A MODEL FOR THE EFFECT OF TEMPERATURE AND RAINFALL ON THE POPULATION DYNAMICS AND THE EFFICIENCY OF CONTROL OF *Aedes aegypit* MOSQUITO

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Vector-borne diseases

- Recrudescence of several long-known vector borne diseases: malaria, leishmaniosis, dengue, etc
- Dengue is the most important mosquito-borne viral disease of humans (WHO, 2005).
- 2.5 billion people live in areas where dengue viruses can be transmitted. (WHO, 2007)
- There is a currently estimation of 50 to 100 million dengue infections-year worldwide (WHO, 2011)

Environmental Management

- Ecology is a complex science, but it is desired that the determinism should be used to the limit level.
- Environmental Management: the surveillance and control of the *Aedes aegypti*.

Surveillance

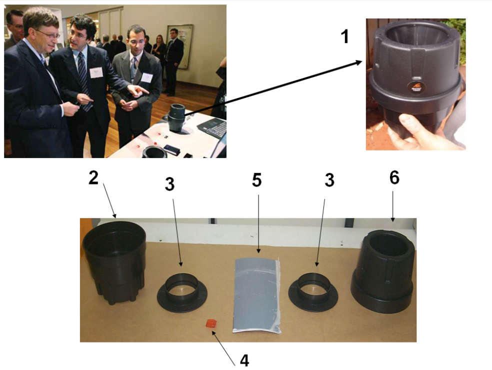
There are some methods to perform the vector surveillance:

- Larval Surveillance;
- Egg trap (Ovitrampas);
- Backpack aspirator;
- Traps for adults.

A *MosquiTRAP*®

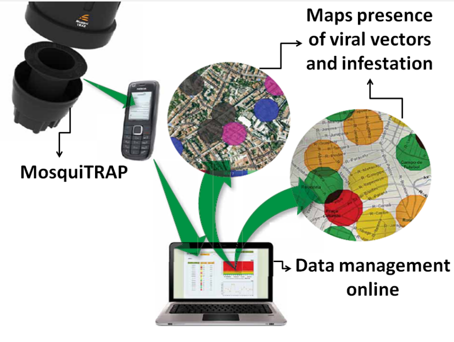
- *MosquiTRAP*® is an adult form trap that captures mainly gravid females.
- It is made by plastic and contains a smell to attract gravid females.
- Gravid females are responsible for the dengue infection as they make blood-meal in order to feed their eggs.
- The blood-meal is only to feed eggs.

A *MosquiTRAP*®



Intelligent monitoring: MI-dengue

It is an integrated system of surveillance from traps to web.



MI-dengue

- Mean Female Aedes Index:

$$MFAI = \frac{\#captures\ \ by\ \ the\ \ traps}{\#traps}$$

- Low infestation: green - (MFAI < 0.2);
- Medium infestation: yellow - ($0.2 <$ MFAI < 0.4);
- High infestation: red - (MFAI > 0.4).

Control

- The control of the *Aedes aegypti*:
- Chemical: pesticides;
- Biological: genetic, sterile males, parasites;
- Mechanical: removal of breeding sites;

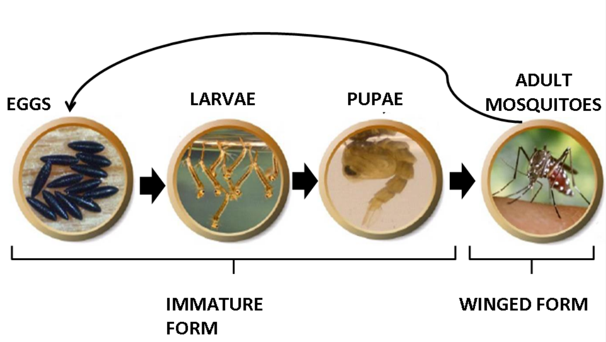
Conjecture to be verifyied

One of the authors, expert in *Ae. aegypti* ecology and environmental management, suggests that:

Conjecture (Eiras, Á. E.)

"The period of the public health dengue vector control should be advanced to the cold and dry seasons of the year in order to reduce the number of annual infections, incurring in a lesser cost and in a lesser social impact."

Aedes aegypti stages of development



Model

The proposed mathematical model describes a biological dynamic control considering that the vector life cycle is divided into four compartments:

- Immature phase of the insect at time t:
  - $E(t)$: eggs;
  - $A(t)$: larvae and pupae.
- Adult phase of the insect at time t:
  - $F_1(t)$: females before mating;
  - $F_2(t)$: mating fertilized females.

