GIS Derived Spatial Constraints for Agent-based Modeling of Aedes Aegypti Population Dynamics

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The Aedes aegypti mosquito is responsible for the spread of several arboviruses including Dengue, Chikungunya, Yellow Fever and more recently the Zika virus. Accurate modeling of the population dynamics of this disease vector within its habitat allows us to understand conditions necessary for Aedes aegypti populations to thrive. Using agent-based modeling, model developers can provide public health administrators with tools to experiment with environmental conditions, intervention strategies and scenarios, and observe the potential effects on local mosquito populations.

Innovative vector control strategies have emerged in recent years, besides the traditional techniques such insecticide sprays and breeding site removal. Some of these methods make use of weaknesses in the reproductive process of Aedes aegypti. Two such methods are the Release of Insects with Dominant Lethal gene (RIDL) and Wolbachia infection (an endosymbiotic bacteria). In the RIDL technique, male mosquitoes carrying a self-limiting gene are released and the resulting offspring of these released males die during emergence into adulthood [1, 2]. Cytoplasmic incompatibility resulting from Wolbachia infected males with uninfected wild females also causes all resulting offspring to die [3]. However, if infected females are released, all resulting offspring will survive into adults carrying the Wolbachia infection, allowing for the possibility of sustaining Wolbachia infection within the population and keeping mosquito numbers lowered [4].

In this study we present an agent-based model coupled with spatial resource constraints for both male and female mosquitoes and effects of monthly temperature fluctuation. This model is used to estimate the population of mosquitoes in a neighborhood in the Key West, Florida. Then, as a demonstration of the use of this model, simulations are performed to compare the sustainability of the two vector control strategies.

The success of RIDL requires released males to successfully compete with wild males for mates [5]. Wolbachia infection also requires the successful mating of infected males and can additionally benefit from the release of infected females if sustained infection is desired [4]. Therefore, both techniques require a prior understanding of the mass and frequency of male and female mosquitoes to be released in order to cause a significant reduction in population.

However, existing models of Aedes aegypti population dynamics focus on factors effecting the distribution of adult females, with little or no attention towards the dynamics of adult male mosquitoes. Originally, models were based off of derivative equations and dynamic life-tables, where mosquitoes populations were considered in aggregates or cohorts, such as CIMSim [6] or its spatially explicit version Skeeter Buster [7]. However, significant advances in computing power have allowed modelers to create individual-based or agent-based models (ABMs), where mosquitoes are modeled on a individual scale. In these models each agent acts and reacts to conditions in the environment according to a set of rules and parameters. These rules and parameters are derived from field studies of the Aedes aegypti and the balance between accuracy and computation time of the model can be controlled through assumptions of the rules and parameters. Additionally, by simply changing the parameters of the model, the modeler can adapt the model to simulate varying environmental conditions or even the behavior of various species of mosquito, making agent-based modeling a highly versatile technique.

We have developed an agent-based model of Aedes aegypti inspired from the literature, coupled with geographical information systems to identify zones with resources vital to the survival of both male and female Aedes aegypti, in addition to modeling possible locations of breeding sites. By using a two class k-means classification algorithm we have identified vegetation zones and urban zones in the neighborhood under consideration, which are rich in nutrition sources for male and female Aedes aegypti, respectively. The identified regions are then overlain with a regular point grid (points spaced 20m apart for the purpose of this study) in order to capture the distribution of resources in the environment. This point grid is then used as the continuous space upon which agents in the ABM exist. Breeding sites are assigned to urban zones at a probability equal to the Aedes aegypti House Index reported by the Florida Keys Mosquito Control District field studies.

The agent-based model of Aedes aegypti extends the computational decision making tree used in [8] to include the nutritional requirement of males. Agents are considered to exist in an aquatic or fetal stage and then emerge into the adult stage. Mortality rate of the fetal stage is temperature dependant and an aggregate of functions of temperature obtained from the literature. Similarly, duration of the fetal stage until emergence, adult life duration and egg count during oviposition are modeled as functions of temperature from the literature. Other parameters such as sensory range, displacement speed and circadian rhythm also use values from field studies and previous models.

The model was applied to a neighborhood in the Key West, Florida, over an area of nearly 30000 m^2 with around 50 households. The resulting grid consisted of 93 urban zones to 288 vegetation zones. The temperature was varied monthly and ranged between a low of ($19°C$ and high of $30°C$). The spatial distribution of the vegetation zones, urban zones and breeding spots together with the temperature, constrained the population to a mean high of approximately 2000 during the fall and around 600 in late winter.

Finally, the model was used to simulate RIDL and Wolbachia infection techniques aiming to reduce Aedes aegypti populations in the neighborhood considered. Preliminary results demonstrated the ability of Wolbachia infection to be sustained into the following year after releases were stopped. In contrast RIDL required periodic releases and showed no such sustainability.

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