

Spatial and climate-driven aspects of *Aedes aegypti* population dynamics modeling

Pedro Lugão, Grigori Chapiro, Raphael Cascelli, Monalisa R. da Silva

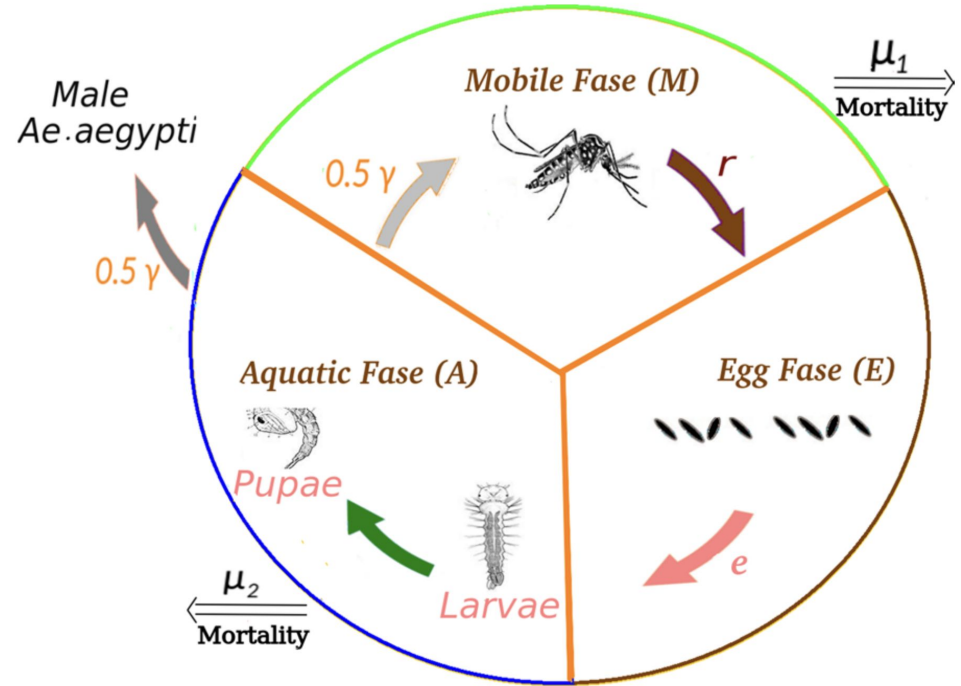


The problem

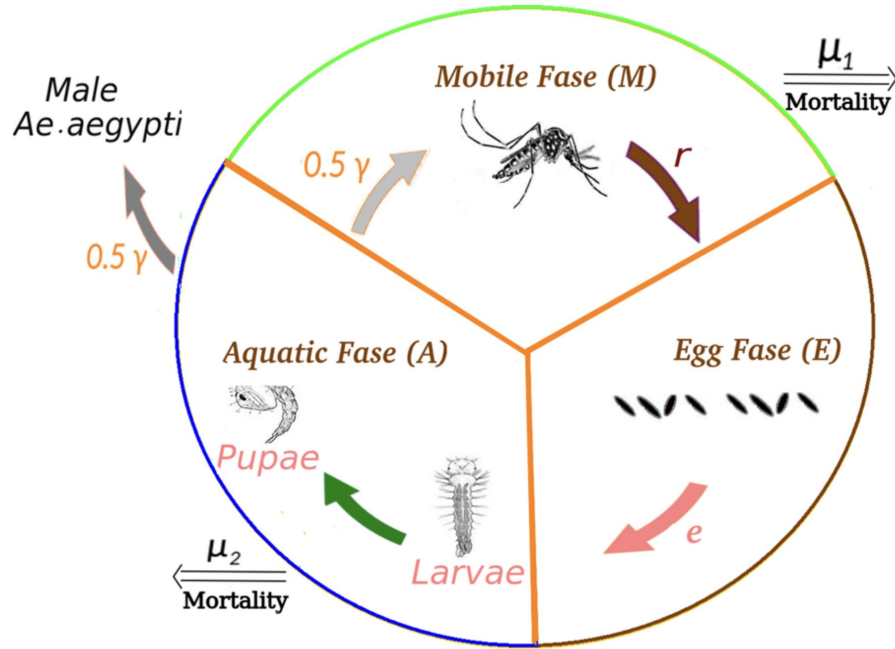


- The mosquito *Aedes aegypti* (Linnaeus, 1762) is the main transmitter vector for Dengue, Zika, Chikungunya and Yellow Fever
- Several factors influence its population dynamics: temperature, precipitation, human action, and others.

Modelling



System of PDEs



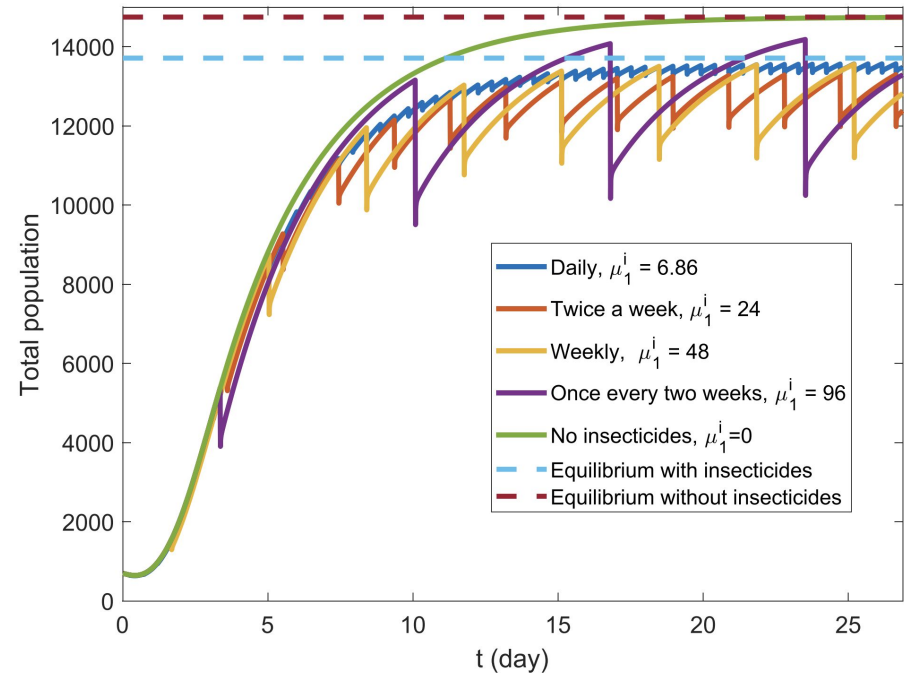
$$\begin{aligned}\frac{\partial F}{\partial t} &= \nabla \cdot (D \nabla F) + \gamma A - \mu_1 F, \\ \frac{\partial A}{\partial t} &= e \left(1 - \frac{A}{k}\right) E - (\mu_2 + \gamma) A, \\ \frac{\partial E}{\partial t} &= r F - (\mu_3 + e) E,\end{aligned}$$

