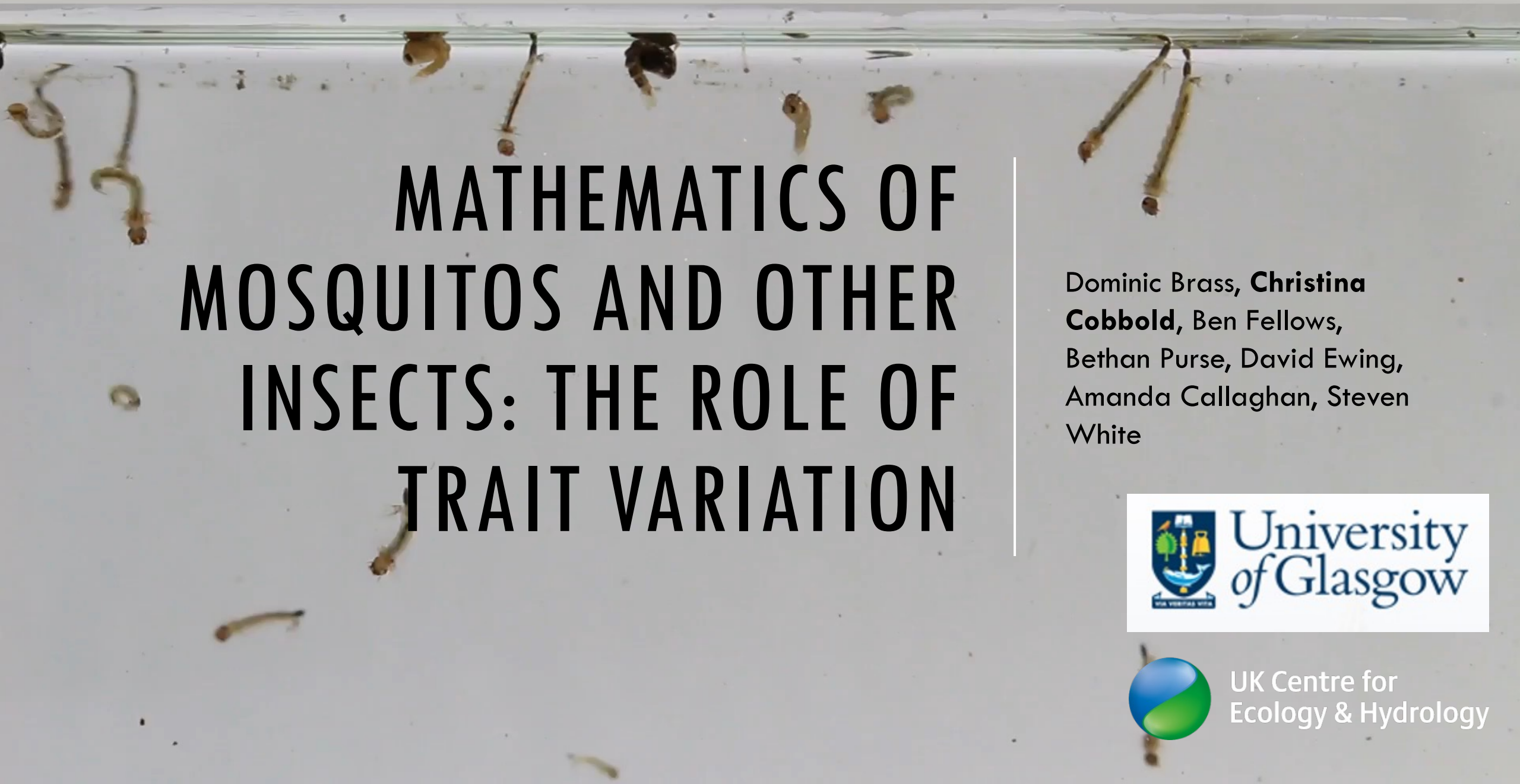


MATHEMATICS OF MOSQUITOS AND OTHER INSECTS: THE ROLE OF TRAIT VARIATION

Dominic Brass, **Christina Cobbold**, Ben Fellows, Bethan Purse, David Ewing, Amanda Callaghan, Steven White

University of Glasgow

UK Centre for Ecology & Hydrology

WHY INSECTS?

