The Potential of Mathematical Modeling to Advance the Sterile Insect Technique for *Aedes aegypti* Control and Dengue Prevention

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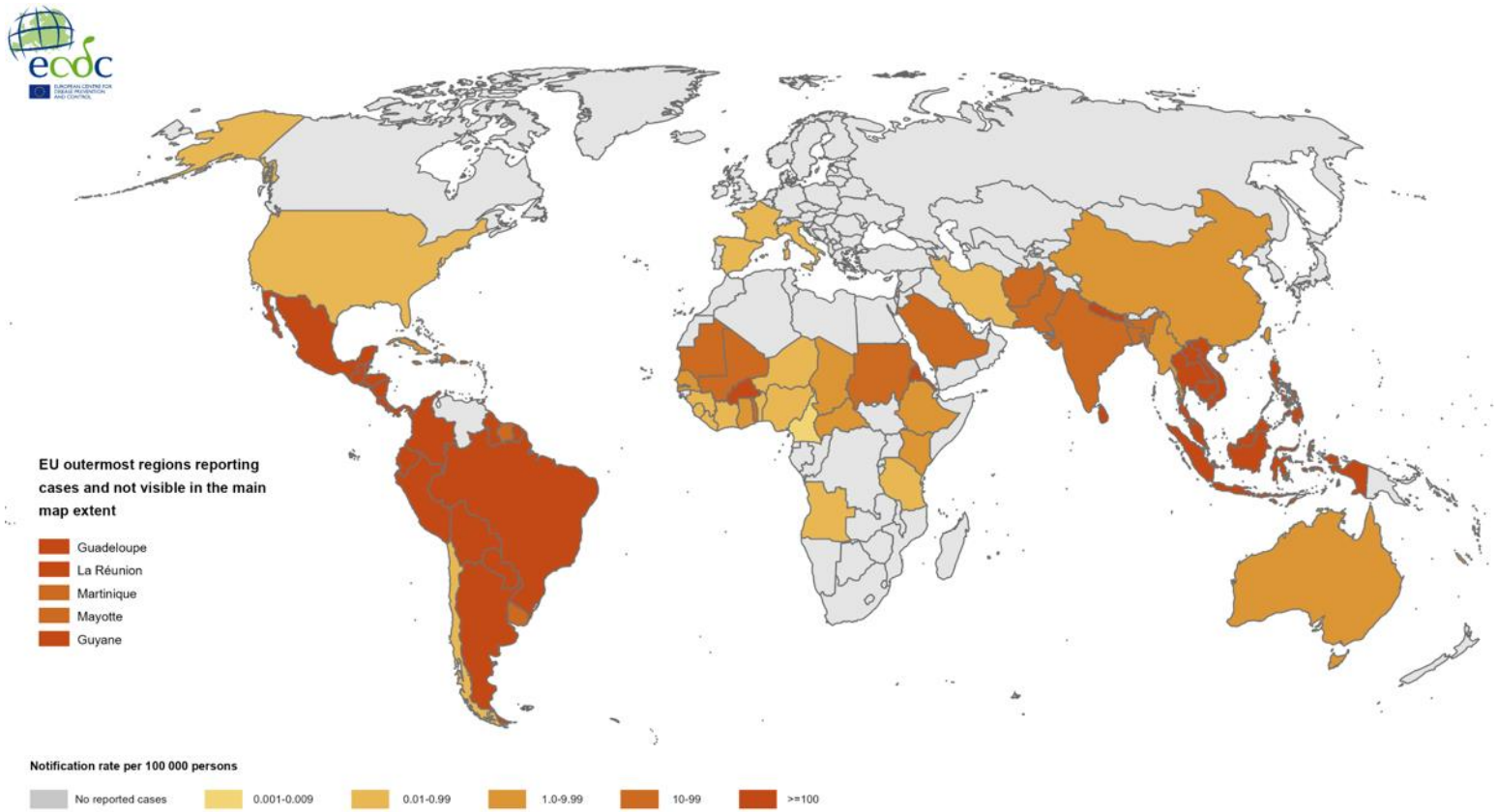
The Arboviral Threat

Dengue virus disease case notification rate per 100 000 population, January–December 2024



Vector-borne diseases remain a global health challenge.

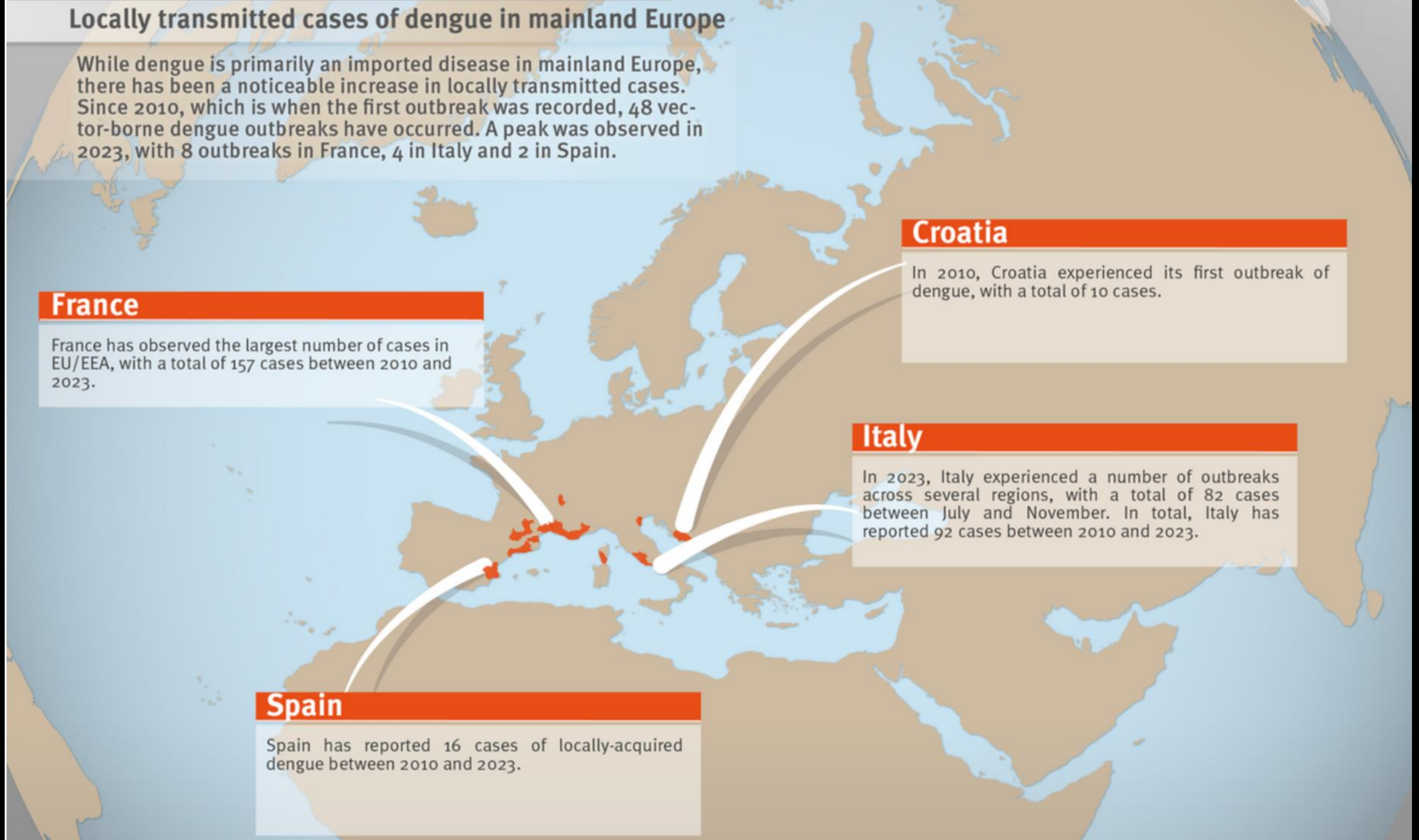
- *Aedes aegypti* is the main vector of dengue, Zika, and chikungunya in the Americas.