Insecticide application

$$\begin{aligned}\frac{\partial F}{\partial t} &= \nabla \cdot (D \nabla F) + \gamma A - \mu_1 F, \\ \frac{\partial A}{\partial t} &= e \left(1 - \frac{A}{k}\right) E - (\mu_2 + \gamma) A, \\ \frac{\partial E}{\partial t} &= r F - (\mu_3 + e) E,\end{aligned}$$

Modeling and simulation of the spatial population dynamics of the *Aedes aegypti* mosquito with an insecticide application

Monalisa R. Silva^{1,2,3}, Pedro H. G. Lugão^{1,4} and Grigori Chapiro^{1,3*}  Abstract



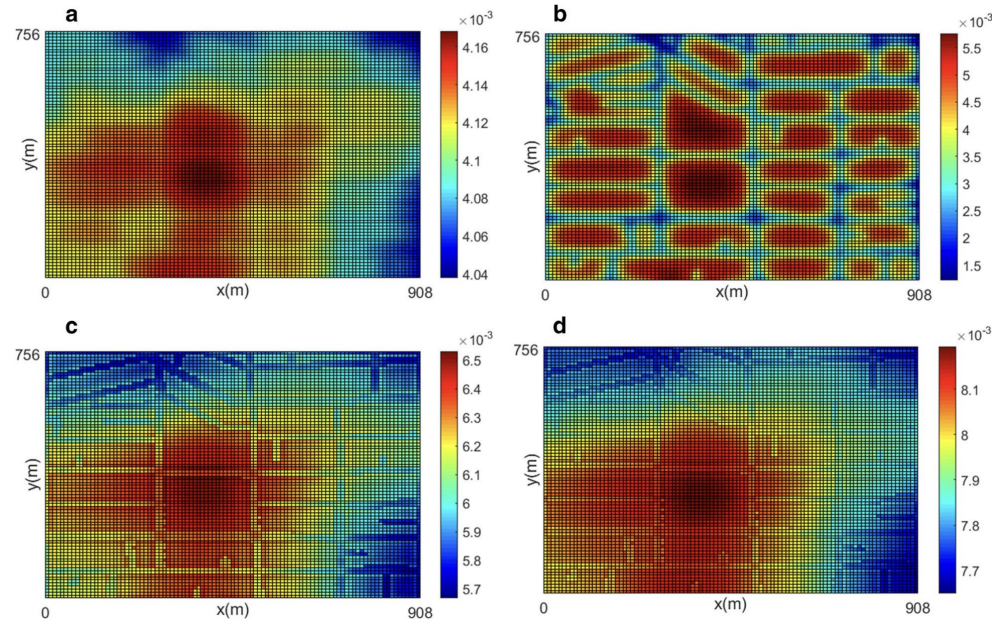
Insecticide application

Modeling and simulation of the spatial population dynamics of the *Aedes aegypti* mosquito with an insecticide application

Monalisa R. Silva^{1,2,3}, Pedro H. G. Lugão^{1,4} and Grigori Chapiro^{1,3*}  Abstract



$$\begin{aligned}\frac{\partial F}{\partial t} &= \nabla \cdot (D \nabla F) + \gamma A - \mu_1 F, \\ \frac{\partial A}{\partial t} &= e \left(1 - \frac{A}{k} \right) E - (\mu_2 + \gamma) A, \\ \frac{\partial E}{\partial t} &= r F - (\mu_3 + e) E,\end{aligned}$$

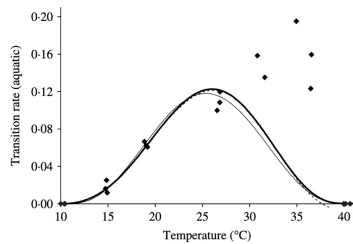
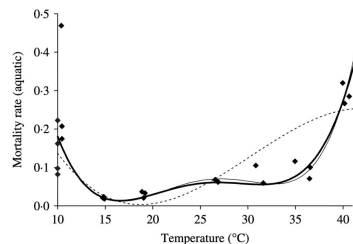


The reality is more heterogeneous! On time

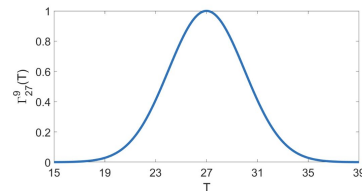
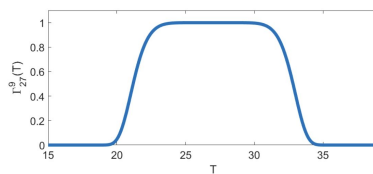
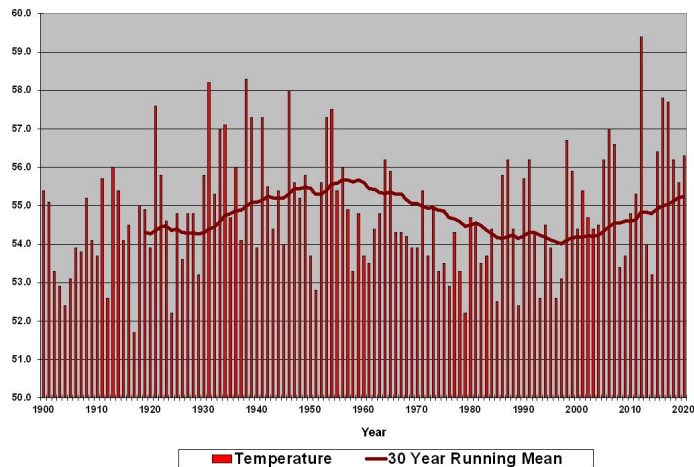
$$\frac{\partial F}{\partial t} = \nabla \cdot (D \nabla F) + \gamma A - \mu_1 F,$$

$$\frac{\partial A}{\partial t} = e \left(1 - \frac{A}{k} \right) E - (\mu_2 + \gamma) A,$$

$$\frac{\partial E}{\partial t} = r F - (\mu_3 + e) E,$$



Yang, HMI, et al. "Assessing the effects of temperature on the population of *Aedes aegypti*, the vector of dengue." *Epidemiology & Infection* 137.8 (2009): 1188-1202.