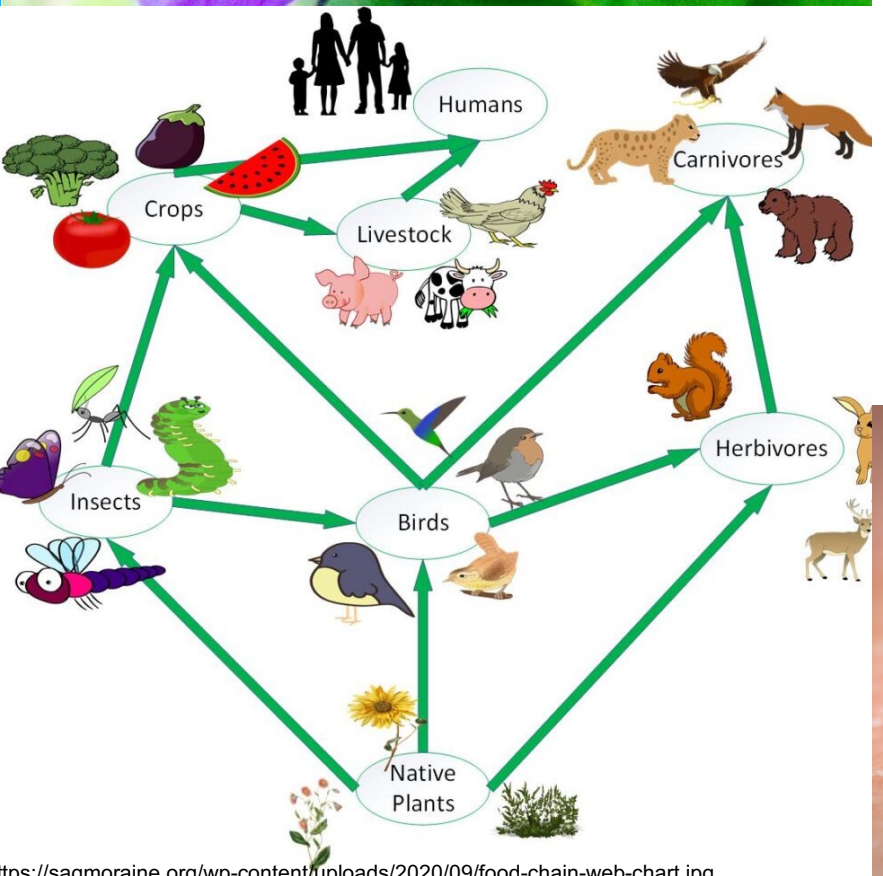
Pollination services

Vectors for disease

Defoliation and carbon sequestration

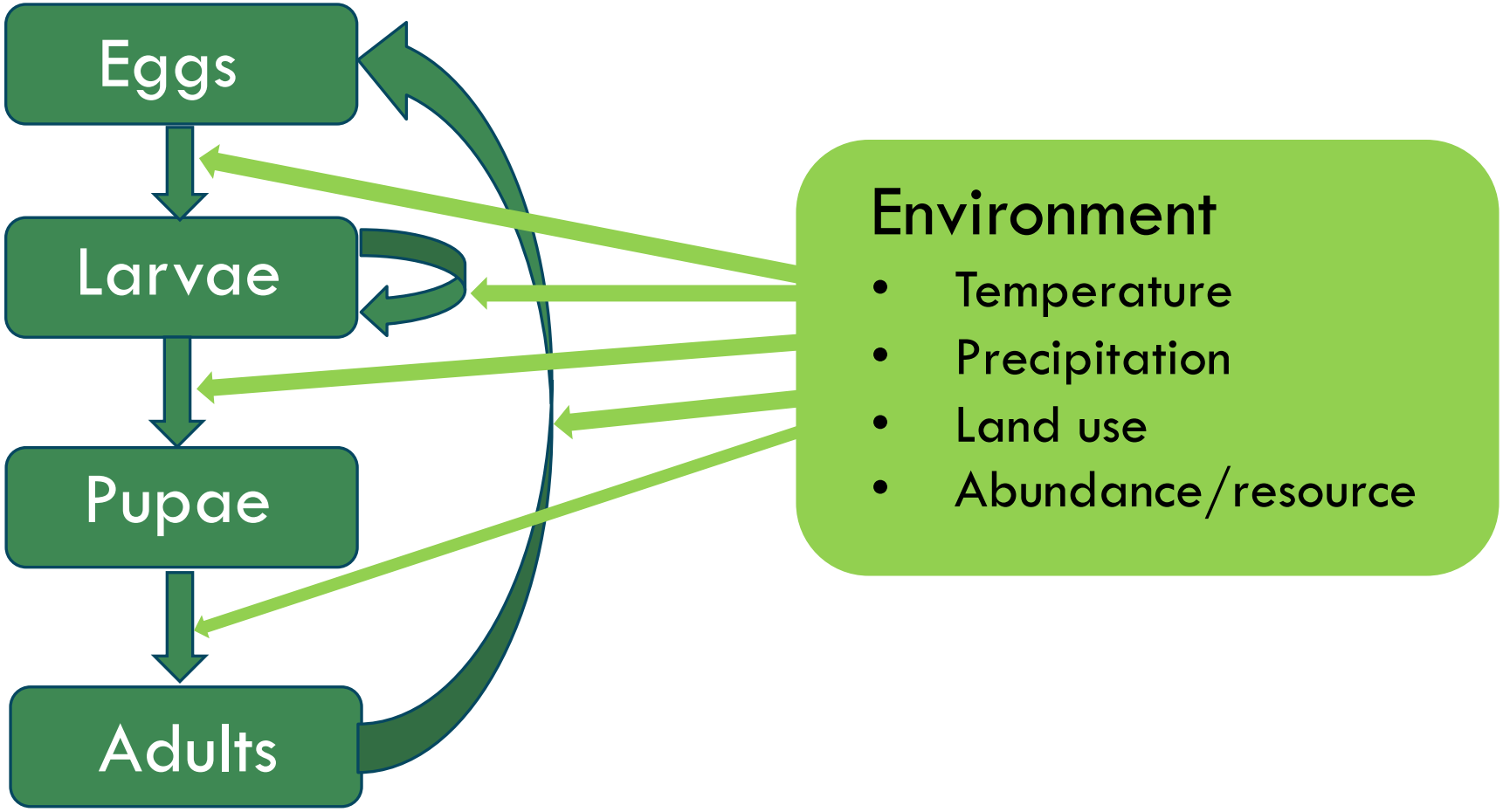
Biodiversity and food webs

Agricultural pests

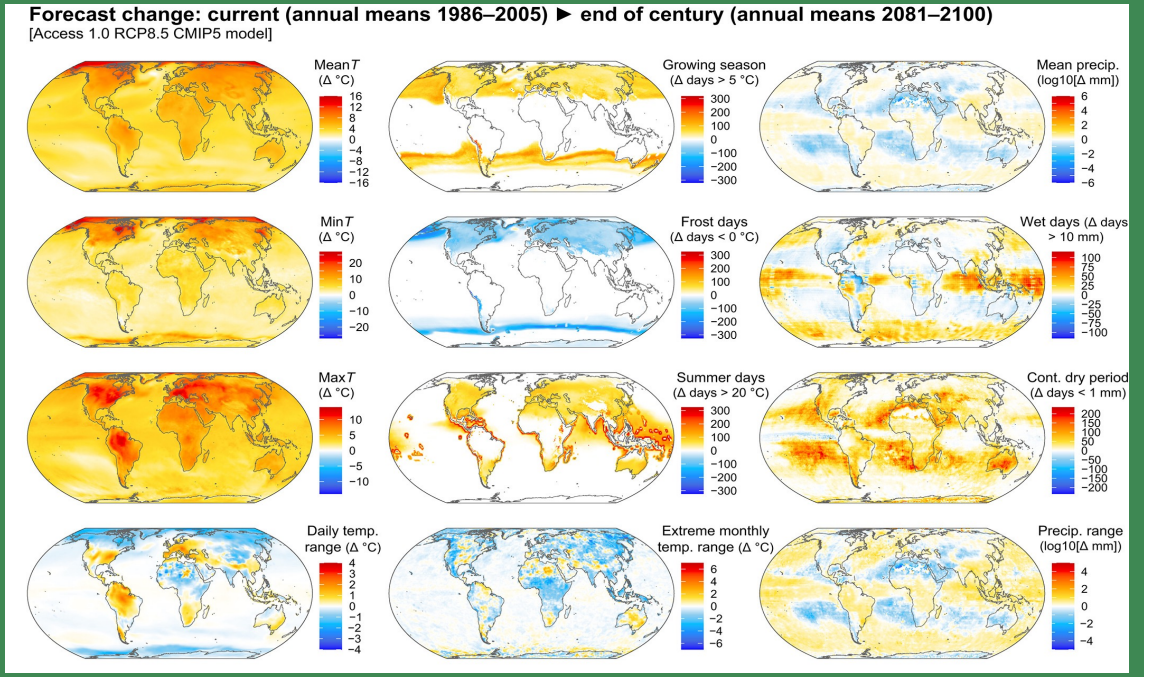


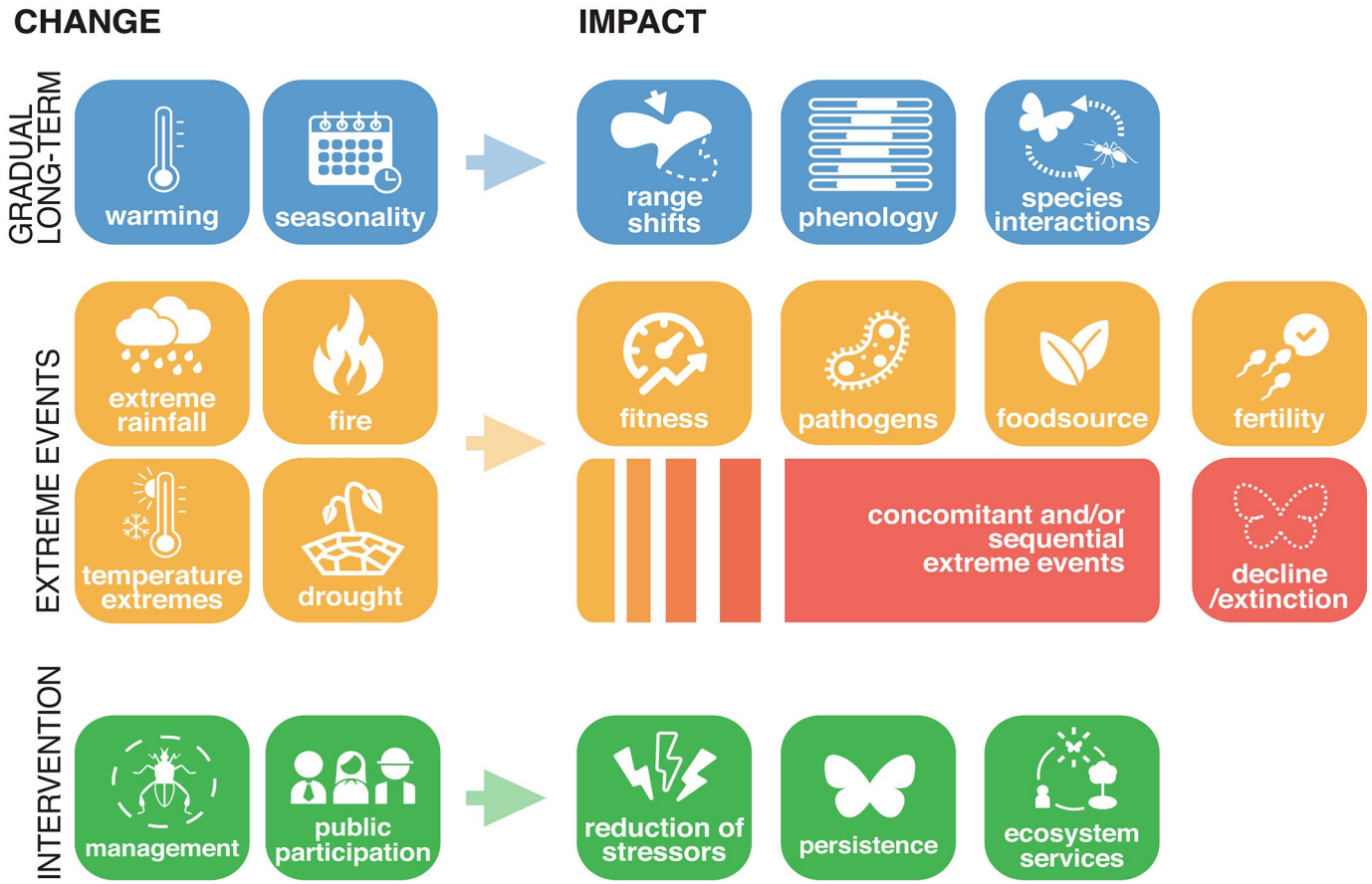
https://sagmoraine.org/wp-content/uploads/2020/09/food-chain-web-chart.jpg

