Modeling Malaria Dynamics: A simulation of Human and Mosquito Interactions in Urban Nigeria for Disease Spread Analysis and Prevention Strategies

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Introduction

Malaria, a devastating disease caused by a parasite, continues to pose a significant threat to human populations globally (Cowman et al., 2016). Without proper treatment, individuals may experience severe complications, leading to fatality. Mosquitoes play a crucial role in transmitting malaria from one person to another. While not all mosquitoes carry malaria, if they bite an individual with the disease, they can become infectious. This initiates a cycle where, upon biting another person, the mosquito continues the spread of malaria. The parasite, originating from an infected human, is thus transmitted through mosquitoes, which initially begin their lives uninfected but become carriers after obtaining multiple blood meals, enabling them to pass on the disease when they bite once more (Centers for Disease Control and Prevention, nd; Cowman et al., 2016). In the year 2020, approximately 241 million cases of malaria were reported globally, resulting in 627,000 fatalities, with a predominant impact on children in sub-Saharan Africa (Centers for Disease Control and Prevention, nd).

Malaria is a major public health concern in Nigeria, with an estimated 68 million cases and 194,000 deaths due to the disease in 2021 (World Health Organization, 2023). Nigeria bears the highest burden of malaria globally, accounting for nearly 27% of the total global malaria burden. Partly because of their dense and high population. As they have the largest population of any African Country The World Bank (2020); WorldOMeter (2023). The risk of transmission exists throughout the country year-round, with the highest incidence of malaria in the northern and northeastern regions.

Beyond the epidemiological aspects, understanding the dynamics of malaria transmission is crucial for devising effective preventive strategies for the country of Nigeria. Cellular Automata (CA) provide a powerful tool for modelling such complex systems (Chopard & Droz, 1998). CA, as a computational tool, allows us to simulate the interactions between humans and mosquitoes in a spatially explicit manner, capturing the intricate dynamics of disease spread. This approach enables a more realistic representation of the transmission process, considering factors such as population density and mosquito bite change.

In Nigeria, the population employs multiple measures to mitigate the impact of Anopheles mosquitoes, the primary vectors of malaria (Fagbohun et al., 2020). These mosquitoes predominantly inhabit urban environments, constituting approximately one-third of the overall mosquito population in Nigeria. According to Statista (2023), the prevalent preventive measures adopted by the population include the utilization of sleeping nets and Indoor Residual Spraying (IRS). Approximately 54% of Nigerians rely on sleeping nets as a nocturnal protective measure, demonstrating efficacy in reducing mosquito bites by 70% (Raghavendra et al., 2011). Considering the average nightly sleep duration of 7.5 hours among Nigerians (Francisca & Maduka, 2021), the use of sleeping nets assumes significance in minimizing exposure during the night. Concurrently, 41% of the population opts for Indoor Residual Spraying (IRS), a method shown to reduce biting incidents by 65% (Zhou et al., 2022). However, this reduction is contingent on achieving substantial coverage, with treated surfaces requiring an 80% or higher coverage rate. Notably, only 1% of the population utilizes nets on windows and doors for preventive purposes, even though according to Fox et al. (2022) this shows a reduction in mosquitos of 37%. In the domain of malaria vaccines and medications, current interventions do not provide absolute prevention but demonstrate a 72.9% reduction in the risk of mortality from malaria (Chandramohan et al., 2021). It is important to note that these vaccines are presently undergoing testing, with 2% of the Nigerian population receiving the vaccine or using malaria medication. These numbers correlate with partial immunity numbers from Lin et al. (2020), which indicate a 15% reinfection rate. Continued research and widespread implementation of these preventive measures are imperative in the ongoing battle against malaria in Nigeria.

Methods

In this simulation, a probabilistic element is introduced, deviating slightly from the strict definition of CA (Chopard & Droz, 1998). The simulation unfolds on a two-dimensional grid, with each cell accommodating at most one human. Humans within the grid can exist in one of four states: susceptible, infected, resistant, or deceased. It is assumed that the overall human population remains stable, signifying that a new human is introduced for every mortality instance.

In contrast to humans, mosquitoes exhibit distinct behaviours within the defined spatial grid. Mosquitoes have the capacity to move freely across the grid in a simulated 'walk.' Their movement is modelled through a random walk, facilitating transitions from one cell to the next. Additionally, mosquitoes can coexist in a single cell, allowing for the representation of multiple mosquitoes in a given location. When a mosquito dies because of age, as a mosquito only lives for a couple of months, a new mosquito is introduced (Cowman et al., 2016).

In this model, time is denoted by the number of updates during the simulation process, with the assumption that each update corresponds to 1 day. For the purposes of this assignment, a simulation duration of 2 years is used.

