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Spatio-Temporal Analysis of Mosquito Populations Through Agent-Based Simulation

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Mosquitoes, particularly Aedes aegypti, are key vectors of diseases such as dengue, Zika, and chikungunya. Estimate mosquito population density is essential for designing and implementing mosquito population control strategies. Traditional models, like [1] focus on temporal dynamics, however, these models cannot explain the spatial aspects of mosquito distribution, which are important for understanding interactions with the environment and designing targeted interventions such as sterile mosquito releases or Wolbachia-based strategies. Agent-Based Models (ABMs) provide a way to address the spatio-temporal distribution problem while incorporating individual heterogeneity and stochastic interactions [2].

To address this gap, we propose extending our previous work [3] asumming that the time-dependent entomological parameters are constants and by integrating spatial dynamics. The spatial heterogeneity as breeding sites and mosquito movement, this approach enhances the ability to model interventions. This model considers adult female movement A and fixed juvenile populations J at breeding sites. The carrying capacity C_k represents the maximum population size each breeding site k can sustain.

The system is defined on an $M \times M$ grid, where each cell i represents a discrete position in the automaton ($\mathcal{G} = \{i \mid 1 \leq i \leq M^2\}$). A subset $\mathcal{K} = \{i_k \mid k = 1, \ldots, N\} \subset \mathcal{G}$ corresponds to the breeding sites BS_k, each located at i_k and capable of hosting juvenile mosquito populations.

The population dynamics are divided into two components: stochastic population variation and movement probability distribution. The population dynamics of juveniles J_k at each BS_k, are regulated by the birth rate$b$ in a limited space C_k, the maturation rate d, and the mortality rates (μ_J and μ_A). The number of juveniles at time $t+1$ is given by:

$$J_k(t+1) = J_k(t) + X_{\text{birth},k} - X_{\text{maturation},k} - X_{\text{death},k}, \tag{1}$$

where the state transition probabilities are binomial distributions given by:
$X_{\text{birth},k} \sim \text{Bin}(A_k, b\Delta t(1 - J_k/C_k))$, $X_{\text{maturation},k} \sim \text{Bin}(J_k, 0.5\Delta t)$ and
$X_{\text{death},k} \sim \text{Bin}(J_k, (d + \mu_J)\Delta t)$, during the time interval Δt. The adult behavior at a BS_k, A_k is given by:

$$A_k(t+1) = A_k(t) + X_{\text{maturation},k} - X_{\text{death},k}, \tag{2}$$

where $X_{\text{death},k} \sim \text{Bin}(A_k, \mu_A \Delta t)$, this means that breeding sites are the primary locations where population changes (through maturation and death) occur.

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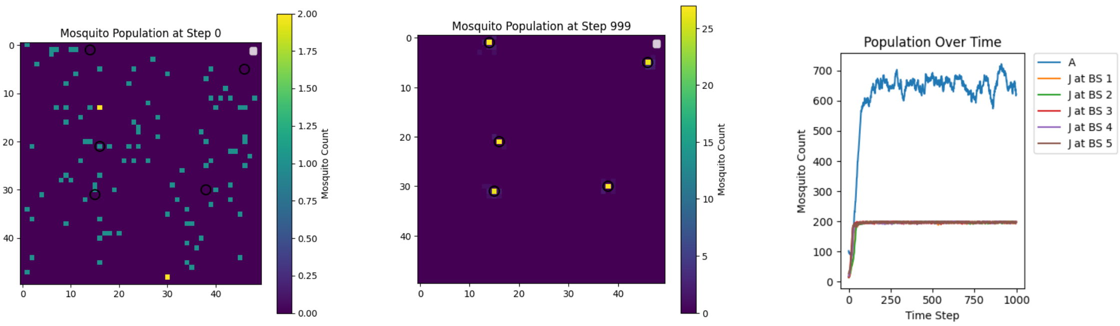
Each adult female has two movement modes: a Moore Neighborhood movement with a probability of 0.2 (moving to any of the eight neighboring cells with probability 0.025 each) and a directed movement with a probability of 0.8 (moving one grid towards the closest breeding site using the Manhattan metric). The probability of an automaton moving from cell k to cell j at time $t+1$ is given by:

$$P(k \to j) = 0.2 \times P_{\text{moore}}(k \to j) + 0.8 \times P_{\text{directed}}(k \to j) \tag{3}$$

To implement the model, we set the following constant parameters: $M = 50$, $b = 4$, $d = 0.05$, $\mu_J = 1/30$, $\mu_A = 1/30$ and $C_k = 200$, for $k = 1, 2, 3, 4, 5$, with an initially homogeneous distribution of adult female mosquitoes across the entire map and a homogeneous distribution of juveniles within the breeding sites. Juveniles were randomly placed on the map. Figure1(a) shows the initial population density distribution per grid, while Figure1(b) illustrates the change in population density after 1000 simulation steps, highlighting a concentration of individuals exclusively at breeding sites. Figure1(c) shows the evolution of the total adult population at each time step, indicating that population stabilizes around a constant value like a steady state.



(a) Initial Conditions (b) Final distribution (c) Time Evolution

Figure 1: Numerical Simulation Preliminar Results. Source: Own elaboration.

The observed convergence provides preliminary evidence for the existence of an equilibrium in the system, particularly as our time step Δt is set to 1 day, ensuring that the numerical transition probabilities remain below 1. This condition is crucial for the stability of the model and aligns with the requirements of Markov transition probabilities. These preliminary results suggest that the model is a valuable tool for understanding and predicting spatio-temporal dynamics in ecological and epidemiological contexts, particularly for designing targeted mosquito control strategies.

References

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