INSECTS AND ENVIRONMENT



CLIMATE CHANGE



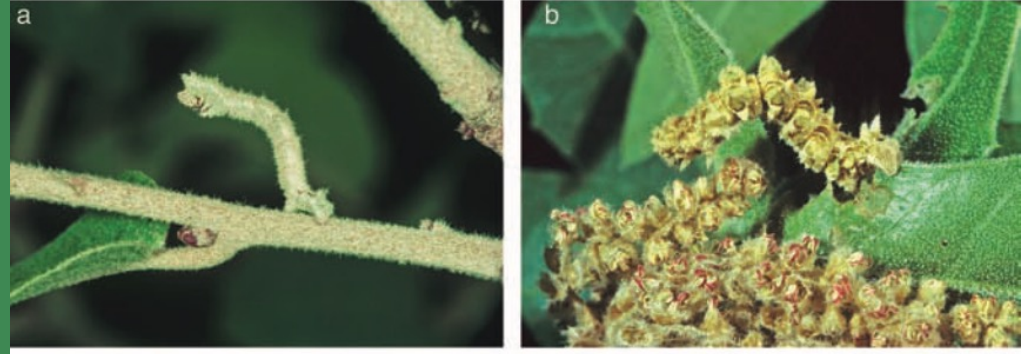


Harvey et al, (2023) Ecological Monographs, 93(1)

PHENOTYPIC PLASTICITY

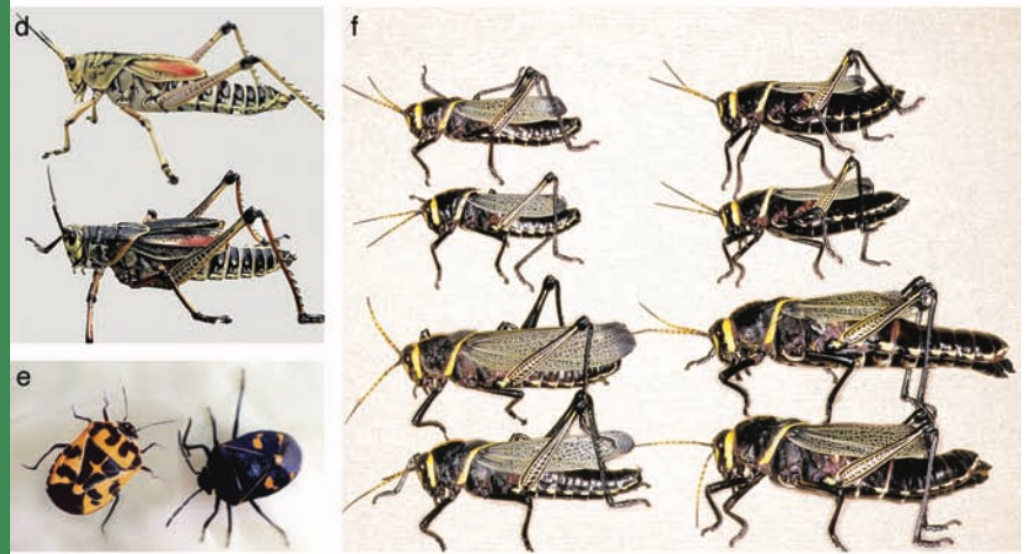
"Ability of individual genotypes to produce different phenotypes when exposed to different environmental conditions"

