Agent-Based Model of *Aedes aegypti* Population Dynamics

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Abstract. The paper presents an agent based model of the *Aedes aegypti* mosquito and it is focused on simulations of population dynamics and population control strategies. The agents model the main aspects of mosquito's ecology and behavior, while the environmental components are implemented as layer of dynamic elements obeying to physical laws. The main objective of this approach is to provide realistic simulations of insect biologic control strategies, namely population suppression by releasing large amounts of sterile males, such as Sterile Insect Technique (SIT) or Release of Insects carrying a Dominant Lethal gene (RIDL). Model verification is done through simulations analysis of parameters variation and qualitative assessment with existing models and simulations. The use of LAIS simulator proved to be a valuable tool allowing efficient agent based modeling (ABM) and simulations deployment and analysis.

Keywords: Artificial Life, Agent Based Modelling, Aedes aegypti, Dengue, RIDL, SIT.

1 Introduction

The dengue is a dangerous disease which still lacks a cure, and it is spread through a specific type of vector, the *Aedes aegypti* mosquito. Currently, the most affected areas are the ones with tropical climates since factors like high temperature and frequent precipitation are favorable to *Aedes aegypti* growth. However, if current predictions about climate change happen, many new areas might start facing the dengue threat [1].

Since an effective treatment is yet to be found, it is particularly important to focus on prevention, keeping the mosquito population under transmission threshold. Various strategies have been developed and used for this purpose, ranging from releasing large amounts of sterile mosquitoes into the environment to clearing areas with still water that might be used as mosquito breeding sites. However, for these defensive measures to be as effective as possible, it is necessary

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to devise ways of predicting their impact, taking into account evolution of the mosquito population and the spread of the disease.

In this paper an agent based model and simulation of *Aedes aegypti* populations is presented. To effectively control the mosquito population, it is crucial that its evolution can be predicted. That is the aim of this model; while it still does not implement the spread of the dengue virus, it is already a functional model that simulates mosquito behavior and how the mosquito population evolves over time. The model can be used to determine the best approaches to contain the population size. In particular, the effect of the RIDL strategy as a containment method was studied.

In section 2 the state-of-the-art on mosquito population modeling is presented. The methods and materials used for developing the mosquito model, namely the ABM approach and the LAIS simulator, are discussed in section 3. The model itself is described in greater detail in section 4. In section 5 simulations and results are presented and discussed. Finally, in section 7 we conclude the presented work, underlining the model's potential and proposing future improvements.

2 State of the Art

There have been numerous models of mosquitoes and mosquito-borne disease, beginning with the classic Ross-Macdonald malaria models [2,3,4] and extending to present day models of vectors populations or aspects of vector biology, not directly considering disease [5,6,7,8].

One example of modeling the dengue vector mosquito population dynamics is by Focks and colleagues [9,10], examining the biology of *Aedes aegypti*. This is an exceptionally detailed model, with numerous types of containers for larval development. Hydrology (water levels and drying), temperature-dependent larval development, food availability and survival are explicitly tracked in each container type. Detailed weather data are used to drive the hydrological and biological functions. This level of detail has both costs and benefits; it enables consideration of detailed aspects of the mosquito biology, but also makes true sensitivity analysis of the model difficult or impossible. Thus, to develop a model with this level of detail, it is necessary to have extensive data available for parameter estimates and validation.

The use of ABM methodologies to model *Aedes aegypti* populations has been scarce at best. Some interesting ideas are presented in a work by Deng *et. al* [11], namely the use of an utility function to determine mosquito movement, taking into account factors such as population, wind direction, land use type and landscape roughness. However, the practical implementation of the model is very limited, with coarse spatial discretization (30x30) and a small number of agents representing a large number of model components and their behaviors.

Models can be useful to evaluate different strategy of mosquito control. Recently, techniques like releasing genetic modified mosquitoes have been considered as an enhanced SIT to control the mosquito population, as the genetic manipulation in insects result in sterility or lethal genes [12,13]. Although there wasn't any genetic modified mosquito open field release conducted yet, a couple of mathematical modeling works have been done to assess the control efficacy [14,15,16]. But none of those could provide a tool to simulate the interaction between mosquito individuals such as mating behavior, spatial distribution, and immigration etc. All these are important for the evaluation and guidance of genetic control approach.