- In Europe, *Aedes albopictus* is rapidly expanding its range, increasing transmission risk.

- Conventional control methods are often inadequate or unsustainable.

Locally transmitted cases of dengue in mainland Europe

While dengue is primarily an imported disease in mainland Europe, there has been a noticeable increase in locally transmitted cases. Since 2010, which is when the first outbreak was recorded, 48 vector-borne dengue outbreaks have occurred. A peak was observed in 2023, with 8 outbreaks in France, 4 in Italy and 2 in Spain.



France

France has observed the largest number of cases in EU/EEA, with a total of 157 cases between 2010 and 2023.

Croatia

In 2010, Croatia experienced its first outbreak of dengue, with a total of 10 cases.

Italy

In 2023, Italy experienced a number of outbreaks across several regions, with a total of 82 cases between July and November. In total, Italy has reported 92 cases between 2010 and 2023.

Spain

Spain has reported 16 cases of locally-acquired dengue between 2010 and 2023.

Aedes albopictus, May 2023

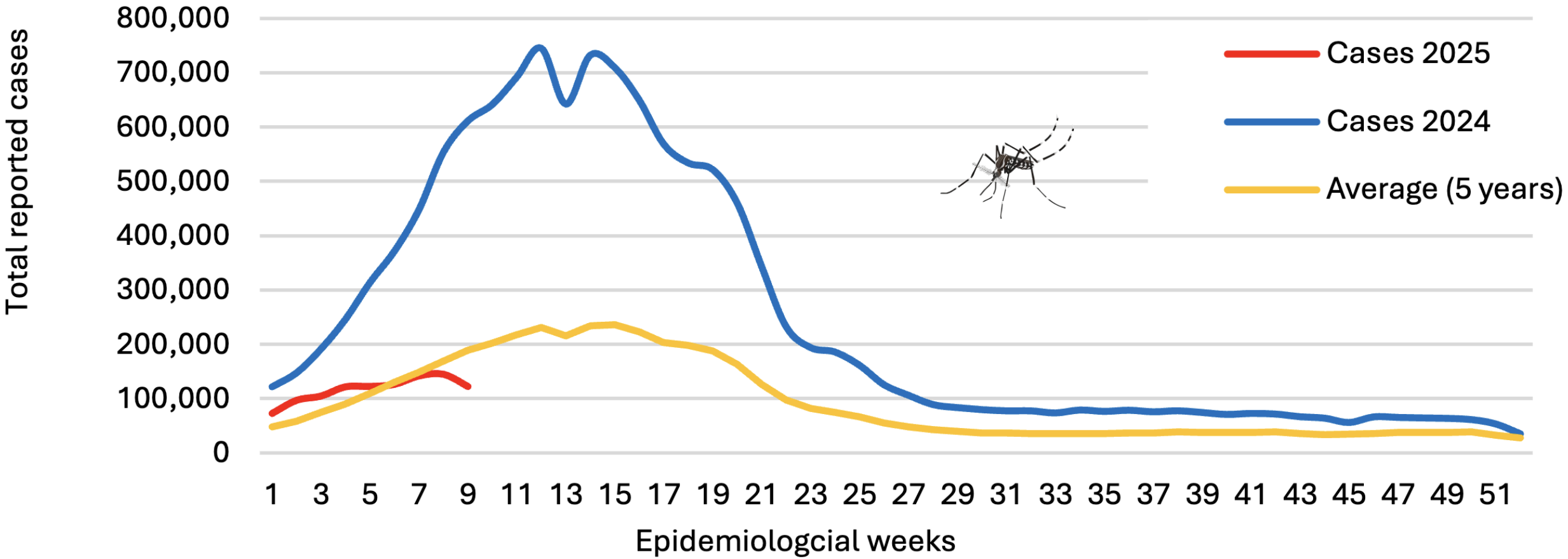
Legend

- Established
- Introduced
- Absent
- No data
- Unknown

Countries/Regions not viewable in the main map extent*

- Malta
- Monaco
- San Marino
- Gibraltar
- Liechtenstein
- Azores (PT)
- Canary Islands (ES)
- Madeira (PT)
- Jan Mayen (NO)

Figure 1. Suspected dengue cases as of EW 9 in 2025 and 2024, and average of the last 5 years. Region of the Americas



Report on the epidemiological situation of dengue in the Americas

As of epidemiological week 9, 2025. Update: March 20, 2024, 14:00 PM (GMT-5)