$$\mu_i(T) = (2 - \bar{\Gamma}_?^?(T)) \cdot \bar{\mu}_i.$$

$$\gamma(T) = 0.5596 \cdot \Gamma_?^?$$

The reality is more heterogeneous! On space

$$\begin{aligned}\frac{\partial F}{\partial t} &= \nabla \cdot (D \nabla F) + \gamma A - \mu_1 F, \\ \frac{\partial A}{\partial t} &= e \left(1 - \frac{A}{k}\right) E - (\mu_2 + \gamma) A, \\ \frac{\partial E}{\partial t} &= r F - (\mu_3 + e) E,\end{aligned}$$

$$\mu_i(T) = (2 - \bar{\Gamma}_?^?(T)) \cdot \bar{\mu}_i.$$

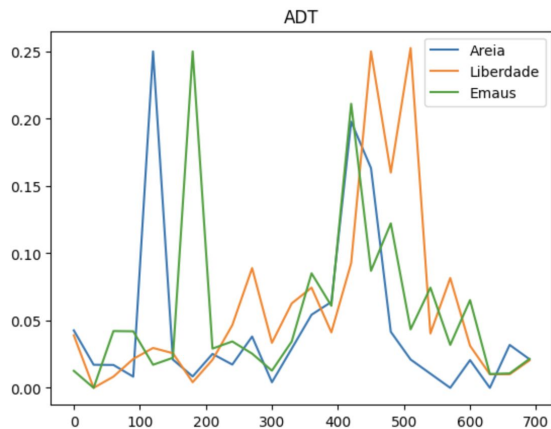
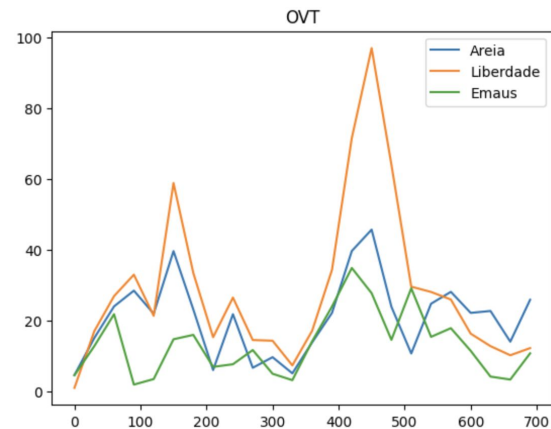
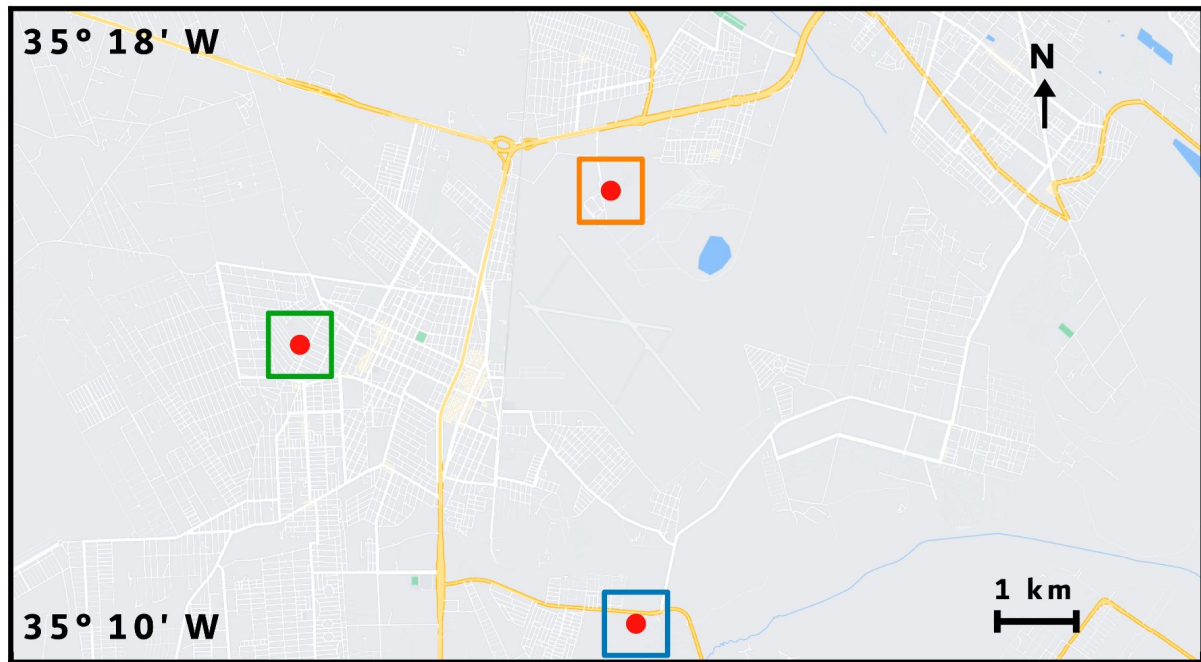


