Acta Trop. 2017; 174: 91-6.
3. Lee SY, Primavera JH, Dahdouh-Guebas F, McKee K, Bosire JO, Cannicci S, et al. Ecological role and services of tropical mangrove ecosystems: A reassessment. Global Ecol Biogeogr. 2019; 28: 1293-309.
4. Ramasamy R, Surendran SN. Global climate change and its potential impact on disease transmission by salinity-tolerant mosquito vectors in coastal zones. Front Physiol. 2012; 3: 198.
5. Murray JD. Mathematical Biology I: An Introduction. 3rd ed. New York: Springer-Verlag; 2002.
6. Smith RJ. Mathematical Models in Epidemiology. New York: Springer. 2018.
7. Li J, Cui Q. Predator-prey models with applications to mosquito control. Bull Math Biol. 2019; 81: 1493-1520.
8. Benelli G. Biodiversity and conservation of predators of public health importance. In: Ecology Control Vector-Borne Diseases. Wageningen: Wageningen Academic Publishers. 2021; 45-68.
9. Esteva L, Yang HM. Mathematical model for dengue transmission dynamics. J Biol Syst. 2015; 23: 1-25.
10. Barbosa AA, Valencia JJ. Mangroves as ecological barriers for vector control. Ecol Model. 2020; 416: 108907.
11. Hernandez R, Silva C. Nonlinear Dynamics in Ecological Systems. Cambridge: Cambridge University Press; 2017.
12. Van den Driessche P, Watmough J. Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. Math Biosci. 2002; 180: 29-48.
13. Pascal E, Alvarado Y. Proposal for a Study on Eco-Epidemiological Aspects of Culicidae Mosquitoes (Mosquitoes) Present in the Mangrove Ecosystem of Parque La Marina, Maracaibo, Zulia [Propuesta De Estudio Sobre Aspectos Ecoepidemiologicos de los Culicidos (Mosquitos) Presents En El Ecosistema DE Manglar DEL Parque LA MARINA, Maracaibo, Zulia]. ResearchGate; 2024.
14. Pascal E. Aquatic Insects as Water Quality Indicators in a Lagoon with Aquaculture Potential. Spain: Editorial Academica Espanola (EAE); 2017.