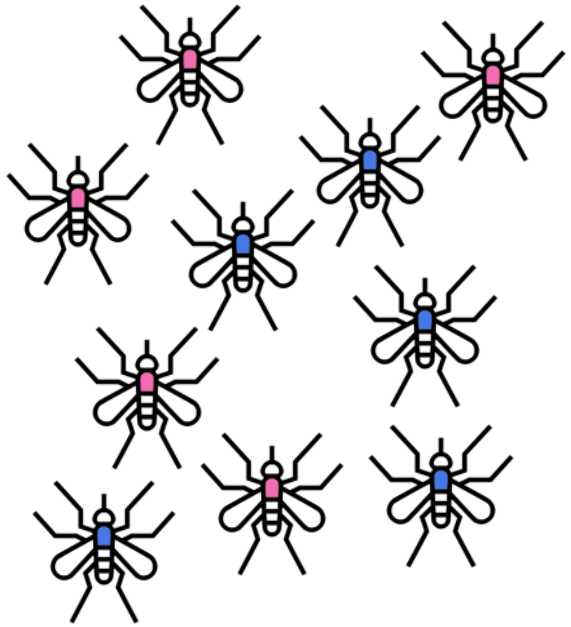
Current control methods

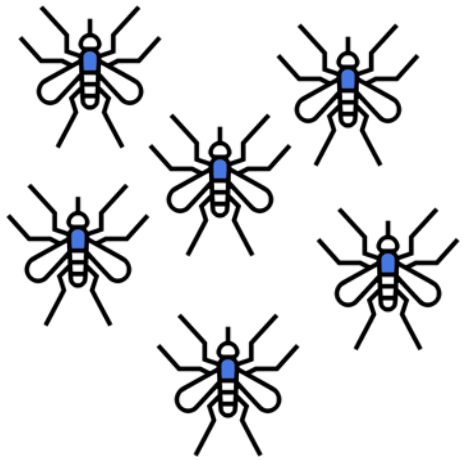
1. Larval Source Management
2. Larvicides: Biological (e.g., Bti), or chemical: IGRs
3. Insecticides: residual, space spraying, treated nets

Addressing challenges: the imperative for innovation

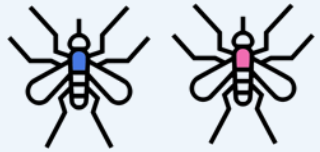
1. Operational issues in the context of new urban environments
2. Resistance to insecticides
3. Enviromental pollution and non-terget effect of pesticides
4. High economical cost
5. Impact of climate change

insect mass rearing → sex sorting * → modification





irradiation	Wolbachia	genetic engineering
		
↓	↓	
field release		
↓	↓	
population suppression	population suppression	population suppression
	or	or
	population replacement	population replacement



MASS REARING & RELEASE TECHNOLOGIES

SIT

IIT

GMOs

Progress in the evaluation of mass rearing technologies for *Aedes* control

Notable initiatives are ongoing: Brazil, China, Cuba, France, Germany, Greece, Italy, La Reunion, Mexico, Sri Lanka, Portugal, Spain, Switzerland, Thailand, USA

Effective implementation requires a deep understanding of biological and ecological processes

Field experimentation is time and resources demanding

A number of parameters should be controlled to obtain success

SIT implementation: key questions

How many mosquitoes

How often

How long

How many points

The strategy

SIT implementation: key questions

How many mosquitoes 5 – 10 sterile per wild males?

How often

How long

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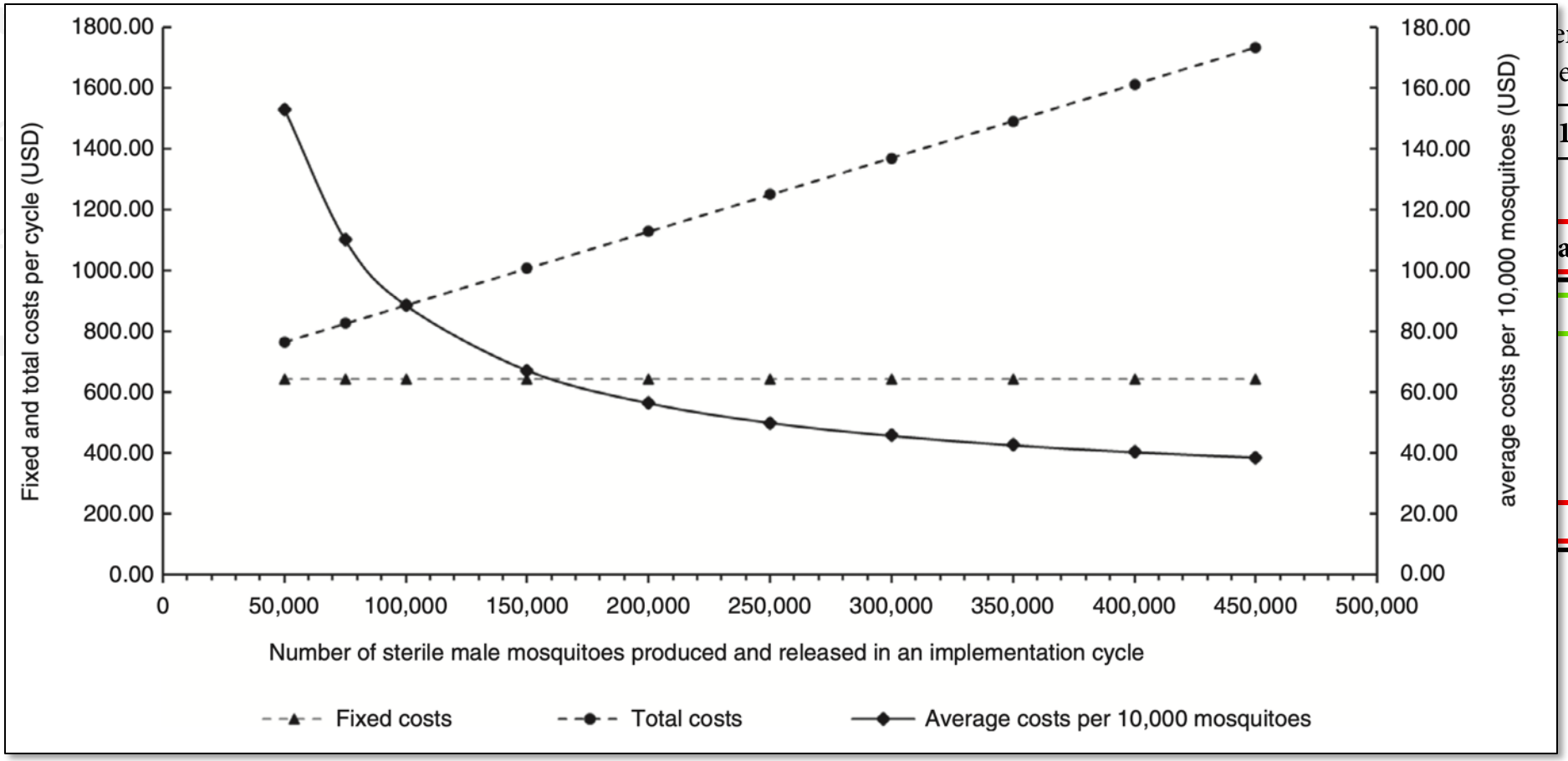
TABLE 4 Cost (USD) per 10,000 sterile male mosquitoes released, per hectare covered, and per inhabitant, in an implementation cycle utilising 85% of the installed production capacity, in function of the number released per hectare. Havana, Pedro Kourí Institute of Tropical Medicine, 2021.