The standard parameters used within the model are seen in Figure 1. Hereby a grid size of 50 by 50 cells is used. The total human population is initialized with a stable size based on the population density of Nigeria (The World Bank, 2020; WorldOMeter, 2023). Hereby 20% of the population is already infected, to simulate that this is a continues process (Severe Malaria Observatory, 2023). The parameters in Figure 1 without a source where given by introduction to the assignment and mostly used to kickstart the simulation and fitting process. To run the code, the program needs to have the malaria_visualize.py file included. Besides that, Plotly, Matplotlib and NumPy must be installed.

Parameter type	Parameter name	Parameter value	Source
float	mosquitoPopDensity	0.35	Fagbohun et al. (2020); World Population Review (2023)
float	humanPopDensity	0.23	The World Bank (2020); WorldOMeter (2023)
float	initMosquitoHungry	0.5	
float	initHumanInfected	0.2	Severe Malaria Observatory (2023)
float	humanInfectionProb	0.90	
float	humanImmuneProb	0.01	
float	humanReInfectionProb	0.15	Lin et al. (2020)
float	illnessDeathProb	0.03	Effiong et al. (2022)
int	illnessIncubationTime	4	Centers for Disease Control and Prevention (nd)
int	illnessContagiousTime	30	Vlaanderen Departement Zorg (2022)
float	mosquitoInfectionProb	0.9	
int	mosquitoMinage	21	Centers for Disease Control and Prevention (nd)
int	mosquitoMaxage	31	Centers for Disease Control and Prevention (nd)
int	mosquitoFeedingCycle	7	Cape May County (nd)
float	biteProb	1.0	
NoneType	prevention	None	

Table 1: Standard parameters within the initial model.

Fitting

In refining the model to align with real-world data, a fitting process was employed through manual adjustment of the model's parameters. Initially, parameters were iteratively fine-tuned, and the simulation was run for an extensive number of time steps. The stability of prevalence was assessed until a satisfactory match with the real target value was achieved. This approach offers a direct method of aligning the model with observed data, and the effectiveness of the fitting process was clarified through the creation of Figure 1 and 2. Figure 1 shows how the model performs with zero intervention to decrease infection and also the current methods of prevention. The prevention used is 54% of the population with sleeping nets, 41% of the houses sprayed with IRS, 1% house modification nets and 2% vaccine/medication use. Both interventions use the same parameters from table 1.

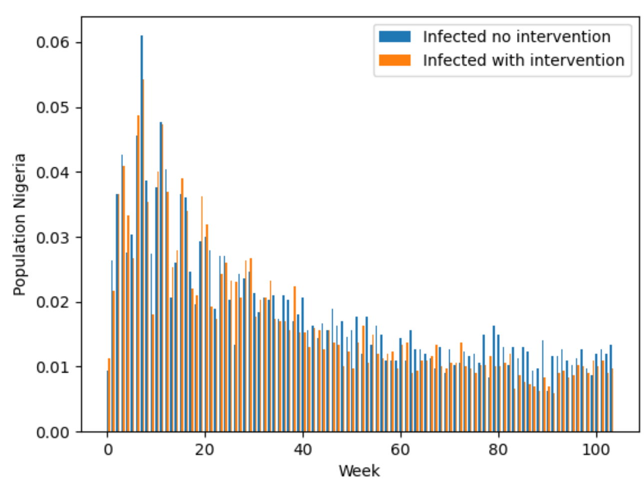

Figure 1: Fraction of Nigerian population which is infected per week in two-year timespan.

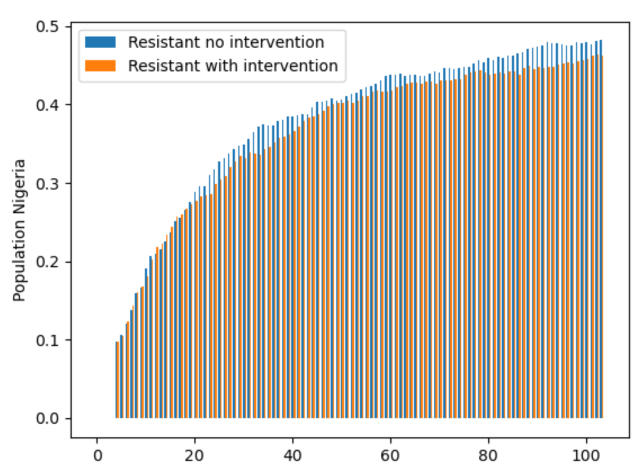

Figure 2: Fraction of Nigerian population which gas gained partial immunity in two-year timespan.

Experiment

In the fitting of the model after 50 weeks, the amount of infected people stays on average the same, so the goal of the experiment is to decrease or even stop malaria altogether. Since vaccines and medications are not readily available, a real live implementation with nets and IRS is more realistic the experiment entails different population percentages of prevention methods. The three most readily available methods are sleeping nets, IRS and window/door nets. The experiment shows what effect 0% until 100% with steps of 25% will have on the infection rate in a one-year timespan.