$$\mu_i(T) = (2 - \bar{\Gamma}_?^?(T)) \cdot \bar{\mu}_i.$$

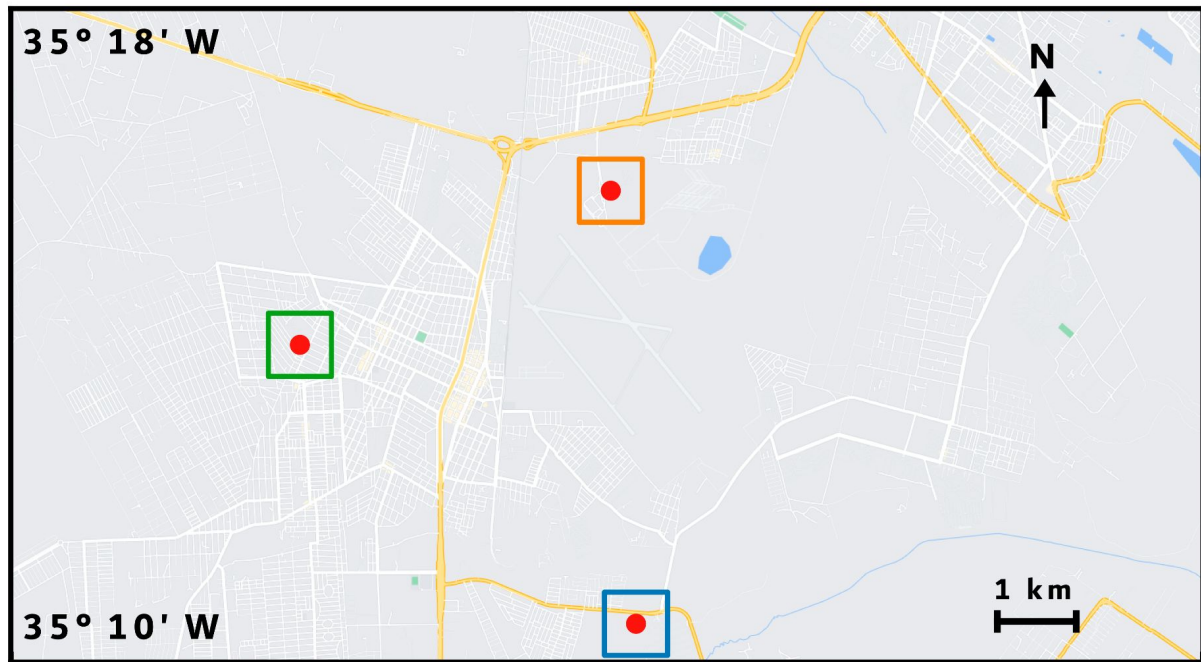


$$\mu_i(T) = (2 - \bar{\Gamma}_?^?(T)) \cdot \bar{\mu}_i.$$

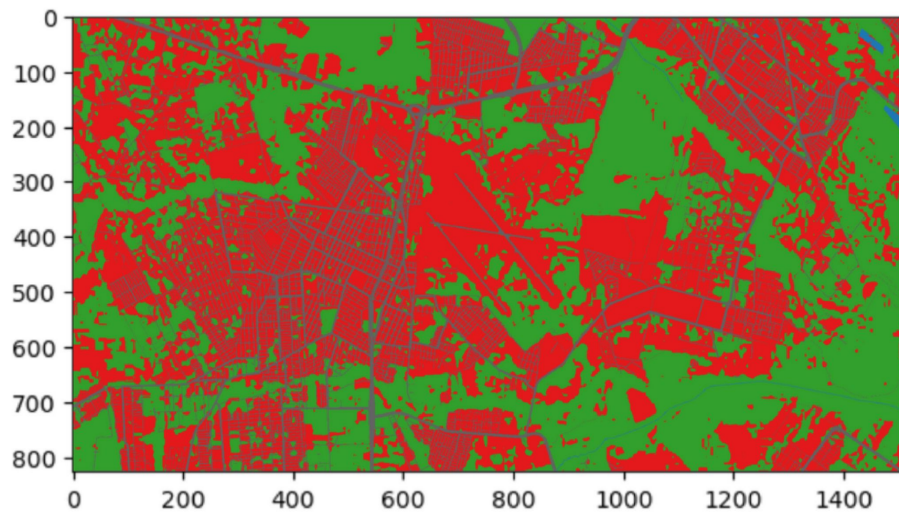
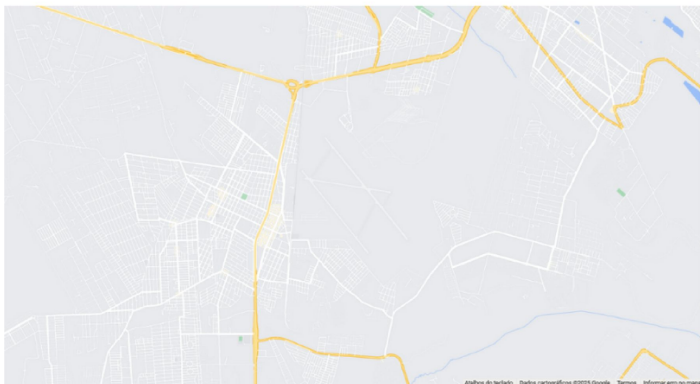
Our data



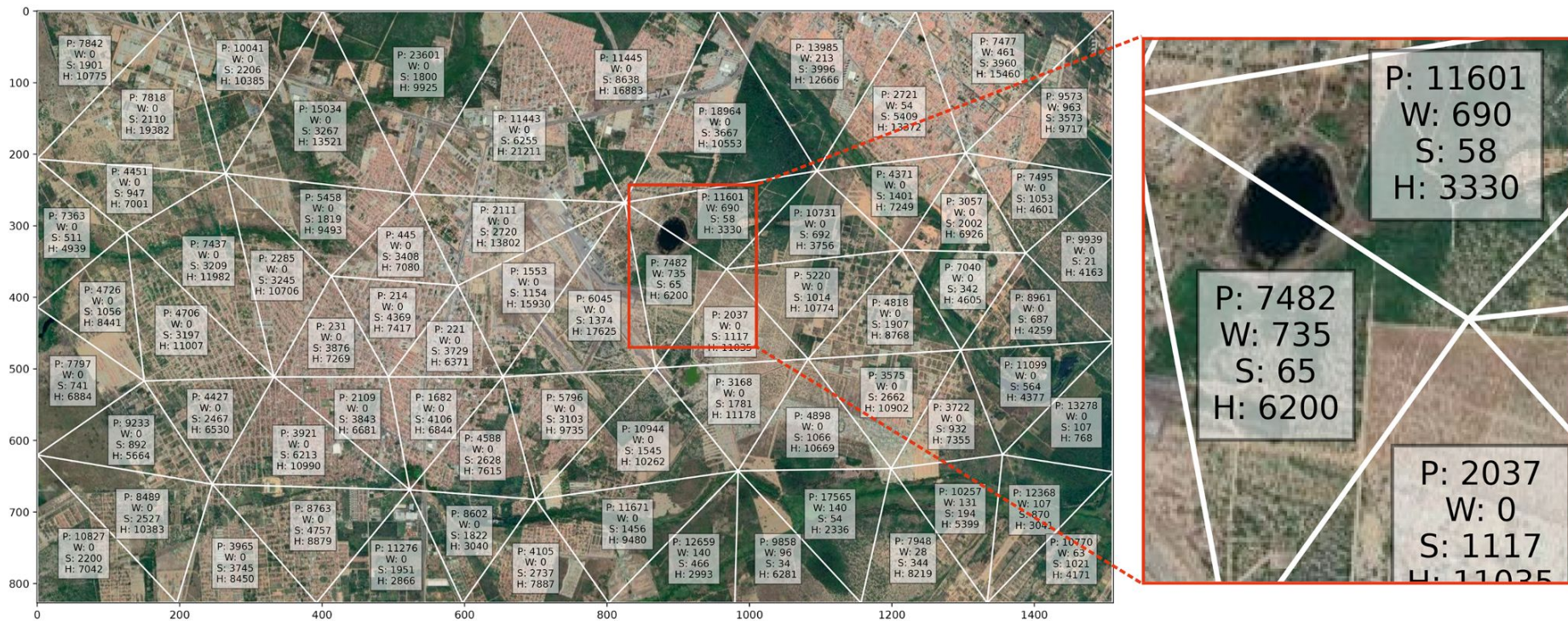
Our data



Preprocessing



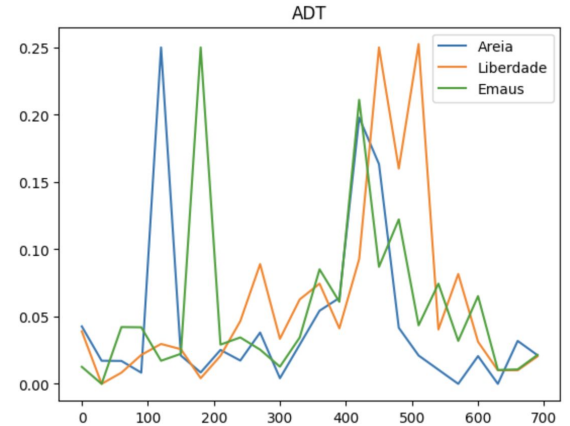
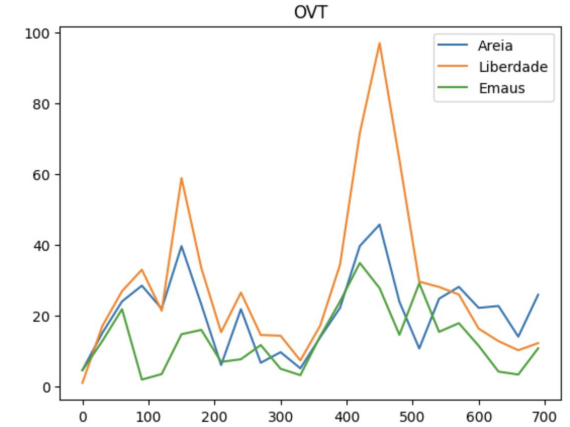
Preprocessing