Number of mosquitoes released per hectare	Number of hectares covered	Cost per 10,000 mosquitoes released	Cost per hectare covered	Cost per 100 inhabitants	
				25 inh./ha[a]	500 inh./ha
500	765	53.99	2.70	10.80	0.54
1500	255	41.06	6.16	24.64	1.23
2500	148	38.47	9.62	38.48	1.92
3500	106	37.36	13.08	52.32	2.62
4500	85	36.74	16.54	66.16	3.31

[a]inh./ha: inhabitants per hectare.

SIT implementation: key questions

How many mosquitoes 5 – 10 sterile per wild males?



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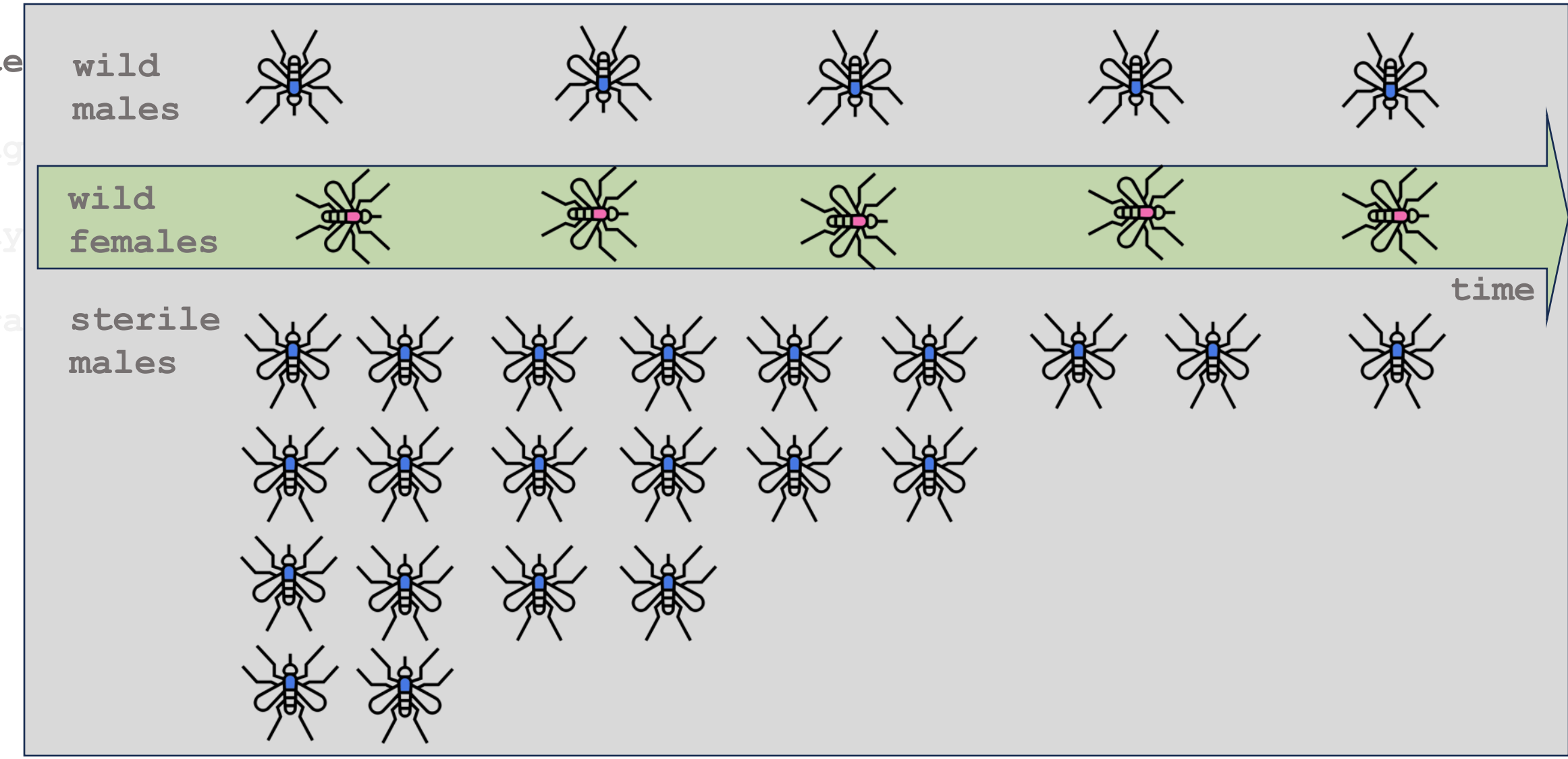
Survival of sterile mosquitoes into the field