3 Methods and Materials

ABM is well suited for describing complex systems in general and disease transmission in particular, providing a way to represent the true diversity of intervening components, such as environmental factors, disease vectors and disease hosts. Other advantages include the possibility to determine spatial behavior distribution, rapid insertion of new components and natural consideration of non-linear interactions between agents. This approach is not without problems of its own: it requires considerable computational power to simulate individual agents; parameter tuning is not trivial; and, being a relatively recent modeling methodology, lacks the formal framework provided by other approaches, such as differential equation modeling (although work concerning ABM formalism already exists [17]). Nonetheless, for explicitly spatial models, such as the one presented here, the advantages of ABM clearly outweigh its limitations.

The model was developed using the LAIS simulator, a multithreaded agent-based simulation platform, offering a modeling paradigm and a set of tools for the simulation of complex systems [18]. The platform is implemented in Java and makes use of several open source libraries which provide tools for spatial organization and visualization, event scheduling, simulation output (e.g., charts, CSV files, movies) and simple class development and instantiation using XML. Simulations are performed in discrete time and two-dimensional discrete space. As such, space is divided into blocks, which are independently processed by different threads, making LAIS scalable on modern multiprocessor systems.

There are two main actors in the LAIS framework: *agents* and *elements*. Agents are typical ABM discrete and independent decision-making entities. When prompted to act, each agent analyzes its current situation (e.g. what resources are available, what other agents are in the vicinity), and acts accordingly, based on a set of rules. These rules incorporate knowledge or theories about the respective low-level components. On the other hand, elements are real-valued objects which obey predetermined rules, such as physical laws (e.g., diffusion).

4 Model Description

The *Aedes aegypti* LAIS model implements a square topology where each spatial block has 8 neighbors. Five different agents are considered: Wild Male Mosquitoes (WM), Wild Female Mosquitoes (WF), Sterile Male Mosquitoes (SM), Humans (H) and Oviposition spots (OS). Five different elements are also used, and they fall into one of the following categories: mosquito attractors (of

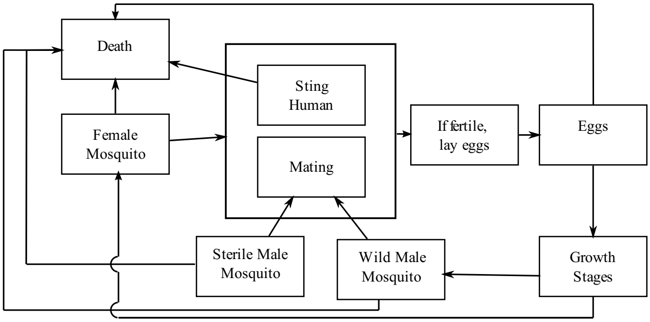

Fig. 1. Model overview

Table 1. Base mortality and maturing chances for mosquitoes

Parameter	Egg	Larva	Pupa	Adult
WF Base Mortality Rate	0.15	0.05	0.05	0.05
WF Maturing Chance	1	0.99	0.6	-
WM Base Mortality Rate	0.15	0.15	0.15	0.15
WM Maturing Chance	1	0.99	0.7	-
SM Base Mortality Rate	0.15	0.15	0.15	0.15

which there are three kinds), mosquito density measure and observable mosquito properties.

The interactions between the various agents are represented in a simplistic way in fig. 1. Table 1 shows various parameters related to the agents.

4.1 Agents

Female Mosquito (WF). The Female Mosquito (WF) is by far the most complex agent in the simulation. Adult females try to find humans nearby (by following the concentration of the *body heat* element) and attempt to sting them in order to obtain blood. Exposure to humans is a risky activity however, and might result in the death of the mosquito. If the female succeeds, it then starts moving randomly waiting for a male to mate with, and then looks for an Oviposition Spot (by moving to areas with a higher concentration of the *humidity* element). If it has already found a mate before finding a Human it goes directly to the OS after stinging the Human. During the first two steps, looking for humans and mates respectively, the female regularly deposits pheromones for the males to follow. When it reaches the Oviposition spot it lays its eggs if the mate was fertile, and then starts looking for another human, resuming the cycle.