Model

Parameters:

- μ_X: natural mortality rate of the vectors;
- c_X: mortality rate of the vectors induced by control;
- ϕ: rate of oviposition of fertilized females;
- C: capacity of the environment related to the number of nutrients available;
- α_X: rate at which the vectors are evolving from one phase to the another.

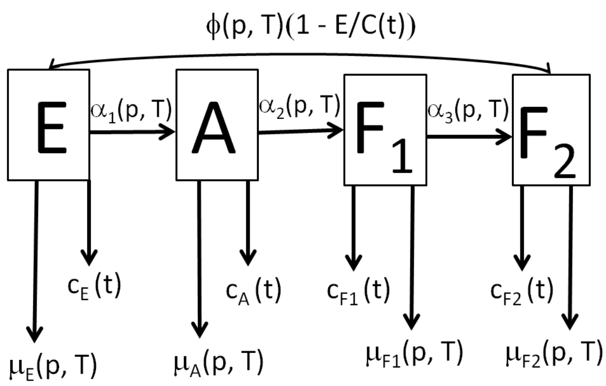
Vector climate dependence

- This work pretends to consider the seasonal characteristic in the time evolution of *Aedes aegypti* population.
- It is proposed to consider the variations of the parameters being proportional to:
    - Rainfall;
    - Temperature.

Model

$$
\begin{cases}
\dfrac{dE}{dt} = \phi(p,T)\left(1 - \frac{E}{C(t)}\right) F_2 - \alpha_1(p,T)E - \mu_E(p,T)E - c_E(t)E \\[2ex]
\dfrac{dA}{dt} = \alpha_1(p,T)E - \alpha_2(p,T)A - \mu_A(p,T)A - c_A(t)A \\[2ex]
\dfrac{dF_1}{dt} = \alpha_2(p,T)A - \alpha_3(p,T)F_1 - \mu_{F_1}(p,T)F_1 - c_{F_1}(t)F_1 \\[2ex]
\dfrac{dF_2}{dt} = \alpha_3(p,T)F_1 - \mu_{F_2}(p,T)F_2 - c_{F_2}(t)F_2
\end{cases}
$$

Model diagram



Model

The parameters were obtained in part from the literature and in part were estimated by specialists.

Rate	Range	Rate	Range	Rate	Range
ϕ	0.56 – 11.2	C	1 – 1	α_1	0.01 – 0.5
μ_E	0.01 – 0.01	c_E	0.3 – 0.3	α_2	0.06 – 0.16
μ_A	0.164 – 0.164	c_A	0.3 – 0.3	μ_{F_1}	0.043 – 0.17
$c_{F_1} = c_{F_2}$	0 - 0	α_3	0.2 – 0.2	μ_{F_2}	0.057 – 0.17

Model

Each of the coefficients is supposed to depend on the temperature and rainfall. If we have:

$$\Pi = (\phi, \alpha_1, \alpha_2, \alpha_3, \mu_E, \mu_A, \mu_{F1}, \mu_{F2}),$$

than:

$$\Pi(p, T) = \frac{1}{2}\left(\Pi_1(p) + \Pi_2(T)\right)$$

where $\Pi_1(p)$ represents the dependence of rainfall and $\Pi_2(T)$ dependence on temperature.

Dependence of rainfall

It adopts a power parametrization for the dependence of the model parameters ϕ, α_1,α_2, α_3:

$$\Pi_1(p) = \Pi_{1min} + \frac{(\Pi_{1max} - \Pi_{1min})}{(p_{max} - p_{min})^r}(p - p_{min})^r$$

with

$$r = 0.75$$

It is a linear parametrization for others parameters with rainfall $p(t)$.