SIT implementation: key questions

How many mosquitoes

How often

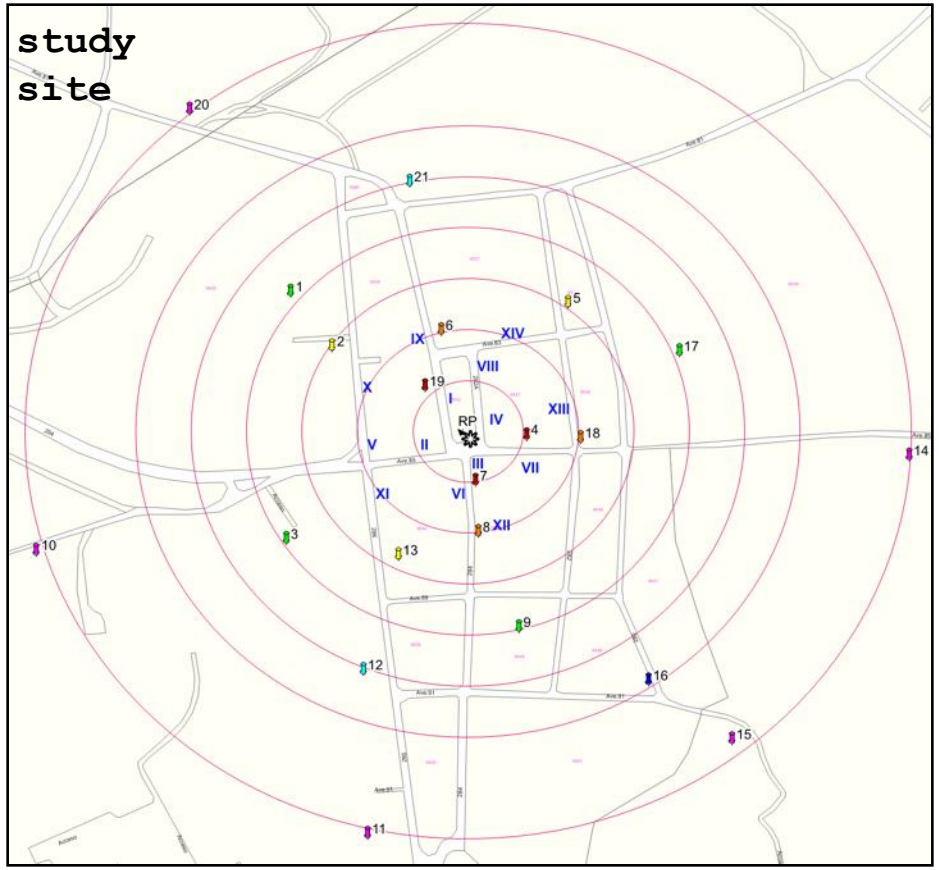
How long should mosquitoes be released for?

How many points: How far apart should the release points be?

The strategy

SIT implementation: key questions

The answer of biology: mark – release –recapture trials



Monitoring system

Roman numbers (blue): eggs traps

Symbols: BG-Sentinel traps

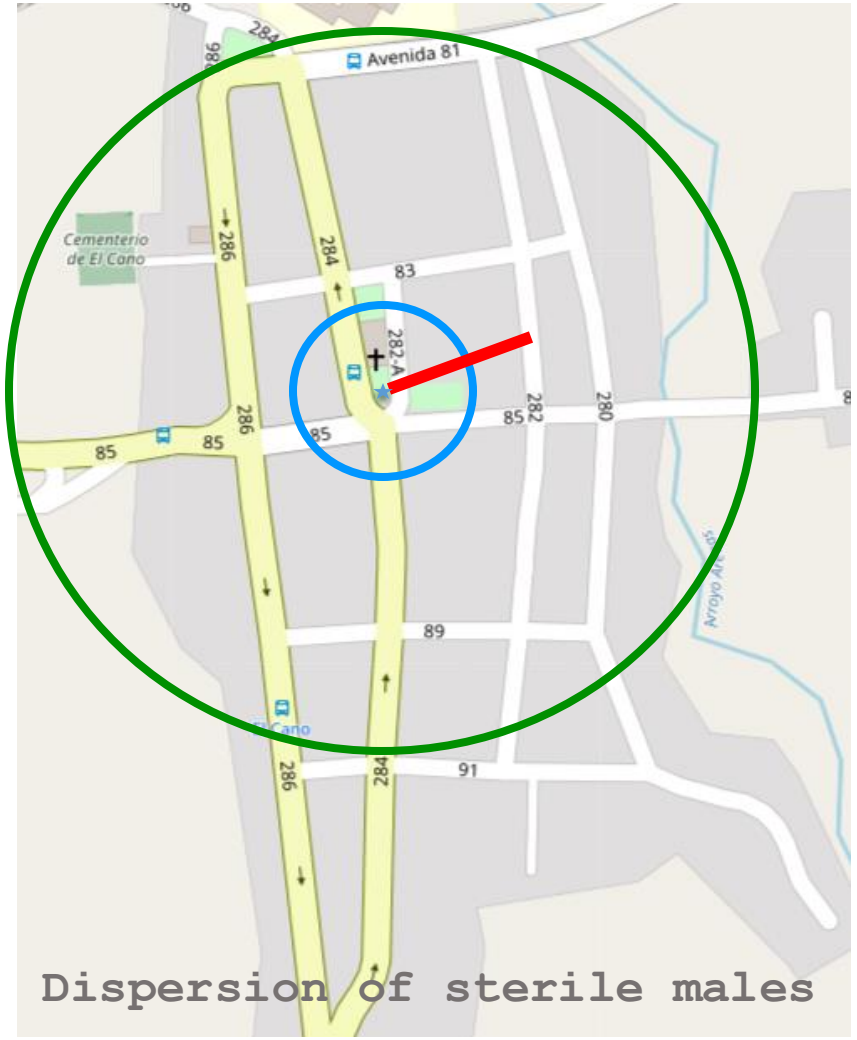
Sterile mosquitoes

- Dispersion
- Diffusion
- Survival
- Mating competitiveness

Mosquitoes wild population

- Abundance

The answer of biology: mark – release –recapture trials



Dispersion of sterile males

Dispersal of sterile males into the field

- Mean distance traveled: **100 m**
- Fly range$_{50}$: 57 m
- Fly range$_{90}$: 250 m

Survival of sterile *Ae. aegypti* males in field

- Probability of daily Survival (PDS): 0,81 (SD 0,01)
- Mean lifespan expectancy (ALE): **3,48 days**
- Max time of survival (t max): 15 days