The female has a certain chance to die at each iteration (table 1), and that chance will vary with the density of other mosquitoes in the area. New females start as eggs, and then go through a number of growth stages (currently larvae

Table 2. More parameters related to the WF

Parameter	Value
Chance to die when meeting a Human	0.5
Chance to successfully sting a Human	0.9
Number of male eggs laid	16
Number of female eggs laid	11
Chance to mate with wild males	0.7
Chance to mate with sterile males	0.7

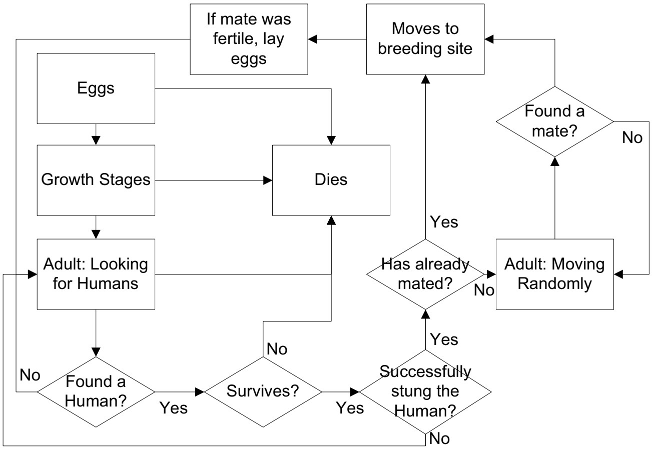

Fig. 2. WF mosquito model

and pupa), before maturing into an adult (maturing chances for each stage can also be found on table 1). Table 2 provides various parameters related to the WF and figure 2 shows a summary of the WF sequence of actions.

Male Mosquito (WM). The Wild Male Mosquito (WM) is much simpler when compared to the female version. Adult males follow the pheromone released by females, trying to find one to mate with, and continue with this behavior until they die. Like females, males always have an intrinsic chance to die that increases with the amount of mosquitoes in the area, and new males also start as eggs and go through some growth stages before reaching the adult state.

Sterile Male Mosquito (SM). Sterile Male Mosquitoes (SM) act in exactly the same way as WM. It is the females that check whether their mates were sterile or not. Sterile males do not have growth stages because they are never generated by the mosquitoes, they have to be inserted manually. The parameters associated with the SM in this model are the same as the ones for the WM. This makes this particular implementation of the SM closer to the RIDL approach than the SIT one, since the competitiveness of the SM is the same as the WM.

Oviposition spot. This agent is also extremely simple. It is immobile and only executes two different actions: It is constantly releasing humidity for the females to find them, and it clears the toxicity (*density* element) in its spatial block to ensure they do not become deadly to mosquitoes (since there will be a large number of mosquitoes in such spatial blocks - eggs, growing mosquitoes, females, and the occasional male that wanders into it in search of females).

Human. Humans are perhaps the most basic agent in the model. They simply move randomly in the environment, releasing body heat that the WF follow. They provide the blood that the WF need to lay eggs.

4.2 Elements

Most of these elements have already been presented in the previous section, while describing the agents that use them. It should be noted that elements are used to model mosquito behavior and might not correspond to the exact process the mosquitoes use to follow their targets. For example, females might not track humans based on their body heat, but through other means, be it vision, or some other property the female identifies.

Element diffusion and degradation is performed using a simple method where element concentration in each local block is determined by eq. 1. In this equation, C^n is the substance concentration at tick n, C_i is the substance concentration at neighbor i, N is the number of neighbor blocks (8 in this case) and α and β are the diffusion and evaporation coefficients, respectively. The parameters related to each element are presented on table 3

$$C^{t+1} = \beta \left(C^t + \alpha(\sum_{i=1}^{N} C_i^t - C^t) \right) \tag{1}$$

Attractive Elements: Pheromone (Ph), Body Heat (BH) and Humidity (Hu). These three elements are quite similar, differing only on the agents that release them and the agents that react to them. Pheromone (Ph) is released by WF and attracts males (WM and SM). Body Heat (BH) is released by Humans and attracts WF that are seeking blood. Humidity is released by OS and attracts WF that are looking for a place to lay their eggs.

Table 3. Elements Parameters

Element	Diff. Rate	Evap. Rate	Qty. released	Attractive influence
Ph	0.3	0.05	1	0.5
BH	0.3	0.05	1	0.9
Hu	0.3	0.05	1	0.5
De	0.001	0.2	0.0041	-

Adult Pheromone. This element is placed by WM on themselves when they become adults. This is simply a way for WF to identify them as suitable mates.