Phenotype=collection of traits belonging to an individual



Morphological change:
Summer: resemble oak twigs
Spring: resemble oak catkins

Morphological change:
Wet-season vs Dry-season



Nutrition and body size: Grasshoppers

Top: Poor rain and poor vegetation
Bottom: Ample raid and lush vegetation

Harlequin bugs and temperature:
Yellow: reared at 30oC
Black: reared at 22oC

Phenotypic Plasticity of Insects, Ed. Whitman (2009) CRC press

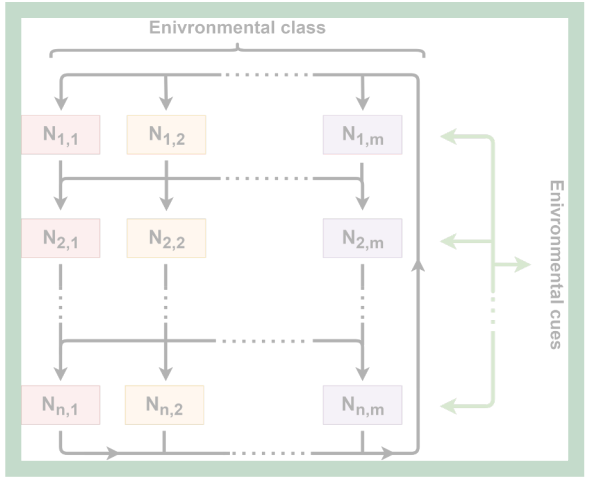
OVERVIEW

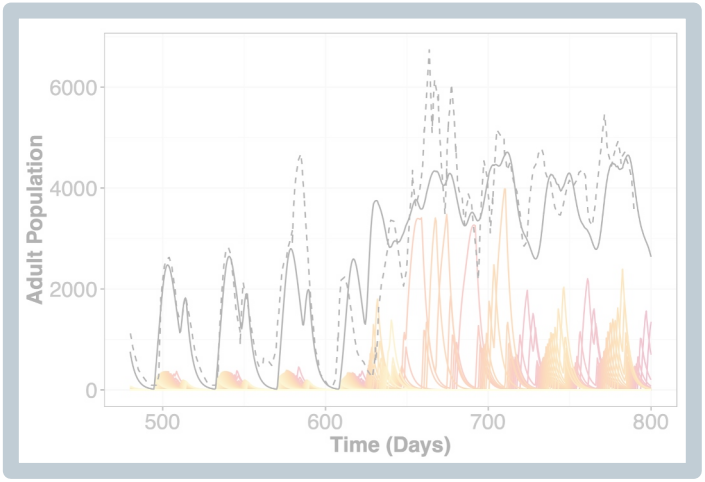
Including phenotypic plasticity into insect life-cycle models