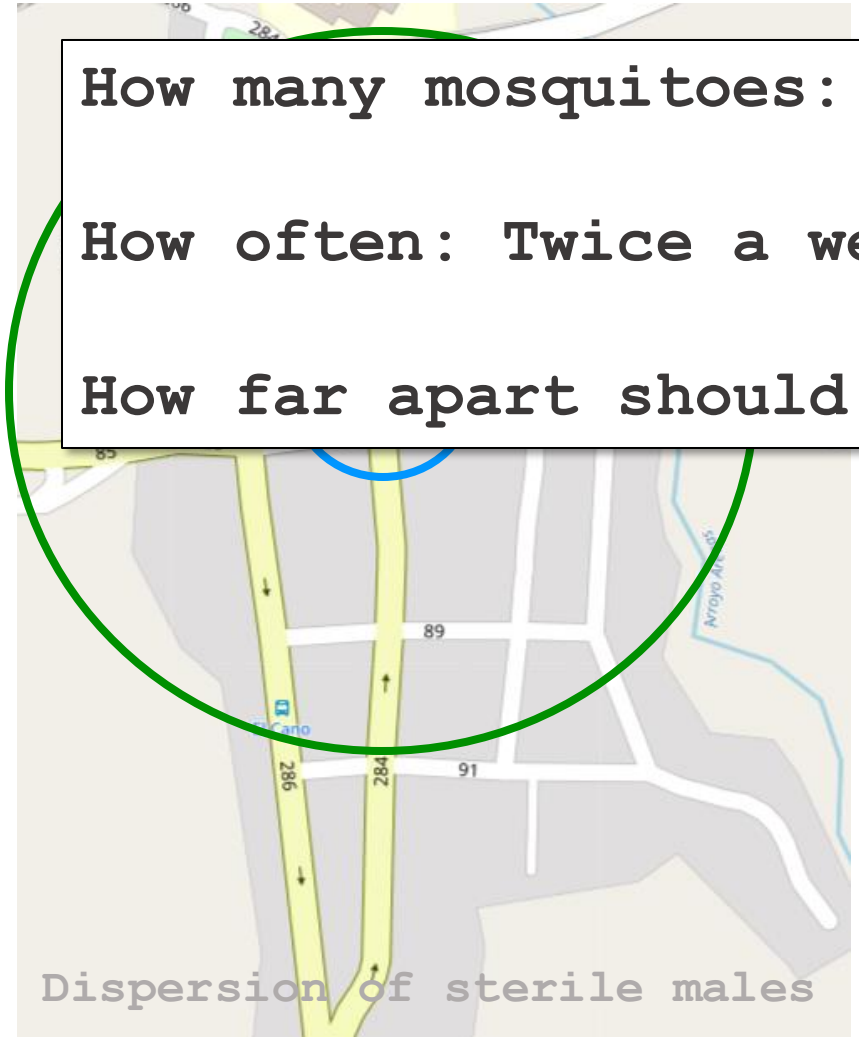
Sterile mating competitiveness into the field

- Sterile to wild ratio: 6.1
- Fried index: **0,56**

Abundance of wild mosquito population

- **108 males/ Ha** = 6 males/ house = 1.44 males/ person

The answer of biology: mark – release –recapture trials



Dispersion of sterile males

How many mosquitoes: 1000 sterile males /Ha

How often: Twice a week

How far apart should the release points be? 200 meters

Dispersal of sterile males into the field

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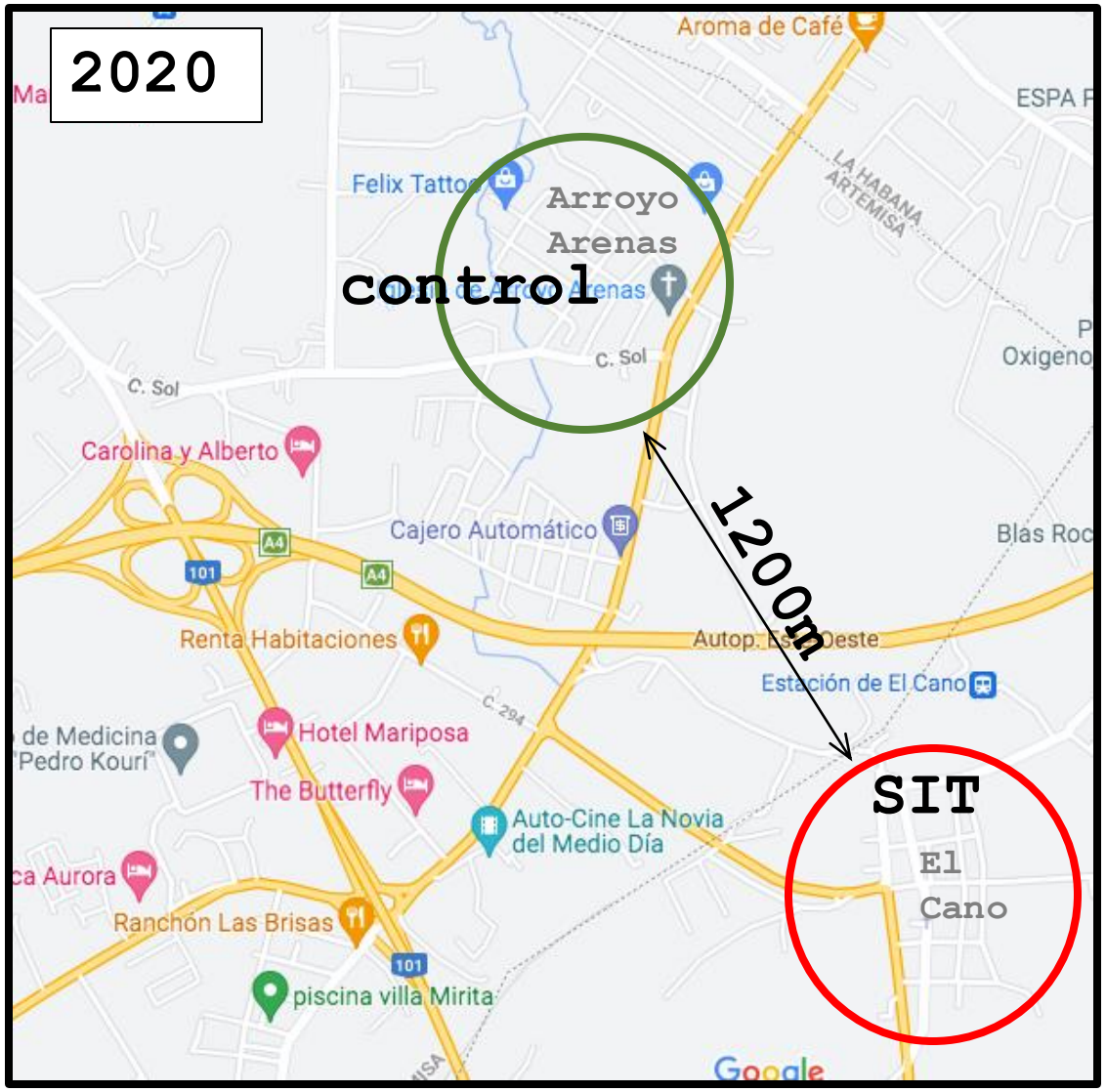
Cuba experience in evaluating SIT for mosquito control