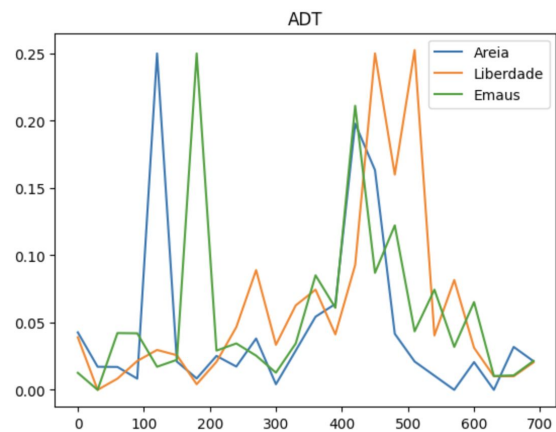
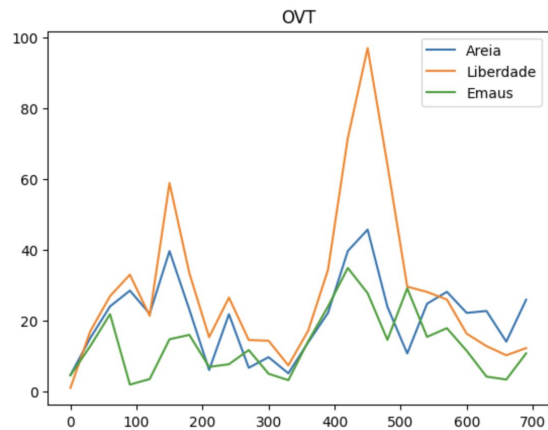
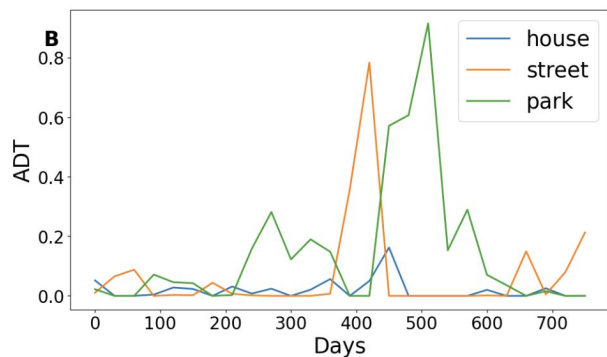
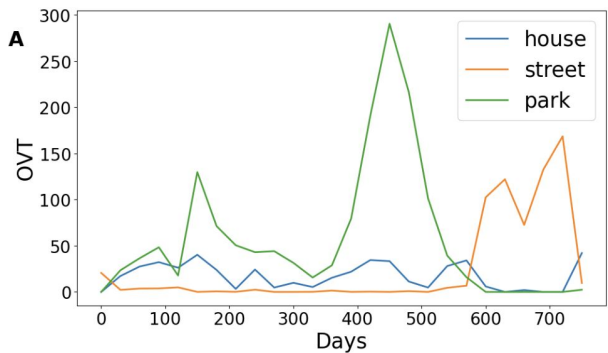
Recovering urban form curves

$$\begin{cases} 0.0671 OVT_p^E + 0.2013 OVT_s^E + 0.7314 OVT_h^E = OVT_{\text{emaus}}^R \\ 0.2632 OVT_p^E + 0.1239 OVT_s^E + 0.6128 OVT_h^E = OVT_{\text{liberdade}}^R \\ 0.0704 OVT_p^E + 0.1727 OVT_s^E + 0.7569 OVT_h^E = OVT_{\text{areia}}^R \end{cases}$$

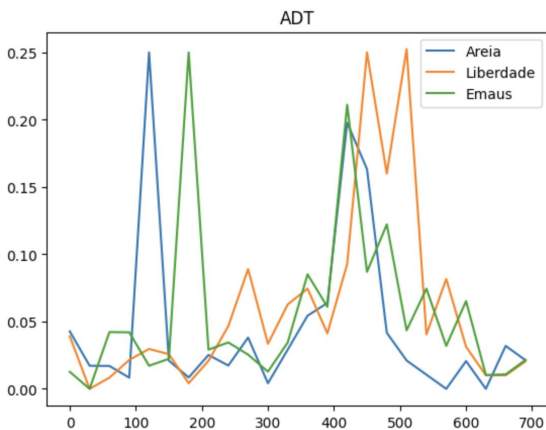
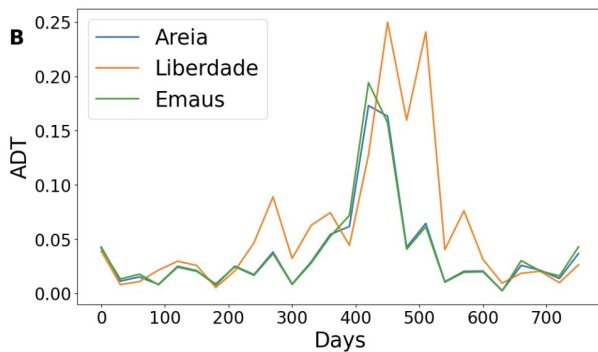
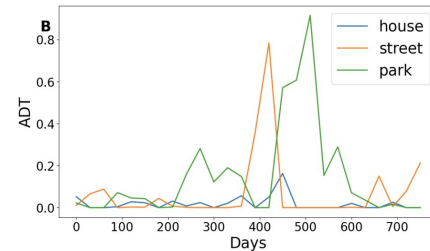
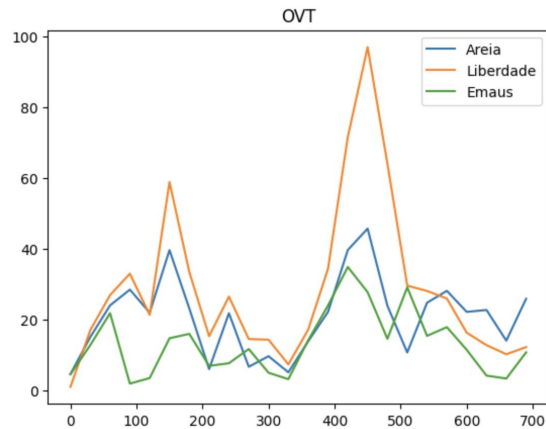
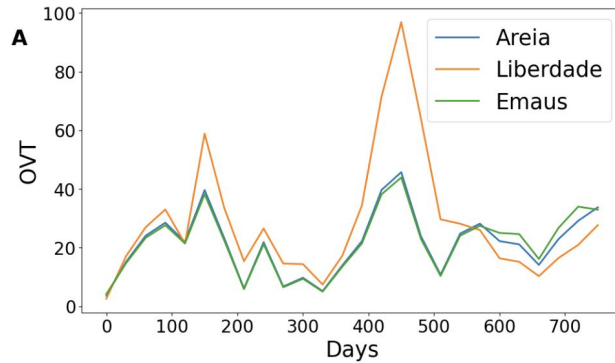
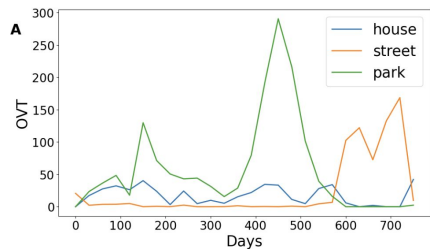
$$\begin{cases} 0.0671 ADT_p^E + 0.2013 ADT_s^E + 0.7314 ADT_h^E = ADT_{\text{emaus}}^R \\ 0.2632 ADT_p^E + 0.1239 ADT_s^E + 0.6128 ADT_h^E = ADT_{\text{liberdade}}^R \\ 0.0704 ADT_p^E + 0.1727 ADT_s^E + 0.7569 ADT_h^E = ADT_{\text{areia}}^R \end{cases}$$