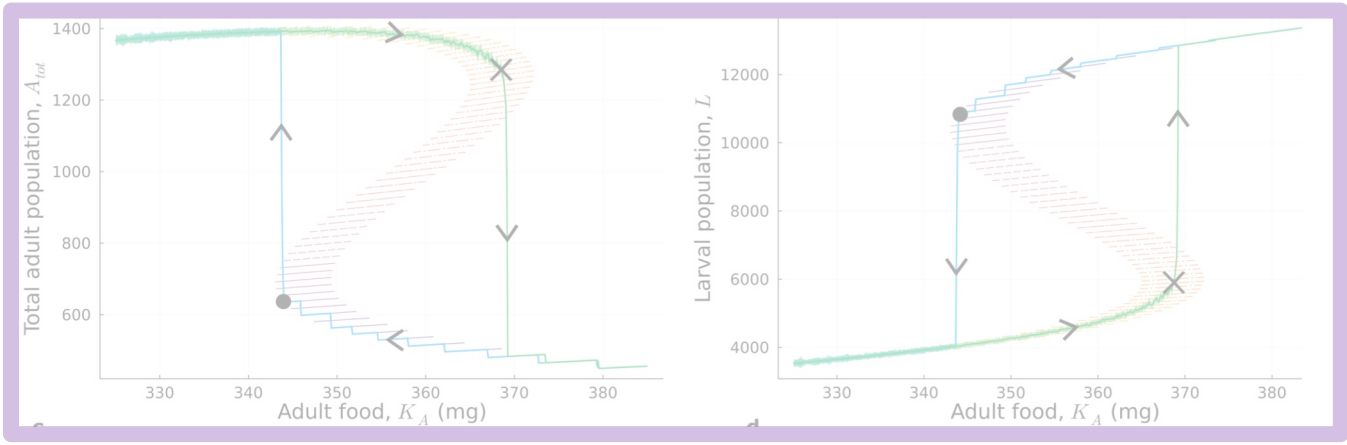
Nicholson's blowflies

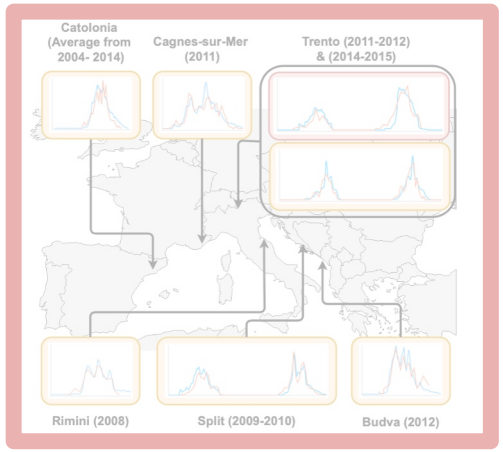
Plasticity and hysteresis

Application to mosquitoes and vector-borne disease: Dengue









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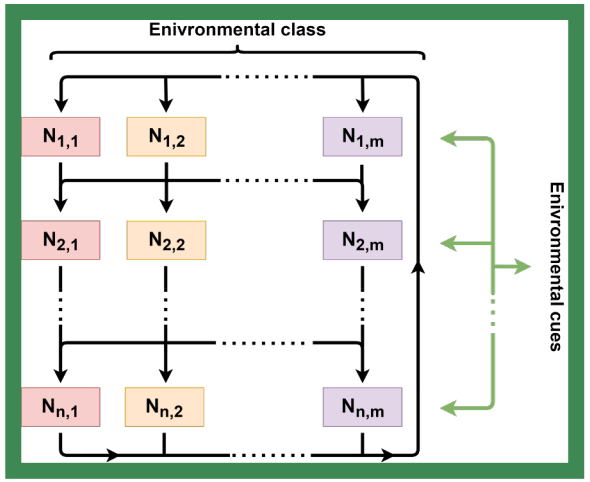
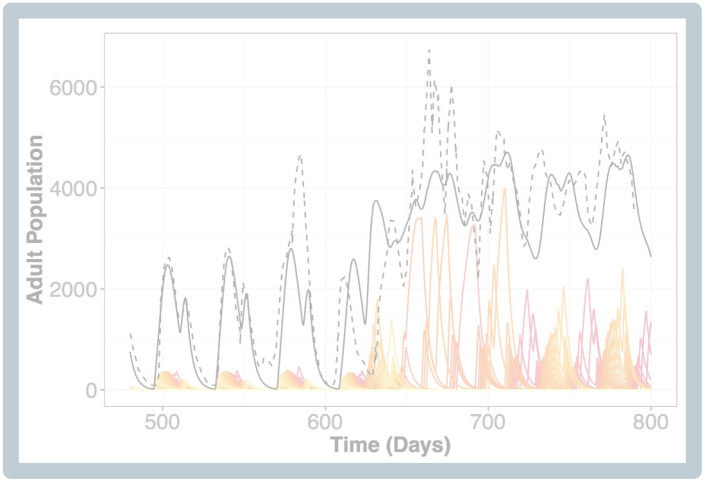
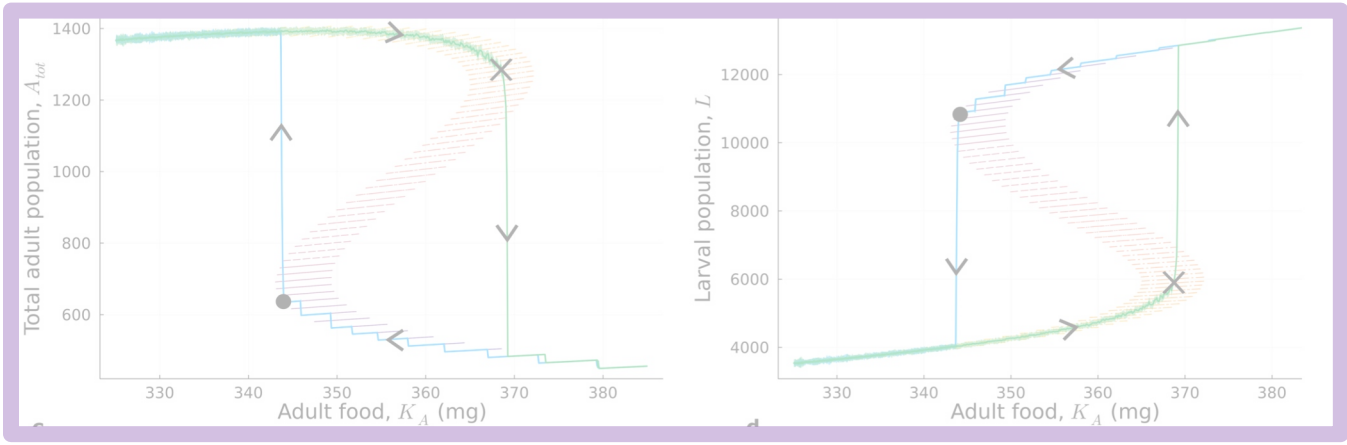
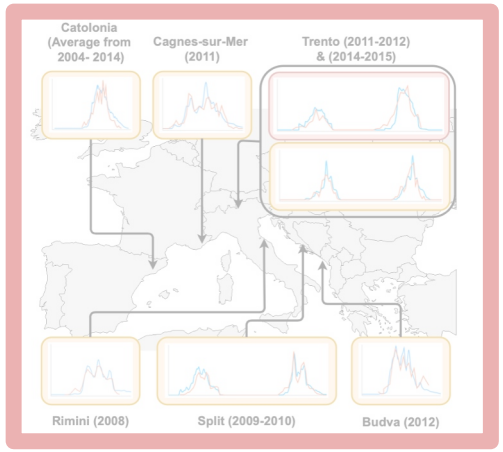