Density. This element is released by all types of mosquitoes, and is consumed by Oviposition spots. It is used to model the impact a high density of mosquitoes has on their mortality rate. The reason it is consumed in Oviposition spots is to ensure that they do not become a deadly site for mosquitoes due to the high amount of mosquitoes that will be there.

5 Experiments and Results

This section details the various tests and simulations performed with the LAIS *Aedes aegypti* model. Table 4 shows the default model parameters used for all tests. The 100x100 default size for the test area was chosen because it was a good compromise between the quality of the results and the processing time required for each simulation. Excluding test 5.1 (which just shows the basic evolution of the mosquito population over time), all graphics were determined by averaging the population values of 20 similar simulations. Each block represents around 100 square meters, and each iteration corresponds to a single day.

Table 4. Model default parameters

Parameter	Value
Model width (blocks)	100
Model height (blocks)	100
Initial number of Male Mosquitoes	1250
Initial number of Female Mosquitoes	750
Number of Humans	700

5.1 Default Model

This test is a basic simulation to show the normal evolution of the mosquito population with no treatment (fig. 3). The number of OS used was 300. The mosquito population seems to reach a steady state between 1000 and 2000 individuals from each gender, values that are independent of their initial number. These variations suggest the presence of homeostasis and limit cycles that depend on the various WF and WM parameters.

5.2 Varying Number of Oviposition Spots

In this test the impact of OS availability was studied (fig. 4). As was expected, the final population increases in a linear fashion with the number of OS, since more places to breed makes it easier for more females to lay their eggs. There is probably a maximum number of OS that still significantly affects the number of mosquitoes, as there are other factors that limit their growth, namely death by density and the number of available humans.

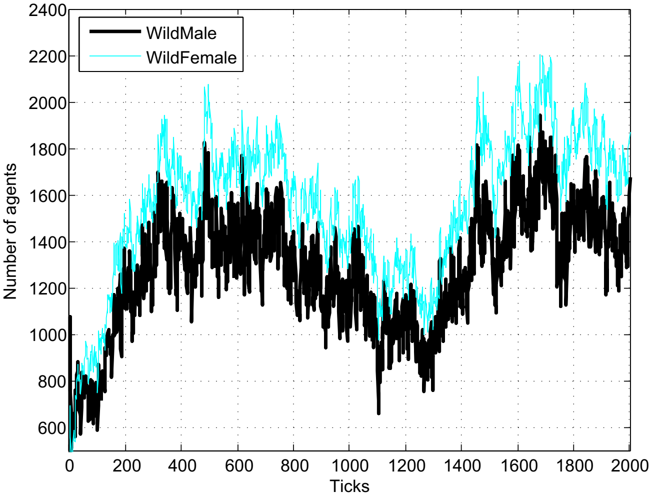

Fig. 3. Mosquito population over a period of 2000 iterations with no treatment applied (300 OS)

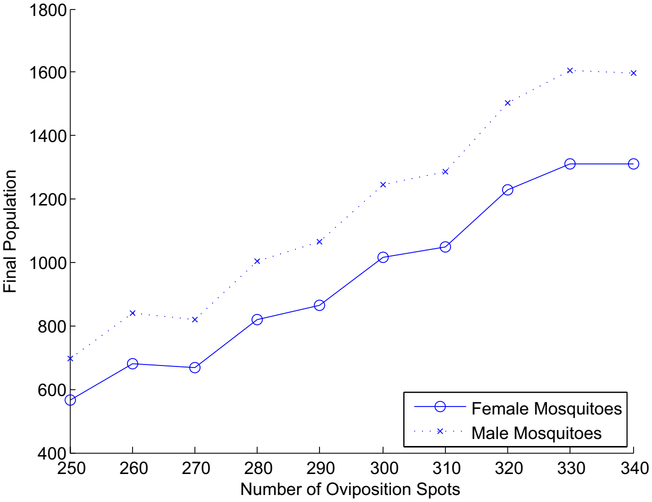

Fig. 4. Final Mosquito Population as a function of the number of Oviposition Spots

