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Review

# A spatial agent-based simulation model of the dengue vector *Aedes aegypti* to explore its population dynamics in urban areas

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ABSTRACT

MOMA (Model Of Mosquito Aedes) is a spatially explicit agent-based simulation model of *Aedes aegypti* female mosquito, the dengue vector. The model aims to produce statistical data on mosquito behaviours and population dynamics that are difficult to obtain through field surveys such as population densities in various geographical and climatic conditions. It can also be used to explore effects of vector control strategies on population dynamics. The model simulates adult mosquitoes as 'agents' which interact with their local environment. The latter provides resources for their biological development and can also constrain their flight or egg-laying behaviours. Variations in environmental configurations such as land-use and climate make it possible to explore the dependence of mosquito population dynamics on the context.

This paper gives a detailed description of the model's various components and the overall approach used to calibrate and validate it. Study of simulated mosquito behaviours reveals the model's ability to produce the mosquito's realistic life cycle. The mosquito cohort's flight distance in various urban landscapes is also explored. The latter represent a developing neighbourhood in Delhi (India) processed using a Geographical Information System (GIS). The initial results reveal a significant relation between urban topology, human densities and adult mosquito flight.



**Contents**



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## 1. Introduction

Dengue virus annually infects an estimated 390 million people worldwide (Bhatt et al., 2013), mostly in tropical and sub-tropical countries. *Aedes (Ae.) aegypti*, the main mosquito vector, has adapted to a peri-domestic environment and is widespread in urban areas. Thus, while large-scale spatio-temporal distribution of *Ae. aegypti* depends strongly on meteorological factors such as temperature and humidity (Descloux et al., 2012; Hopp and Foley, 2003), the role of urbanization (Rocha et al., 2009), land-use (Thammapalo et al., 2008) and social practices (Rogers and Randolph, 2006) have led to an increasing vector presence. Nowadays, entomological surveillance and vector control represent important action tools to reduce dengue transmission risk (World Health Organization, 2012). In order to increase efficiency and reduce the cost of vector control, areas and periods of high presence of mosquitoes must be prioritized.

Studying spatio-temporal dynamics of *Ae. aegypti* population requires a well-designed entomological surveillance system. This system has to provide robust data on local vector density over time to facilitate targeted interventions, specifically in high-density zones and during periods of mosquito population growth. Quality of this data depends not only on available funding but also on skill and abundance of staff. In many countries affected by dengue, such programmes are difficult to implement and sustain. One of the main constraints of mosquito collecting methods is the size of the sample needed to avoid problems associated with spatio-temporal variation in *Ae. aegypti* larval production (Kay and Nam, 2005). Adult *Ae. aegypti* are difficult to catch and are rarely monitored (Focks, 2004; Scott and Morrison, 2009; Tun-Lin et al., 1996).

In its global strategy for dengue prevention and control, WHO pointed out the need for developing models that include space and time to identify the risk of dengue outbreaks at micro-geographical scales (WHO 2012). MOM*A* (Model Of Mosquito *Aedes aegypti*) has been developed in this context, using agent-based models (ABM) and Geographical Information Systems (GIS) to integrate both geographical heterogeneity of urban landscape and detailed mosquito behaviour into the same model.

## 2. Background

MOM*A* is a behavioural model of *Ae. aegypti* mosquito which aims to study the effects of factors such as human density, breeding site density and topology at a neighbourhood level on mosquito population dynamics. Compared to previous models in which environments are represented by regular grids described by one factor, such as type of water containers (Magori et al., 2009) or humidity level (Isidoro et al., 2009a,b), MOM*A* is concerned with heterogeneity of space defined by discontinuity of geographical morphology. Behaviours and entomological parameters related to *Ae. aegypti* come from literature and interviews with entomologists.[1] Among existing simulators, Skeeter Buster (Magori et al., 2009), a gene-driven mosquito in an intra-container model, made a significant contribution, in particular to the mosquito's life cycle parameters which are well detailed, notably for aquatic stages. This model focuses on the characteristics of mosquito breeding sites but ignores the importance of blood resources such as human density. SimPopMosq, a multi-agent model developed by Almeida et al. (2010), which is considered here the closest to MOM*A* in terms of methodology, includes the impact of this blood resource on mosquito dynamics. This model allows for interactions between the mosquito and human beings but these occur only at an intra-domiciliary scale. As our objective is to have a simulator capability of covering urban areas measuring several square kilometres with thousands of agents, MOM*A* has been chosen so as not to take into account detailed aspects of breeding containers and intra-domiciliary domain. We assume that breeding site dynamics are related to temperature, precipitation and land-use category of its spatial object. The urban configuration of space and topology of spatial objects will condition the mosquito's population dynamics.

MOM*A* accommodates major known behaviours of *Ae. aegypti* mosquito and allows individual tracking to verify whether circadian activity is in accordance with the general knowledge. Doing so ensures that local context and individual trajectories shape spatio-temporal dynamics of future generations of mosquitoes. This nature of the model, centred on the history of each mosquito and on explicit diverse spatial configurations, makes it possible to build longitudinal indicators.

The next sections present MOM*A* using the ODD (overview, design concepts, details) protocol (Grimm et al., 2010, 2006). Various initial results of the simulations are presented here in order to discuss the expected values of such a model. A detailed description of the various model parameters and state variables may be found in Supplement Material S1.

## 3. Methods

The model and data used in this paper can be downloaded (http://dx.doi.org/10.5281/zenodo.46330). MOM*A* has been designed using Gama 1.6.1 platform (http://gama-platform.org). The platform proposes a graphical modelling tool to support rapid user interface design and allows effective integration and manipulation of GIS data. The latter is the main reason why the model was developed using this toolkit. QGIS (2.6.1) was used to build environmental data and R (x64 3.2.0) to analyze simulation results.

### 3.1. Purpose

The purpose of MOM*A* is to explore mosquito population dynamics in heterogeneous urban configurations. An agent called Aedes[2] represents *Ae. aegypti* mosquito and is able to mate, feed, rest and oviposit. To capture the context dependence of mosquito population dynamics, as a first step, we integrated a detailed

[1] Lambrechts Louis, Failloux Anna-Bella and Richard Paul, Institut Pasteur, Paris, France.

[2] In the following, the term Aedes will be used in the context of agent-based model of *Ae. aegypti* mosquito. When we speak of the genus, we use *Aedes* in italics.