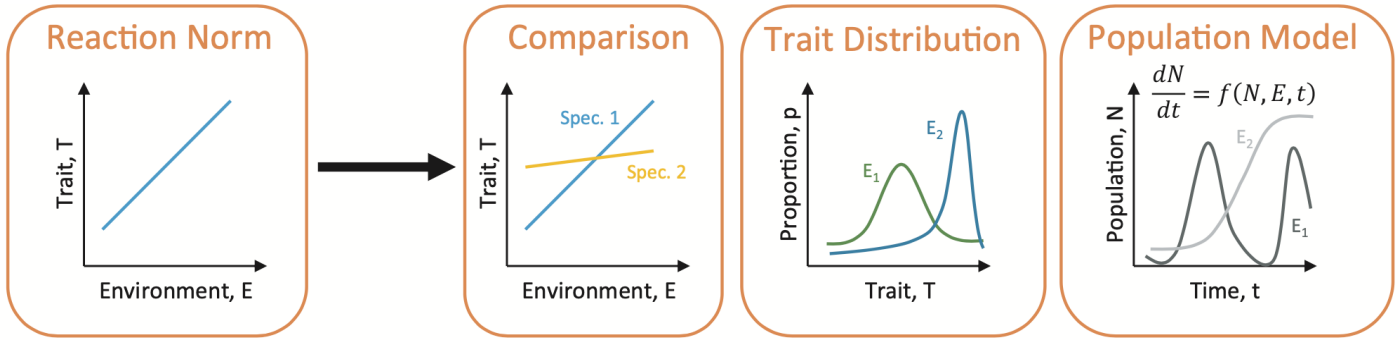






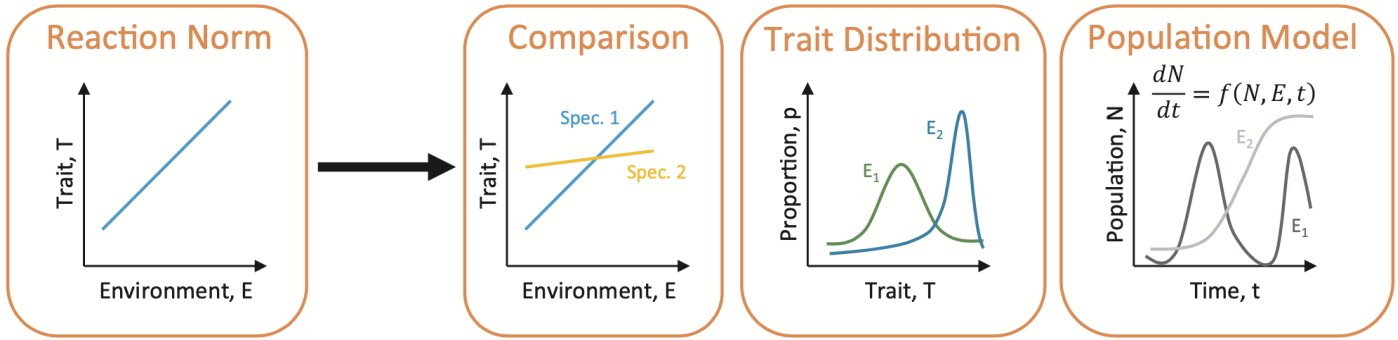
PHENOTYPIC PLASTICITY

Current approaches one-way predictive frameworks

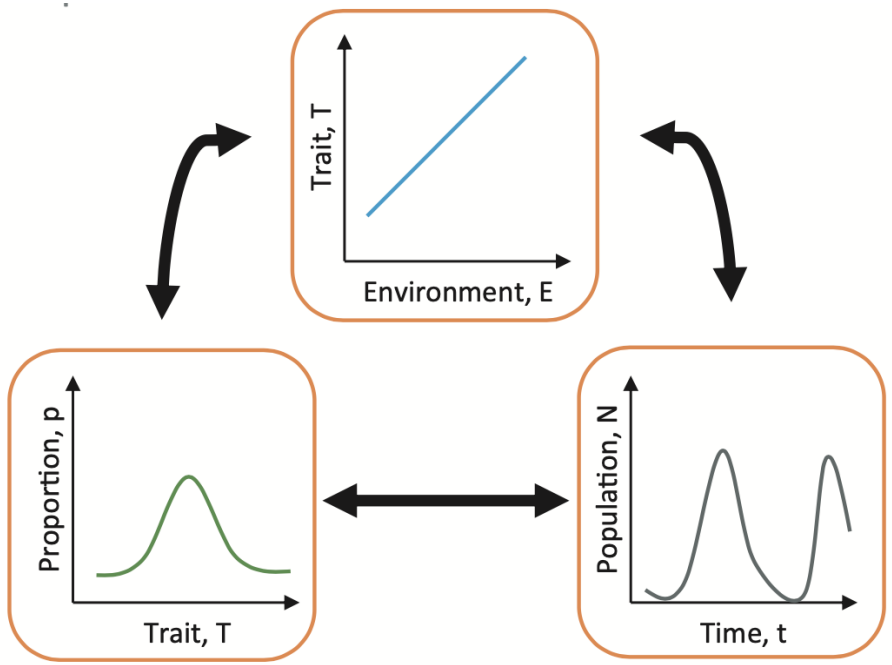


PHENOTYPIC PLASTICITY

Current approaches one-way predictive frameworks

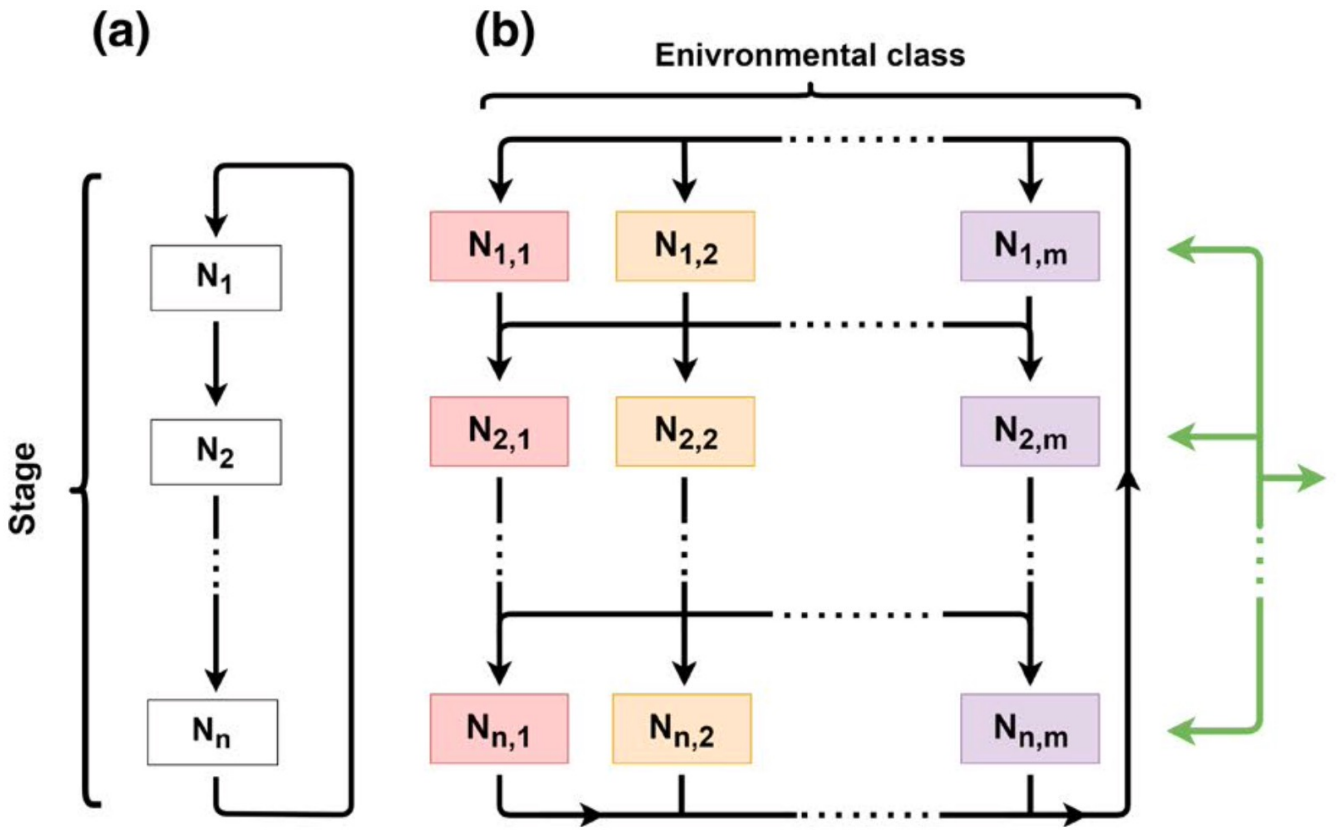


New approach: population-trait-environment interactions



PHENOTYPIC PLASTICITY

Systems of stage-phenotypically structured delay-differential equations



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DOI: 10.1111/ele.13862

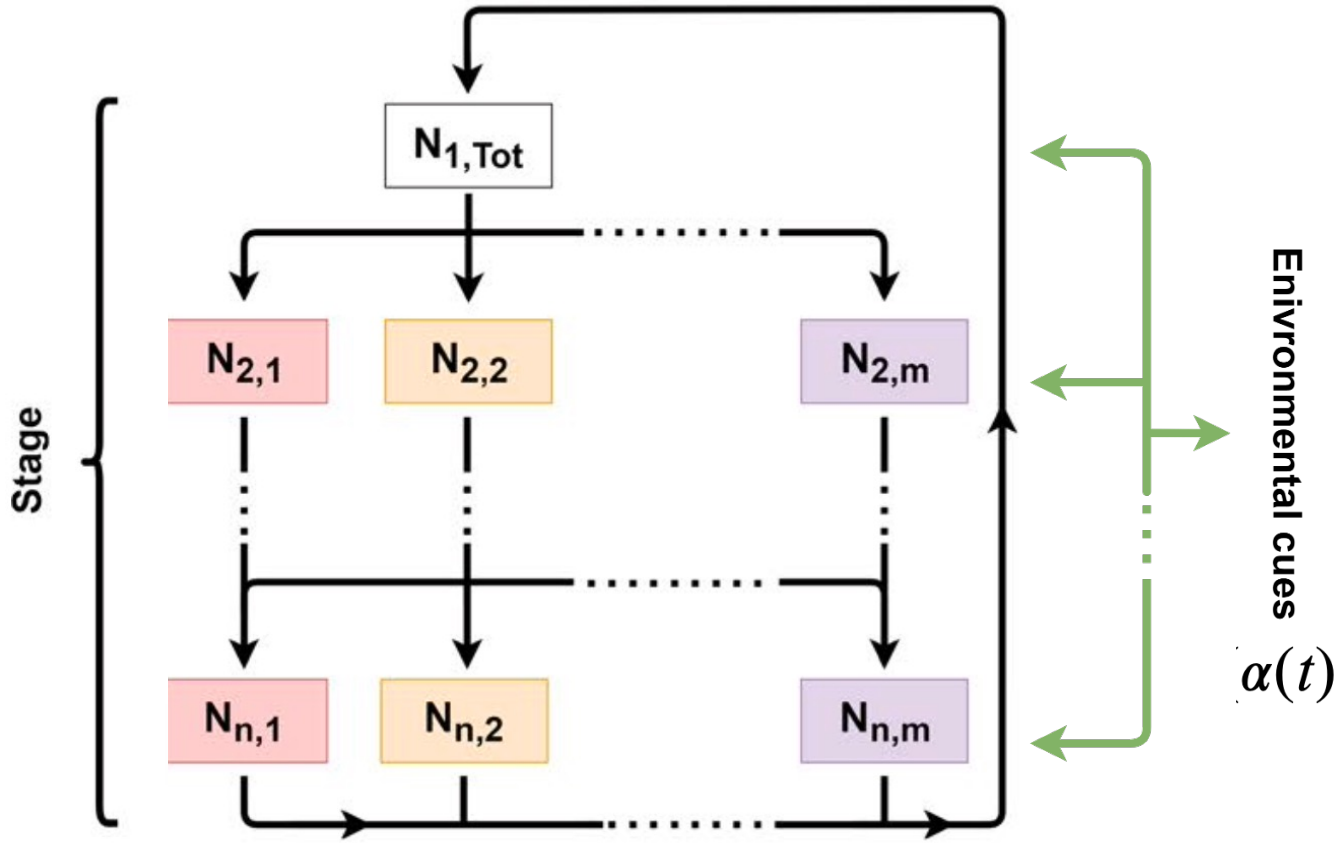
ECOLOGY LETTERS WILEY

LETTER

Phenotypic plasticity as a cause and consequence of population dynamics

Dominic P. Brass[1,2] | Christina A. Cobbold[3] | David A. Ewing[4] | Bethan V. Purse[1] | Amanda Callaghan[2] | Steven M. White[1]