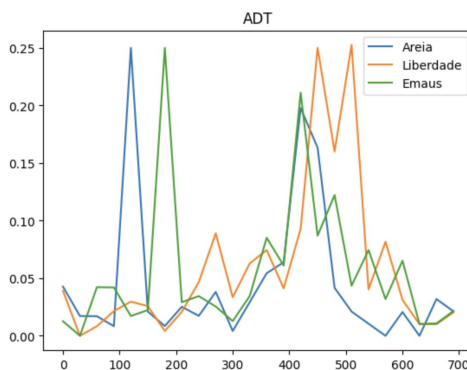
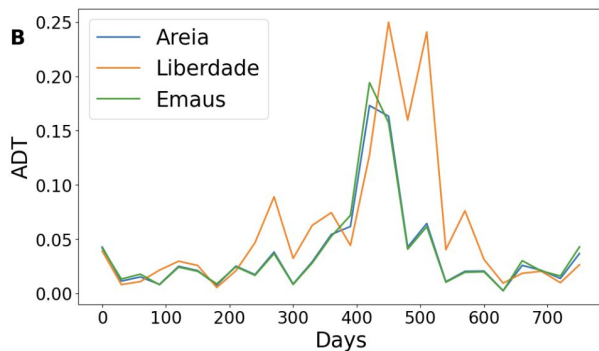
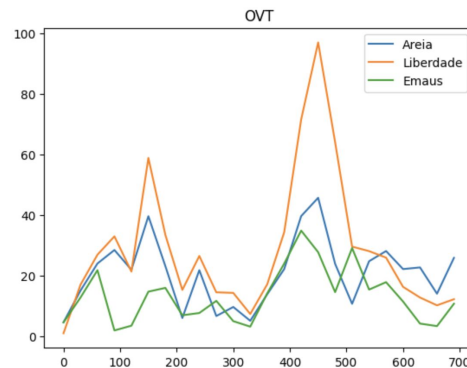
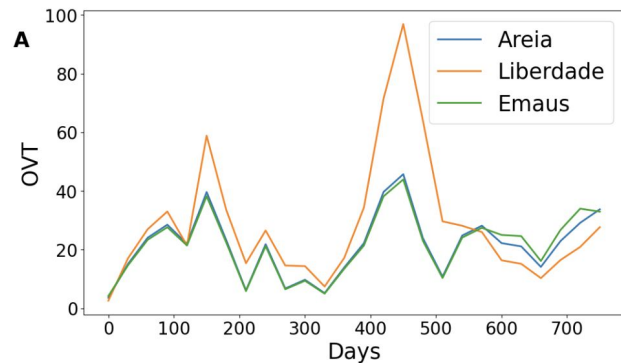
Recovering urban form curves



Recovering urban form curves



Recovering urban form curves



Region	Adults Correlation (ρ)	Eggs Correlation (ρ)
Areia	0.9712	0.9967
Emaus	0.7861	0.7277
Liberdade	0.9933	0.9984

Fitting urban form curves individually

Mechanistic PDE Framework

Three coupled developmental stages:

$$\begin{aligned}\frac{\partial F}{\partial t} &= \nabla \cdot (D \nabla F) + \gamma A - \mu_1 F \\ \frac{\partial A}{\partial t} &= e \left(1 - \frac{A}{k}\right) E - (\mu_2 + \gamma) A \\ \frac{\partial E}{\partial t} &= rF - (\mu_3 + e) E\end{aligned}$$

- D : spatial dispersal and urban boundaries
- μ_i, γ, e, r : climate-dependent biological rates
- $k(x)$: landscape-dependent carrying capacity

ODE Equilibrium-based Predictor

Basic offspring number:

$$Q_0 = \frac{\gamma e r}{\mu_1 (\mu_2 + \gamma) (\mu_3 + e)}$$

$$\begin{cases} Q_0 < 1 : & \text{population extinction} \\ Q_0 > 1 : & \text{positive equilibrium} \end{cases}$$

Stable winged population

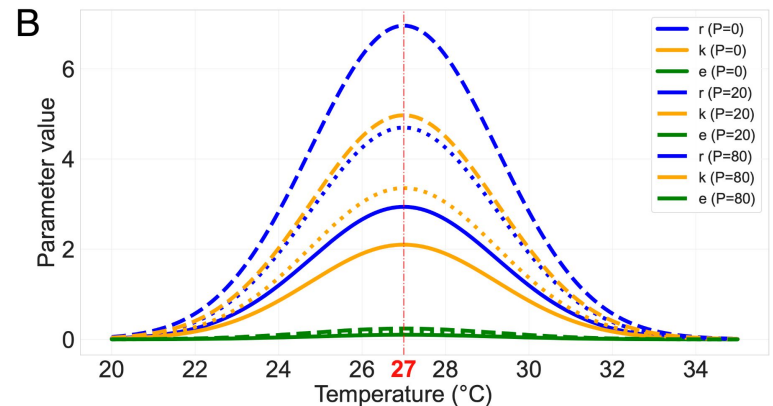
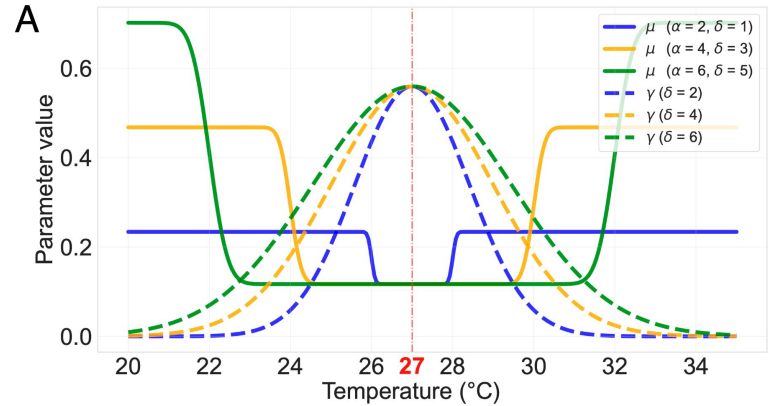
$$F^* = \frac{\gamma}{\mu_1} \left(1 - \frac{1}{Q_0}\right) k$$

Fitting urban form curves individually

- Temperature controls development and survival.
- Temperature and precipitation regulate reproduction and habitat suitability.
- For visualization, maximum activity occurs near the optimal temperature ($\nu = 27^{\circ}\text{C}$).
- Curves also controlled by deviation (δ) and scale factor (α).