Dependence of temperature

	18°C	22°C	26°C	30°C
α_1	0.095511	0.166113	0.240385	0.30303
α_2	0.038491	0.061275	0.09434	0.128866
$\mu_{F1} = \mu_{F2}$	0.023148	0.025202	0.024486	0.040225
	34°C	43°C	46°C	-
α_1	0.324675	-	0	-
α_2	0.116822	0	-	-
$\mu_{F1} = \mu_{F2}$	0.050865	-	-	-

Dependence of temperature

$$\alpha_1(T) = 0,3029 - 0,001339(T - 31,17)^2$$

$$\alpha_2(T) = 0,1178 - 0,0006558(T - 29,88)^2$$

$$\alpha_3 = 1 - \frac{1}{64}(T - 26)^2$$

$$\mu_{F1}(T) = \mu_{F2}(T) = 0,02281 + 0,0001501(T - 20,13)^2$$

$$\mu_A = 0.01 + 0.9725e^{((4.85-T)/2.7035)}$$

$$\phi(T) = -0.0176T^2 + 0.8714T - 9.7903$$

Model Analysis

For each temperature and rainfall level, there are two equilibrium points:

- Trivial equilibrium point:

$$P_0 = \begin{cases} E^{**} & = & 0 \\ A^{**} & = & 0 \\ F_1^{**} & = & 0 \\ F_2^{**} & = & 0 \end{cases}$$

Model Analysis

- Non-trivial equilibrium point:

$$P_1 = \begin{cases} E^* & = & C\left(1-\frac{1}{R_M}\right) \\ A^* & = & \frac{\sigma_A}{(\gamma+\mu_A+c_A)}C\left(1-\frac{1}{R_M}\right) \\ F_1^* & = & \frac{\gamma}{(\beta+\mu_{F_1}+c_{F_1})}\frac{\sigma_A}{(\gamma+\mu_A+c_A)}C\left(1-\frac{1}{R_M}\right) \\ F_2^* & = & \frac{\beta}{(\mu_{F_2}+c_{F_2})}\frac{\gamma}{(\beta+\mu_{F_1}+c_{F_1})}\frac{\sigma_A}{(\gamma+\mu_A+c_A)}C\left(1-\frac{1}{R_M}\right) \end{cases}$$

Stability

R_M : basal reproductivity rate

$$R_M = \frac{\phi}{(\sigma_A + \mu_E + c_E)} \frac{\sigma_A}{(\gamma + \mu_A + c_A)} \frac{\gamma}{(\beta + \mu_{F_1} + c_{F_1})} \frac{\beta}{(\mu_{F_2} + c_{F_2})} > 0$$

- For $R_M > 0$, we have $(E^* > 0,\ A^* > 0,\ F_1^* > 0,\ F_2^* > 0)$.
- For $R_M = 1$, we have $P_1 \ = \ P_0$.

Stability

From the Routh - Hurwitz criteria:

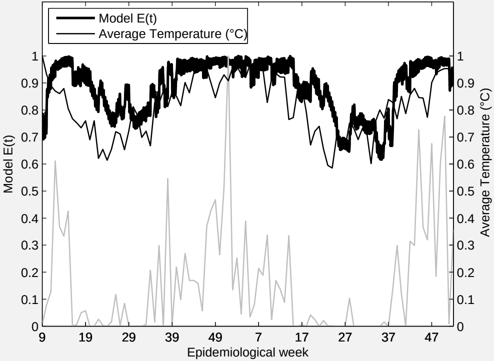
- If $0 < R_M < 1$, P_0 is **locally asymptotically stable** and P_1 is **unstable**.
- If $R_M > 1$, P_0 is **unstable** and P_1 is **locally asymptotically stable**.

Experiments

- A fourth order Runge-Kutta method was implemented in the software *MATLAB*®, version Rb2009.
- We used the parameters with the above rainfall and temperature data.

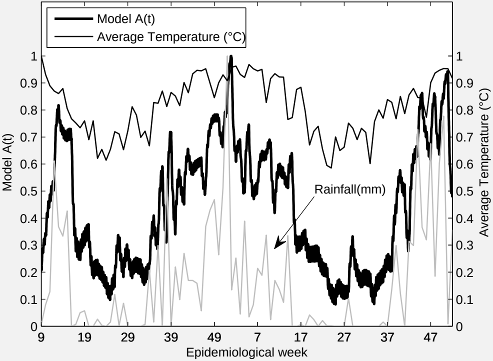
Eggs

Eggs population follows the temperature slope.



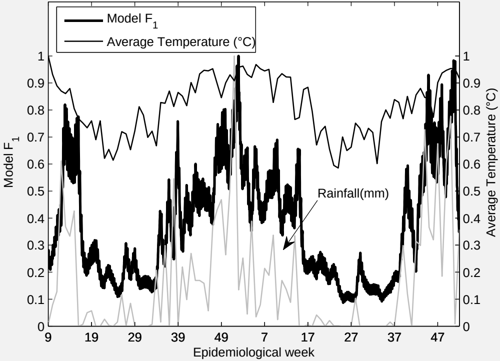
Aquatic immature forms

Aquatic immature population follows both rainfall and temperature.