DELAYED DEVELOPMENTAL PLASTICITY



Density in life-stage i environmental class j

Recruitment – Maturation - Death

$$\frac{\mathrm{d}N_{i,j}(t)}{\mathrm{d}t} = R_{i,j}(t) - M_{i,j}(t) - D_{i,j}(t)$$

Stage duration Survival

$$M_{i,j}(t) = R_{i,j}\left(t - \tau_{i,j}\right) S_{i,j}(t)$$

Survival

$$S_{i,j}(t) = \exp\left\{ - \int_{t-\tau_{i,j}}^{t} \delta_{i,j}\left(t'\right) \mathrm{d}t' \right\}$$

Tracking environmental experience

birth

$$R_{1,j}(t) = \sum_{k=1}^{m} \left(w_{kj}(\alpha(t)) \sum_{v=1}^{n} \beta_{v,k}(t) N_{v,k}(t) \right)$$

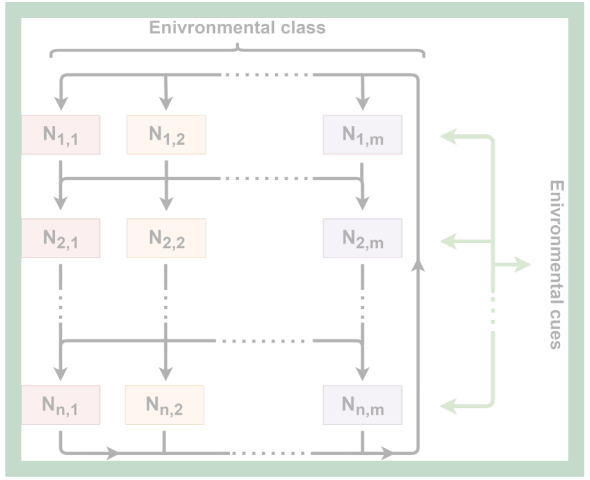
OVERVIEW

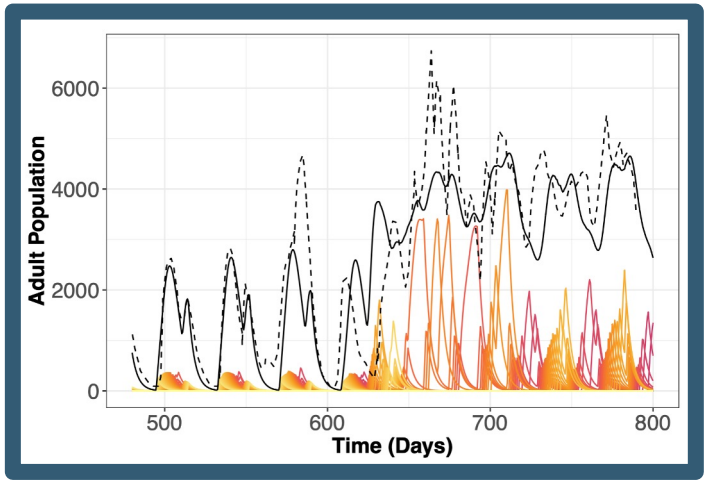
Including phenotypic plasticity into insect life-cycle models