Open field study: crossover



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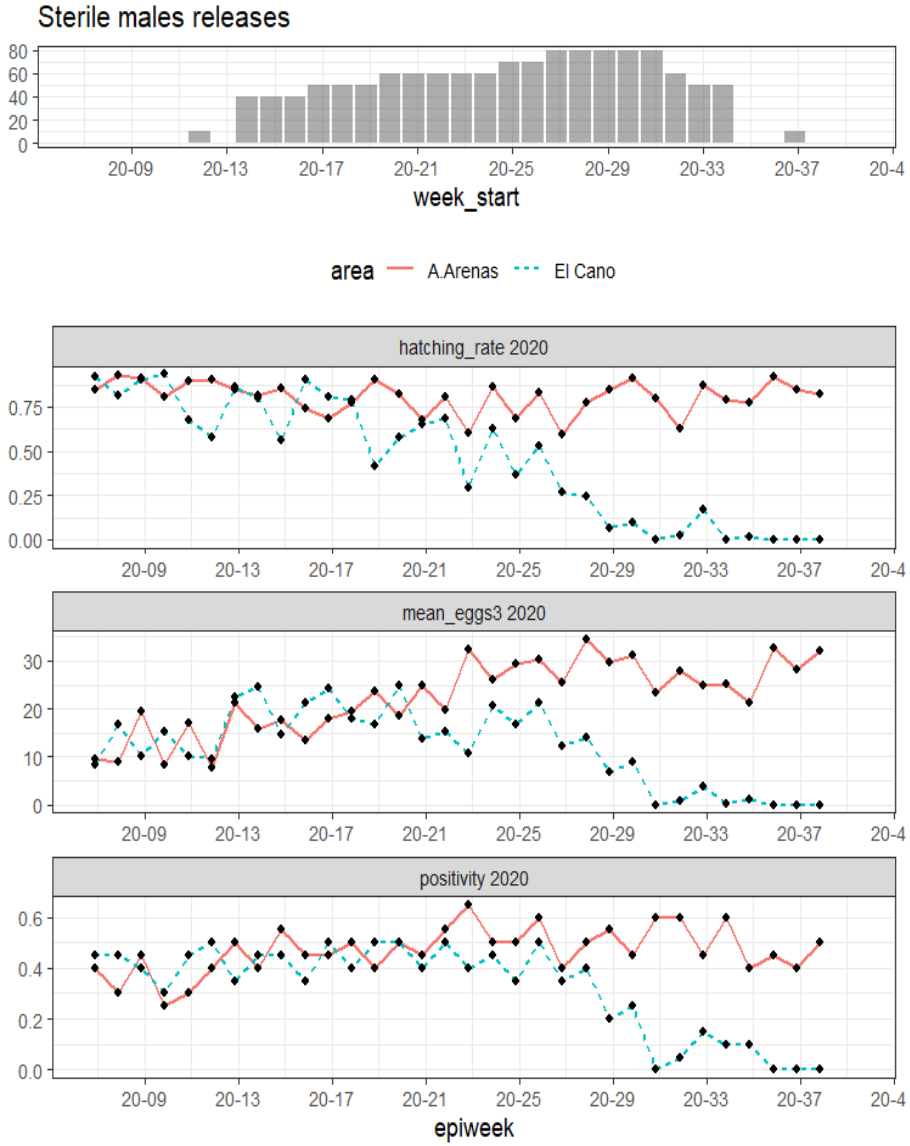
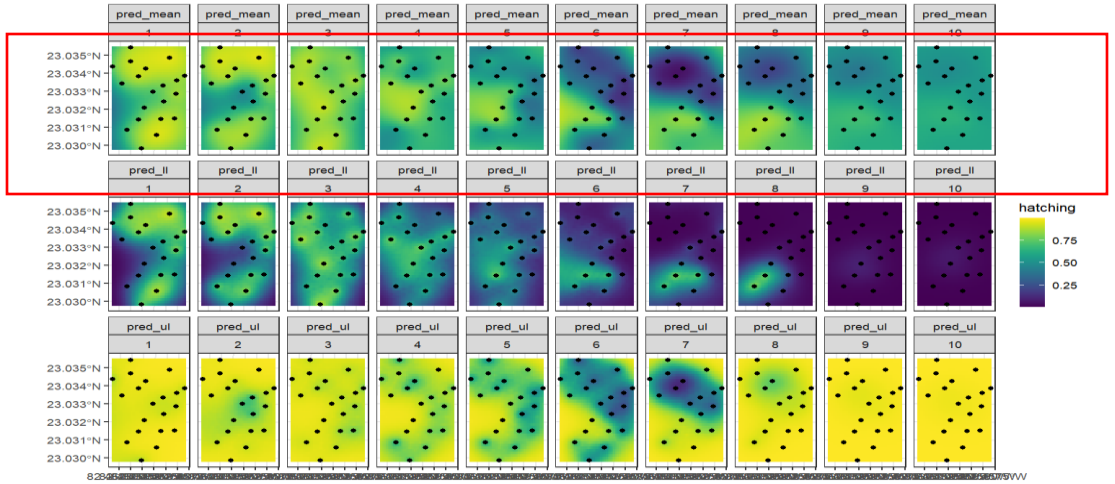
Open field study: crossover



Cuba experience in evaluating SIT for mosquito control

Open field study: crossover. Spatial-temporal analysis

A) SIT area (El Cano,2020)



Estimates of the hatching rate in the SIT area (El Cano or A.Arenas), each month in 2020 and 2023, respectively.