5.3 Efficiency of Sterile Mosquitoes

As has already been said in the introduction, this model was used to study the effect of a specific population control strategy, the RIDL method. Tests were performed to show the impact of two factors on the efficacy of the treatment: a) the amount of SM released, in the form of the sterile to wild ratio SM/WM (fig. 5), and b) the width of the time frame in which the release occurred, T

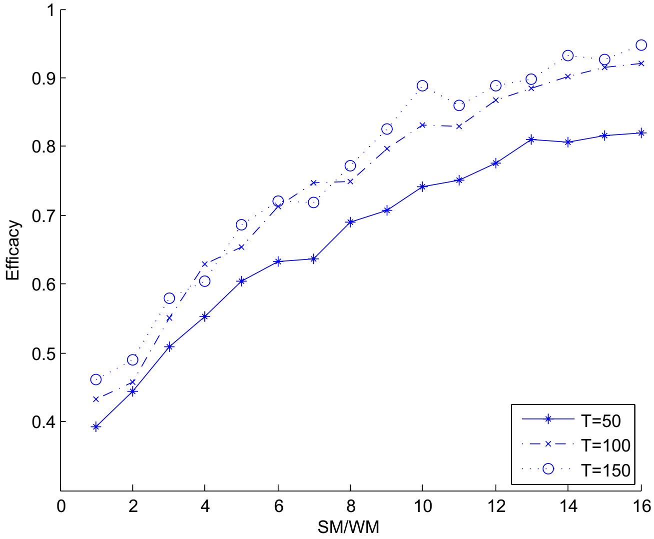

Fig. 5. Efficacy as a function of the SM/WM ratio (300 OS)

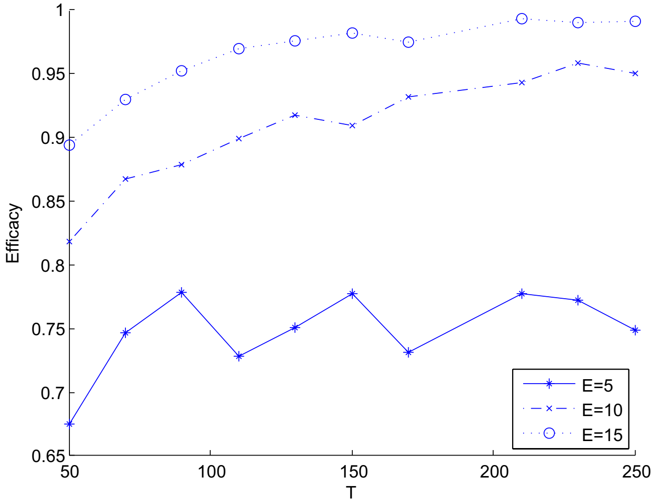

Fig. 6. Efficacy as a function of T (300 OS)

(fig. 6). The efficacy of the treatment is given by eq. 2, where P_i is the population value when the treatment starts, and P_f the minimum population value obtained during the period encompassing the duration of the treatment and a short time after the treatment ends.

$$\text{Efficacy} = \frac{P_i - P_f}{P_i} \tag{2}$$

This kind of simulations are extremely important in order to find the best release strategy and amount of SM to produce, information that is necessary for any control program. The number of OS for all these tests was 300. Fig. 5 shows a sigmoid-like increase of efficacy with SM/WM, with saturation starting for values of SM/WM above 12. There is no significant difference for distinct release periods, but larger values of T tend to yield higher efficacies. The results presented in fig. 6 are consistent with the ones from fig. 5, demonstrating that for values of T above 100 the change in efficiency is negligible, and a higher SM/WM results in higher efficacies.

6 Discussion

The results obtained regarding the effectiveness of this particular population control strategy concerning SM/WM ratio, and the ones related to the width of the time frame of the release are quite similar (from a qualitative point of view) to the ones obtained in [19].

It is also important to comment that these were not the only results that could be obtained from the LAIS simulator, but only the ones that were found to be most important. The LAIS simulator can also yield information about the concentration of all elements for each iteration, the number of agents in a given state (larvae, pupas, adults, etc.), and the 2D representation of the environment gives the possibility of checking the contents of any given block.

7 Conclusions and Future Work

The model presented in this paper is far from complete, since it is missing certain important factors, most noticeably environmental factors like temperature, precipitation and wind. The various parameters also need to be fine-tuned to get a model as close to the real population as possible (in particular, some parameters might not be entirely correct in relation to the amount of time associated with each iteration). The possibility to have infected mosquitoes and humans will also be an important improvement to the model, since then it can also be used to directly predict the spread of the dengue disease.