Example: egg hatching response

$$e(T, P) = e_0 \Gamma_{\nu, \delta}^{\alpha}(T) \Phi(P)$$



Fitting urban form curves individually

Reparameterization Strategy

Directly optimizing the mathematical mean (ν) and scale (δ) can result in biologically impossible ranges. We reparameterize using physical thresholds:

$$T_{\max} = T_{\min} + f \cdot (T_{\text{upper}} - T_{\min})$$

Where:

- $T_{\min}$: Minimum temperature threshold below which development stops.
- $f \in [0.1, 1.0]$: Dimensionless fraction defining the width of the survival window.
- $T_{\text{upper}} = 40^{\circ}\text{C}$: Physical upper physiological survival limit.

Mathematical Translation: $\nu = \frac{T_{\min} + T_{\max}}{2}$ and $\delta = \frac{T_{\max} - T_{\min}}{2}$

Fitting urban form curves individually

Results:

Reparameterization Strategy

Directly optimizing the mathematical mean (ν) and scale (δ) can result in biologically impossible ranges. We reparameterize using physical thresholds:

$$T_{\max} = T_{\min} + f \cdot (T_{\text{upper}} - T_{\min})$$

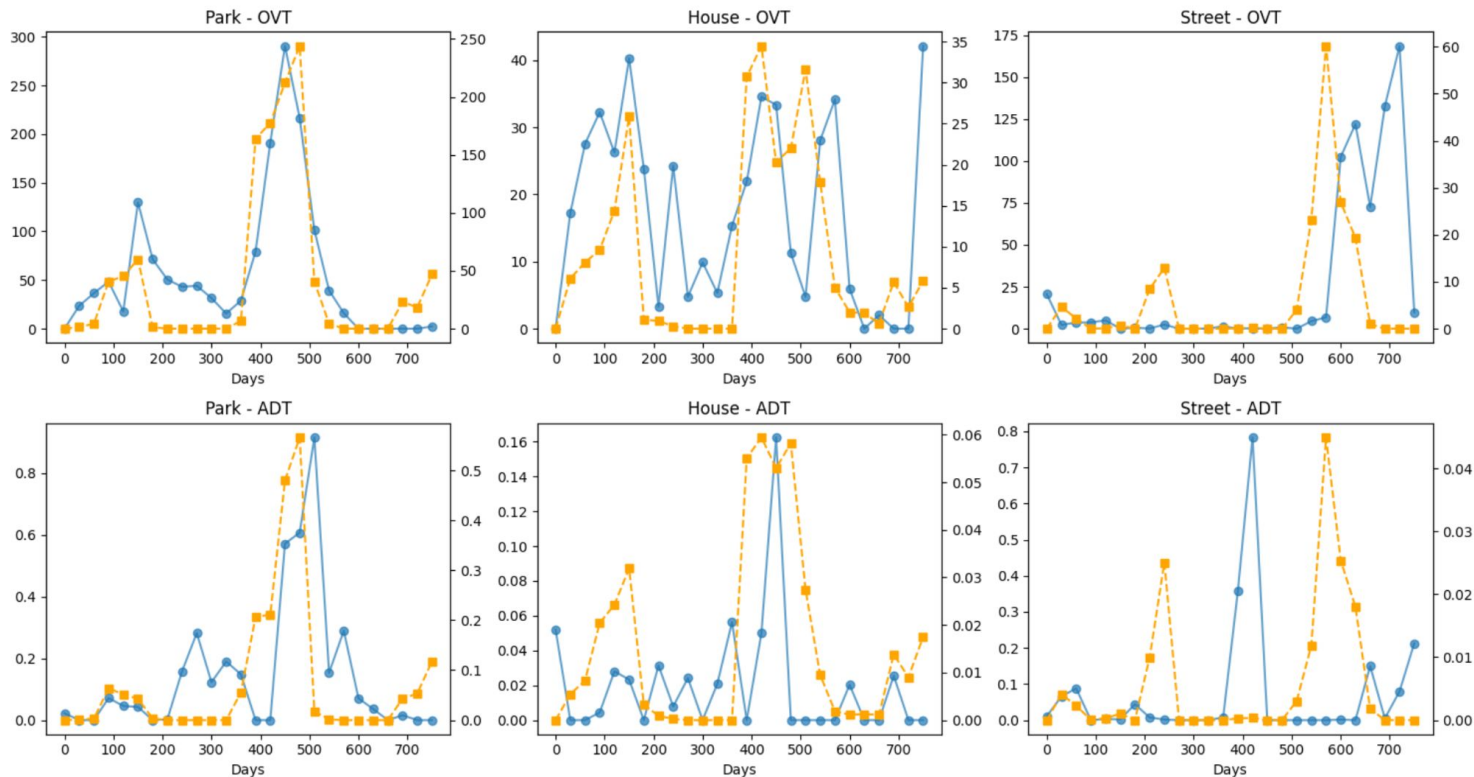
Where:

- $T_{\min}$: Minimum temperature threshold below which development stops.
- $f \in [0.1, 1.0]$: Dimensionless fraction defining the width of the survival window.
- $T_{\text{upper}} = 40^{\circ}\text{C}$: Physical upper physiological survival limit.

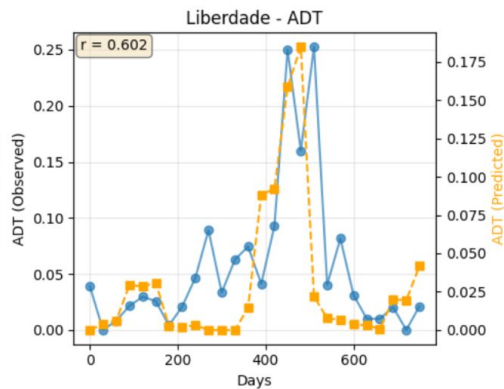
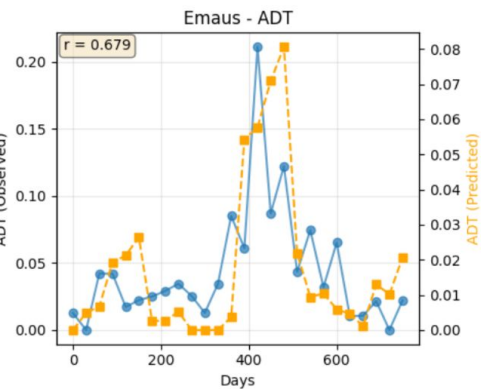
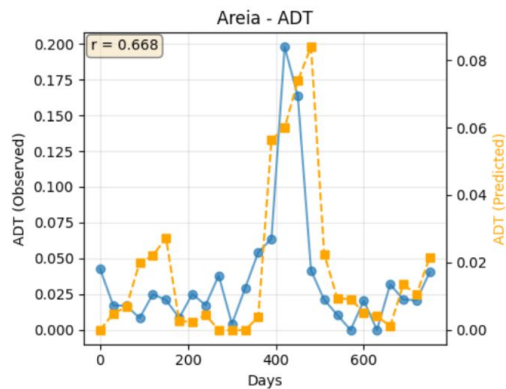
Mathematical Translation: $\nu = \frac{T_{\min} + T_{\max}}{2}$ and $\delta = \frac{T_{\max} - T_{\min}}{2}$