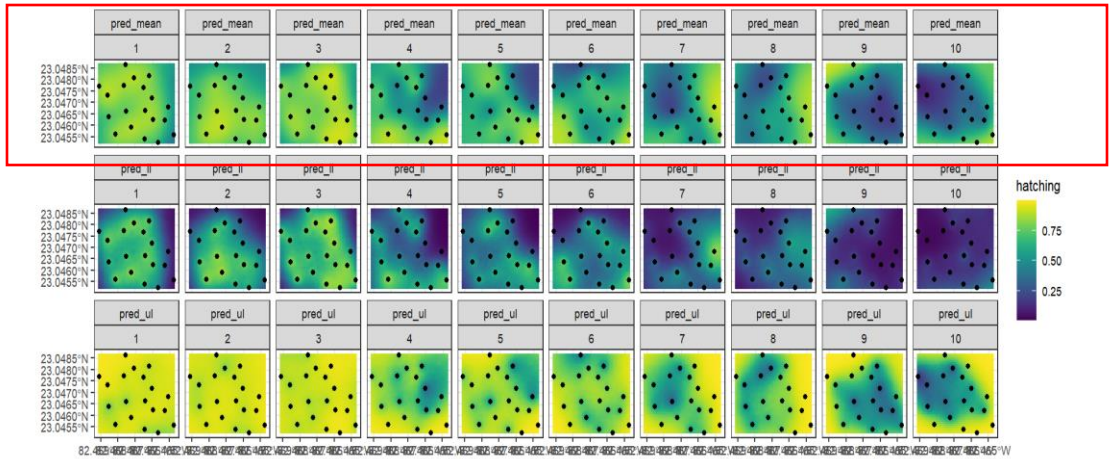
1st row: posterior means of predicted values,

2nd row: lower limit

3rd row: upper limits of the predicted values.

Shows a temporal decrease in the hatching rate with some spatial heterogeneity.

B) SIT area (Arroyo Arenas,2023)



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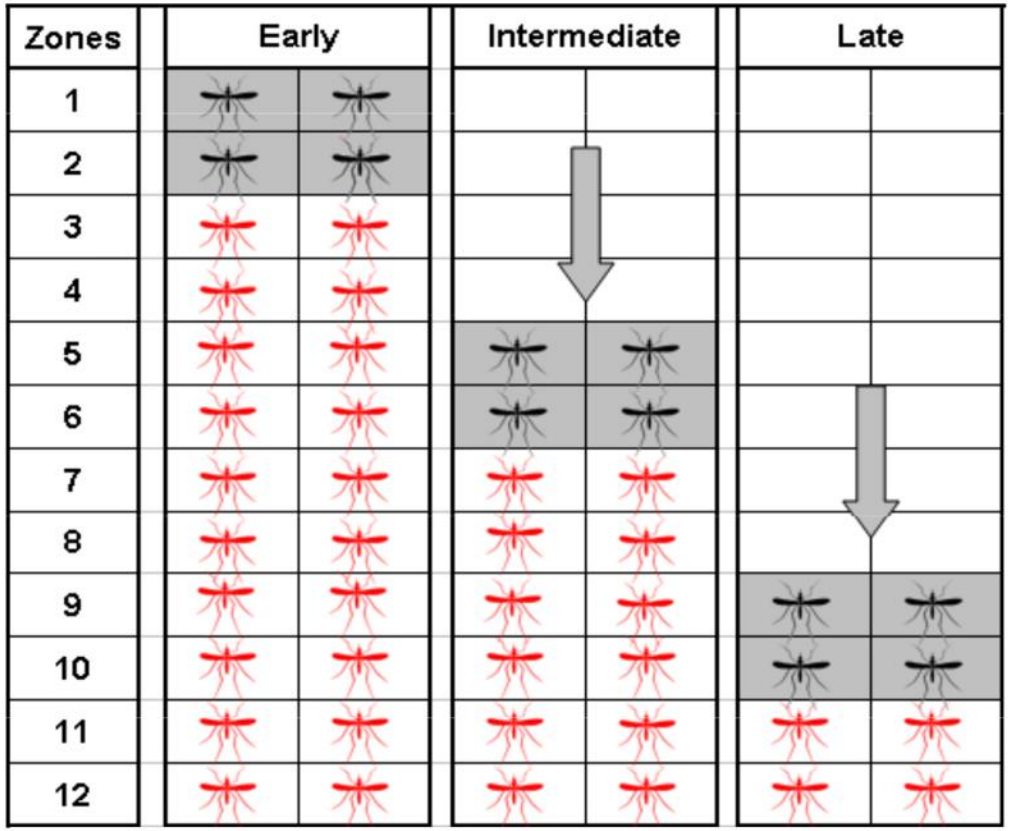

The concept of releasing sterile mosquitoes on a "rolling carpet"

Three phases of a release programme for the same areas are shown.

Red mosquitoes represent natural populations
Black ones: sterile release areas
Open boxes: disinfested zones

The spatial direction of the releases and the accompanying disinfested areas expansion are indicated by the arrows.

This also illustrates the "area-wide control" concept in that there is an increasing disinfested area in return for a continuous level of effort

Luis Almeida, Alexis Léculier, Nicolas Vauchelet. Analysis of the "Rolling carpet" strategy to eradicate an invasive species. SIAM Journal on Mathematical Analysis, 2023, 55 (1), pp.275-309. 10.1137/21M1427243 . hal-03261142

Mathematical modeling: a key tool for SIT optimization

- Enhancing decision-making by providing quantitative insights into mosquito population dynamics and SIT implementation strategies
- Optimizing sterile male releases, enabling refinement of quantity, frequency, and spatial distribution
- Reducing reliance on extensive field experimentation, providing cost-effective and scalable predictive analyses
- Integrating biological and ecological complexities, specifically accounting for environmental variables influencing SIT effectiveness
- Supporting epidemiological forecasting, thereby facilitating the assessment of SIT's potential to reduce dengue transmission