Other strategies to contain the population could also be studied, and even variations on this particular control strategy, like PRP (Prevention Release Program), regularly releasing a lower number of sterile mosquitoes after the population has been reduced below the transmission threshold, in order to keep the population controlled.

Nevertheless, the model presented here can be the basis of an important tool to: a) help in the comprehension of *Aedes aegypti* population dynamics; b) predict the efficacy of mosquito population control strategies; and c) assess the best courses of action to contain the spread of the dengue disease.

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References

1. Senior, K.: Climate change and infectious disease: a dangerous liaison. The Lancet Infectious Diseases 8(2), 92–93 (2008)
2. Ross, R.: The Prevention of Malaria (1911)
3. Macdonald, G.: The analysis of equilibrium in malaria. Trop Dis Bull 49(9), 813–829 (1952)
4. Macdonald, G.: The epidemiology and control of malaria (1957)
5. Eisenberg, J., Reisen, W., Spear, R.: Dynamic model comparing the bionomics of two isolated Culex tarsalis (Diptera: Culicidae) populations: model development. Journal of Medical Entomology 32(2), 83–97 (1995)
6. Eisenberg, J., Reisen, W., Spear, R.: Dynamic model comparing the bionomics of two isolated Culex tarsalis (Diptera: Culicidae) populations: sensitivity analysis. Journal of medical entomology 32(2), 98–106 (1995)
7. Alto, B., Juliano, S.: Precipitation and temperature effects on populations of Aedes albopictus (Diptera: Culicidae): implications for range expansion. Journal of medical entomology 38(5), 646–656 (2001)
8. Ahumada, J., Lapointe, D., Samuel, M.: Modeling the population dynamics of Culex quinquefasciatus (Diptera: Culicidae), along an elevational gradient in Hawaii. Journal of medical entomology 41(6), 1157–1170 (2004)
9. Focks, D., Haile, D., Daniels, E., Mount, G.: Dynamic life table model of a container-inhabiting mosquito, Aedes aegypti (L.)(Diptera: Culicidae). Part 1. Analysis of the literature and model development. Journal of Medical Entomology 30, 1003–1017 (1993)
10. Focks, D., Haile, D., Daniels, E., Mount, G.: Dynamic life table model of a container-inhabiting mosquito, Aedes aegypti (L.)(Diptera: Culicidae). Part 2. Simulation results and validation. Journal of Medical Entomology 30, 1018–1028 (1993)
11. Deng, C., Tao, H., Ye, Z.: Agent-based modeling to simulate the dengue spread. 7143, 714310 (2008)
12. Thomas, D., Donnelly, C., Wood, R., Alphey, L.: Insect population control using a dominant, repressible, lethal genetic system. Science 287(5462), 2474–2476
13. Atkinson, M., Su, Z., Alphey, N., Alphey, L., Coleman, P., Wein, L.: Analyzing the control of mosquito-borne diseases by a dominant lethal genetic system. Proceedings of the National Academy of Sciences 104(22), 9540–9546 (2007)
14. Esteva, L., Mo Yang, H.: Mathematical model to assess the control of Aedes aegypti mosquitoes by the sterile insect technique. Mathematical biosciences 198(2), 132–147 (2005)
15. Li, J.: Simple mathematical models for interacting wild and transgenic mosquito populations. Mathematical biosciences 189(1), 39–59 (2004)

16. Maiti, A., Patra, B., Samanta, G.: Sterile insect release method as a control measure of insect pests: A mathematical model. Journal of Applied Mathematics and Computing 22(3), 71–86 (2006)
17. Helleboogh, A., Vizzari, G., Uhrmacher, A., Michel, F.: Modeling dynamic environments in multi-agent simulation. Autonomous Agents and Multi-Agent Systems 14(1), 87–116 (2007)
18. Fachada, N.: Agent-based Simulation of the Immune System. Master's thesis, Instituto Superior Técnico, Lisboa (July 2008)
19. Ferreira, C., Yang, H., Esteva, L.: Assessing the suitability of sterile insect technique applied to Aedes aegypti. Journal of Biological Systems 16(4), 565–577 (2008)