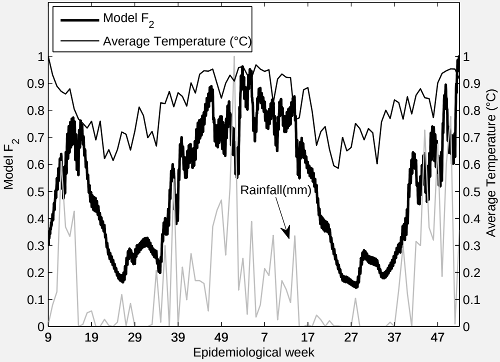
Pre-blood-meal females

The same, but keeps with high values longer.



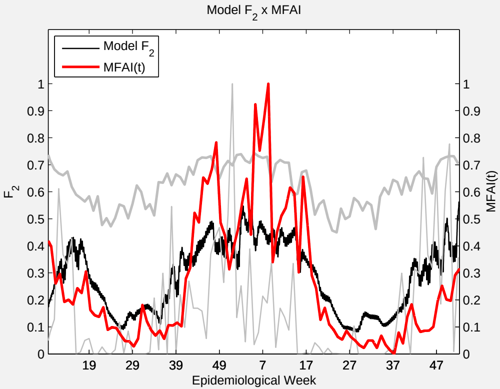
Post-blood-meal females

The same, with a median behavior.



Model validation

Comparison between theoretical $F_2(t)$ and the capture index MFAI.



Modelling control actions

- Control was implemented over the imature phase $E(t)$ e $A(t)$, in order to simulate removal of breeding sites.
- It is supposed that $c_E = c_A = 0.3$ and $c_{F_1} = c_{F_2} = 0$.
- The control was performed over an epidemiological week:
  1. (LRW): control action over a week of low rainfall index;
  2. (HRW): control action over a week of low rainfall index.

Relative differences

For comparison, we define the relative difference indexes:

$$M(t) = \frac{[F_2(t)\ \text{LRW}] - [F_2(t)\ \text{WCW}]}{[F_2(t)\ \text{WCW}]}$$

$$N(t) = \frac{[F_2(t)\ \text{HRW}] - [F_2(t)\ \text{WCW}]}{[F_2(t)\ \text{WCW}]}$$

$[F_2(t)\ \text{WCW}]$ is the quantity without control.

Latency and intensity of control

- It is interested in latency and intensity of the control, the focus is on the areas of the depletion valleys:

$$I_{LRW} = \left| \int_I M(t)dt \right| \quad \text{and} \quad I_{HRW} = \left| \int_I N(t)dt \right|$$

- Further, to compare we define a new relative difference between the above indexes:

$$R = \frac{I_{LRW} - I_{HRW}}{I_{HRW}} \times 100\%$$

Relative effectiveness of control

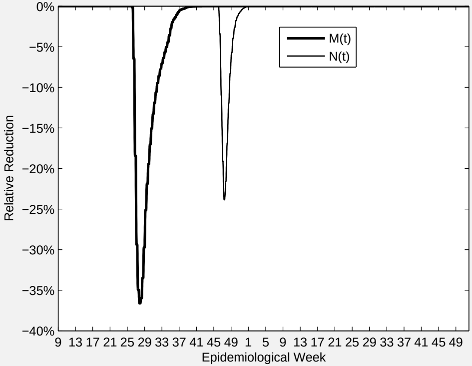
This is the relative differences when conducting control over three weeks of LRW and over three weeks of HRW:

LRW \ HRW	38	47	51
24	71.72%	116.33%	100.55%
27	159.50%	226,91%	203.07%
30	113.37%	168.80%	149,20%

- Comparable: 71.72%.
- Very advantageous: 100.55%, 113.37%, 116.33%.
- Remarkably advantageous: 203.07% and $226,91\%$.

Relative effectiveness of control

Relative effectiveness of control week 27-47.



Conclusion and perspectives

- The control was up to 227% more advantageous when applied in LRW than when applied in HRW.
- A subset of parameters were estimated and needs to be refined.
- The exact power law dependence of the parameters on the rainfall index is to be optimized.

Conclusion and perspectives

- Real data from other cities can be used:
  1. to refine the parameters;
  2. to search for the optimal time-window and quantities to provide public health actions.
- After improvements, we hope the model can potentially be predictive, anticipating indexes from climatic variables.

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