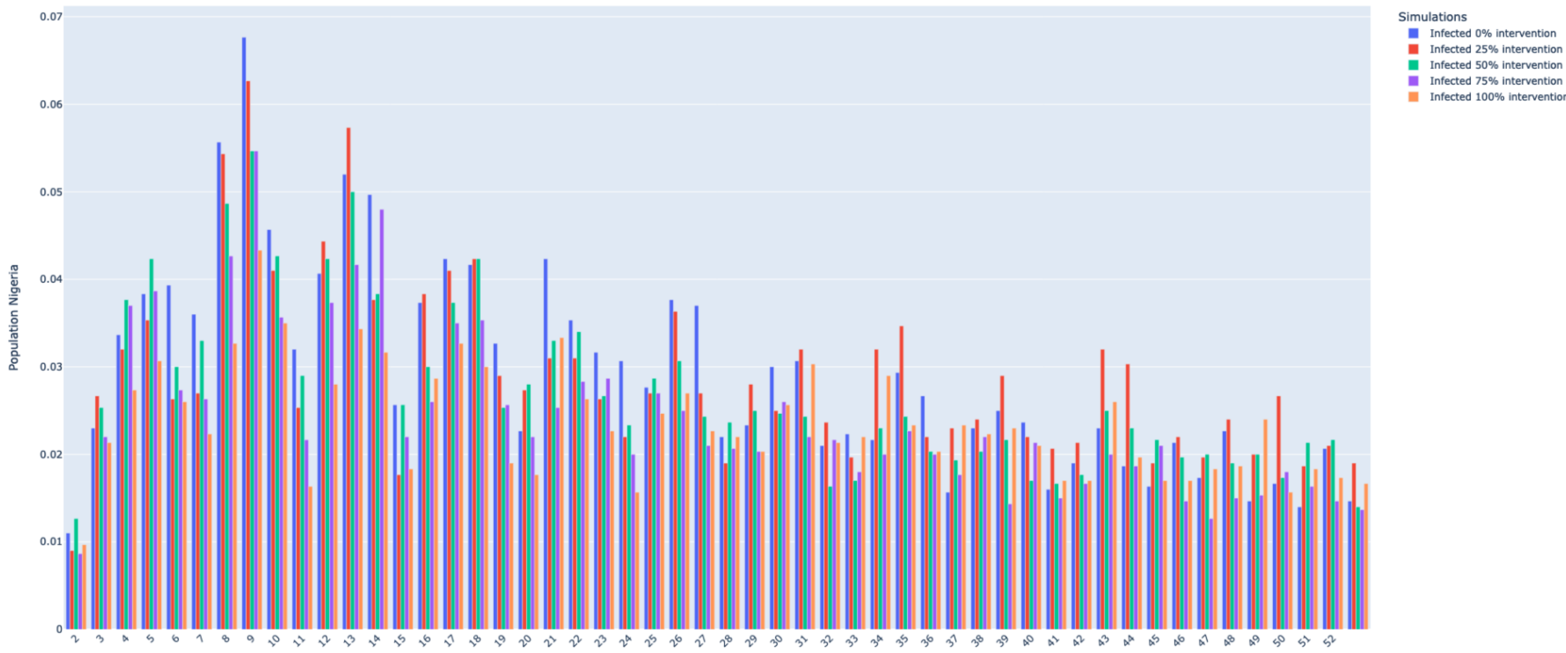

Figure 3: Fraction of population which is protected by prevention methods during one year.

As depicted in Figure 3, an initial escalation in intervention across the population correlates with a reduction in the incidence of malaria infection. However, as the intervention proceeds further over the course of the year, simulations with heightened preventive measures exhibit an increased infection rate compared to those with lower preventive interventions. This phenomenon has a connection to Figure 2, wherein a higher percentage gains partial immunity from those who recover from malaria, which affords superior protection relative to alternative preventive measures. This underscores the dynamic interplay between intervention intensity, infection dynamics, and the nuanced role of acquired immunity in malaria transmission patterns.

Conclusion

Malaria persists to be a substantial health problem in the world, with almost half a million deaths per year worldwide. This disease which is mainly fatal for young children does not have a widely used vaccine or preventative medications. However, according to our experiment in Figure 3 it is possible to delay the infection for a larger part of the population with the use of nets and IRS. Prevention however does not stop the spread of malaria, but since the main fatalities are young children, preventative measures can prevent the early infection of the malaria virus. Currently, the probability of getting malaria in an urban environment in Nigeria is very high, so delaying when people get malaria may save lives. To confirm this, a more comprehensive model is needed, which also contains the age of the people in the model and the corresponding probability of dying from the disease. Delving deeper into the intricacies of malaria transmission, there arises a need for targeted public health interventions tailored to the unique challenges of different communities. The ongoing pursuit of innovative strategies, coupled with advancements in vaccine research and production, is essential for developing breakthroughs in malaria eradication and treatment. In the quest for solutions, cellular automata and knowledge-sharing initiatives can be imperative to confront the nature of this global health concern.

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