Parameter	Parnamirim		
	Park	House	Street
$T_{\min}^{\mu}$	8.2448	19.2819	0.1332
f^{μ}	0.8988	0.6813	0.3385
$T_{\min}^{\gamma}$	23.8327	15.8423	26.6386
f^{γ}	1.0000	0.4018	0.5922
$T_{\min}^r$	13.8021	12.9337	24.8497
f^r	1.0000	1.0000	0.1003
$T_{\min}^k$	33.3520	32.6983	13.1733
f^k	0.9998	1.0000	0.2343
$T_{\min}^e$	28.3857	27.3018	2.4106
f^e	0.2018	0.5304	0.7283
α	1.0000	1.0000	1.0007
$T_{\max}^{\mu}$	36.7867	33.3966	13.6268
$T_{\max}^{\gamma}$	40.0000	25.5483	34.5510
$T_{\max}^r$	40.0000	40.0000	26.3697
$T_{\max}^k$	39.9985	40.0000	19.4588
$T_{\max}^e$	30.7293	34.0374	29.7868

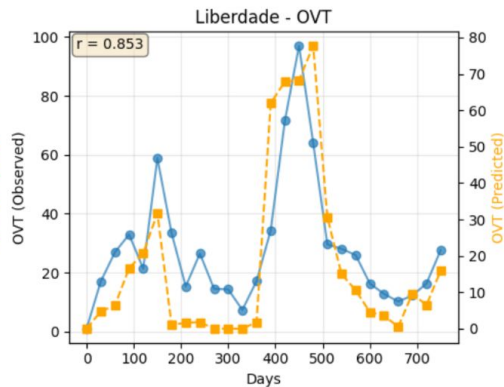
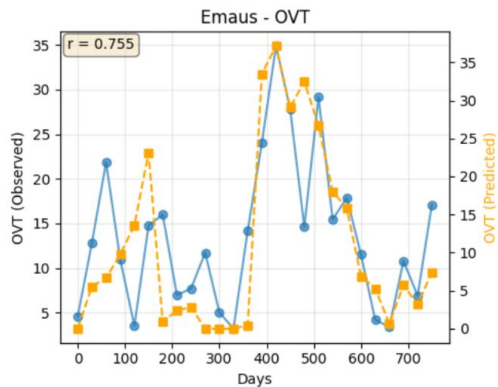
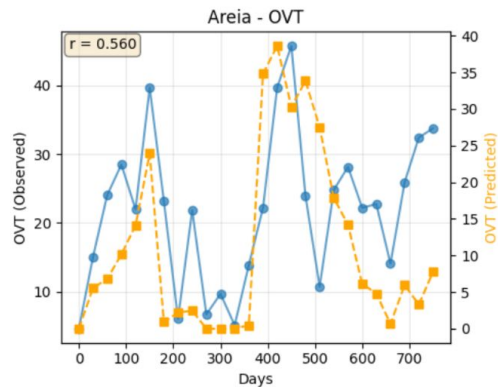
Fitting urban form curves individually



Reconstructing



(b) Parnamirim - ADT by neighborhood



Validation

City	District	OVT	ADT	OVT×ADT
Parnamirim	Areia	0.461	0.683	0.4444
	Emaús	0.749	0.775	0.6662
	Liberdade	0.799	0.730	0.5877
Santarém	Jd. Santarém	0.657	0.529	0.7507
	Republica	0.546	0.477	0.5701
	Santarenzinho	0.687	0.576	0.7316
Nova Iguaçu	Cabuçu	0.758	0.792	0.4581
	Ceramica	0.788	0.594	0.4272
	Moqueta	0.670	0.406	0.3477
D. de Caxias	Saracuruna	0.734	−0.130	0.3183
	Primavera	0.599	0.307	0.6925
	Bilac	0.724	0.229	0.5627
Campo Grande	Carlota	0.306	0.483	0.6346
	Guanandi	0.621	0.441	0.6383
	Planalto	0.533	0.639	0.6915

The districts in bold are used for testing; their data were not used during the training phase. Column OVT×ADT shows the correlation between the real OVT and ADT data.

City	District	Pearson
Parnamirim	Areia	0.527
	Emaús	0.684
	Liberdade	0.590
Santarém	Jd. Santarém	0.492
	Republica	0.428
	Santarenzinho	0.409
Campo Grande	Carlota	0.209
	Guanandi	0.344
	Planalto	0.403
Duque de Caxias	Bilac	0.692
	Primavera	0.556
	Saracuruna	0.619
Nova Iguaçu	Cabuçu	0.793
	Ceramica	0.567
	Moqueta	0.496

The cities in bold were not used in the training phase.

Questions?

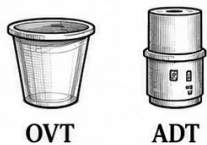
Spatial and temporal prediction of *Aedes aegypti* populations with atmospheric and urban forms dependence

Pedro H. G. Lugo , Monalisa R. da Silva , Raphael Cascelli , and Grigori Chapiro  [Authors Info & Affiliations](#)

FROM DATA TO PREDICTIONS

1. DATA INPUT

Entomological data
(ovitrap and adult traps)



OVT

ADT

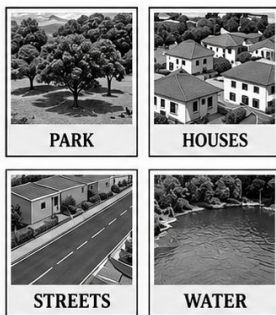
+



Geographic
coordinates

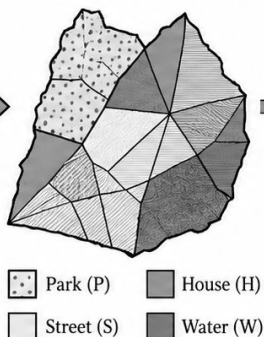
2. LANDSCAPE CLASSIFICATION

Google Maps imagery
automatically classified
into 4 categories



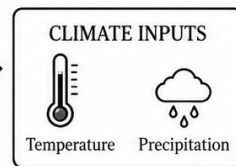
3. SPATIAL DECOMPOSITION

Proportion of each
landscape type in each
measurement subregion



4. PARAMETER ESTIMATION

Calibrate a climate-driven
mechanistic model for
each landscape type
using field data

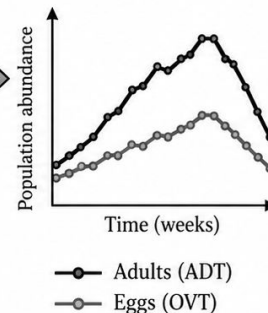


Optimize biological
parameters



5. PREDICTIONS

Model generates population
trajectories for each landscape
and aggregates them
according to local
composition



Validated across neighborhoods and cities