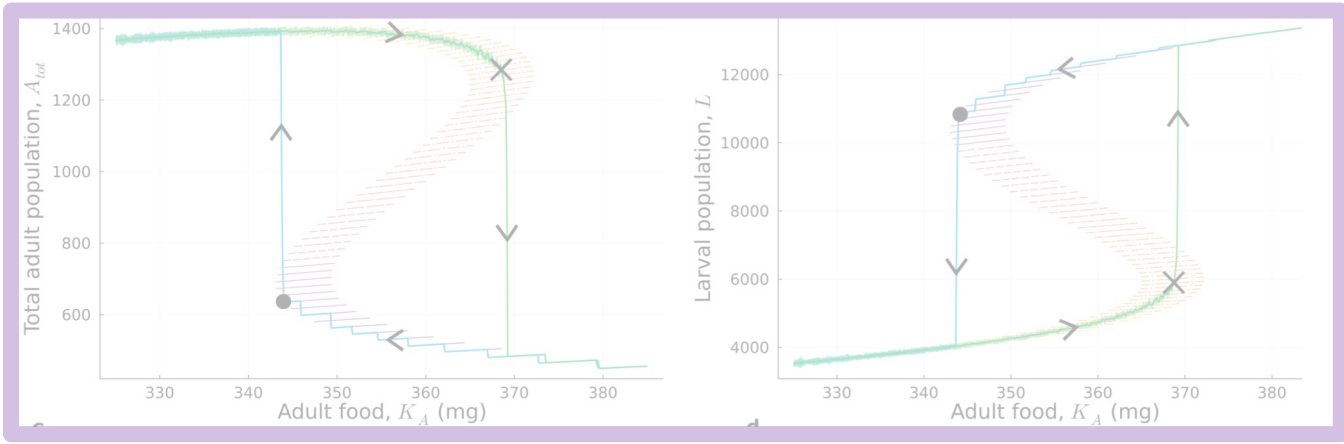
Nicholson's blowflies

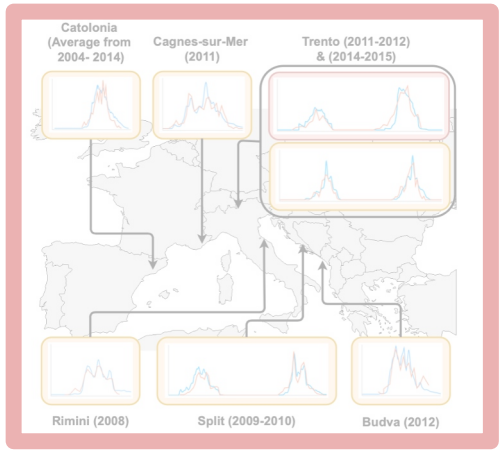
Plasticity and hysteresis

Application to mosquitoes and vector-borne disease: Dengue



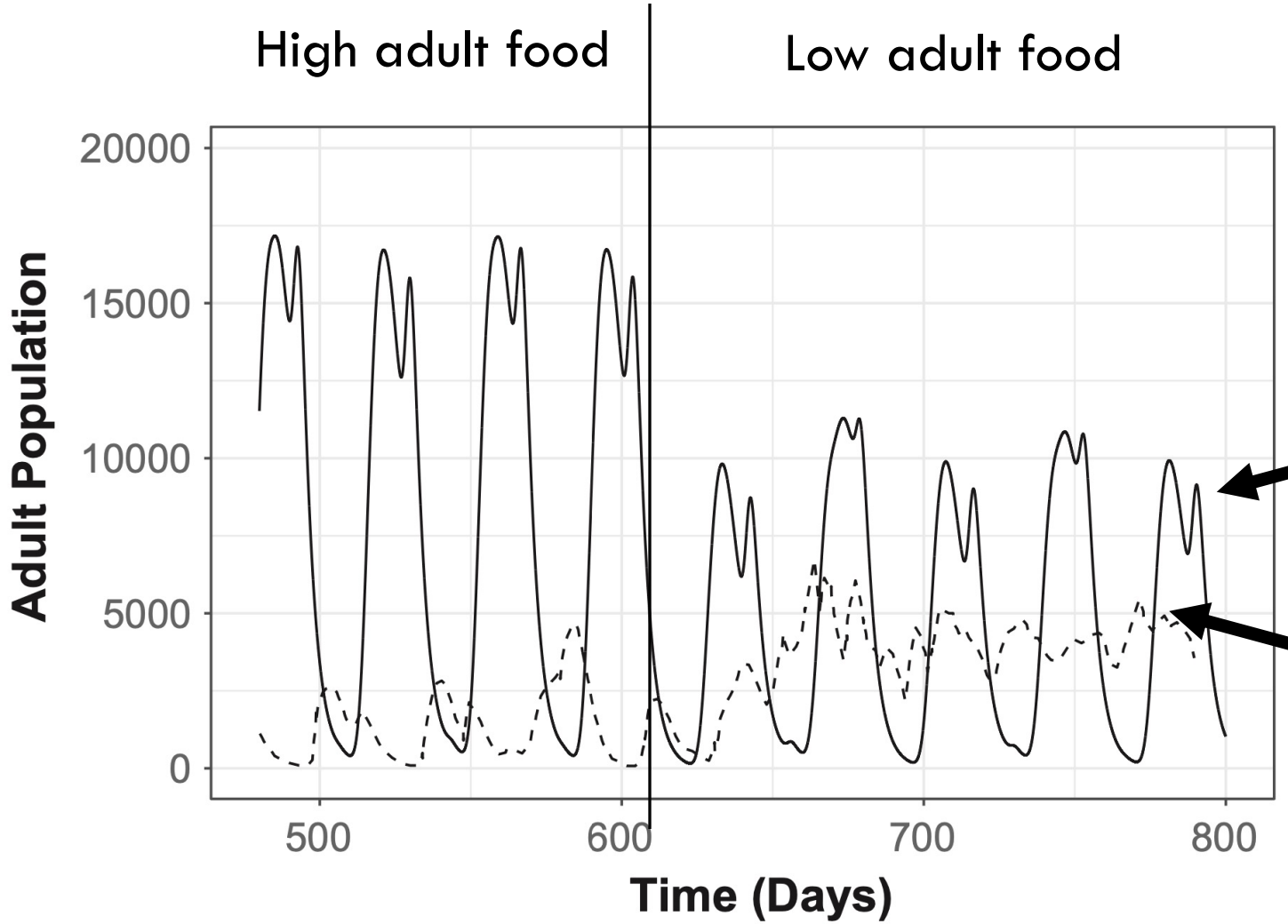






Gurney et al. 1983 J An Ecol

NICHOLSON'S BLOWFLIES



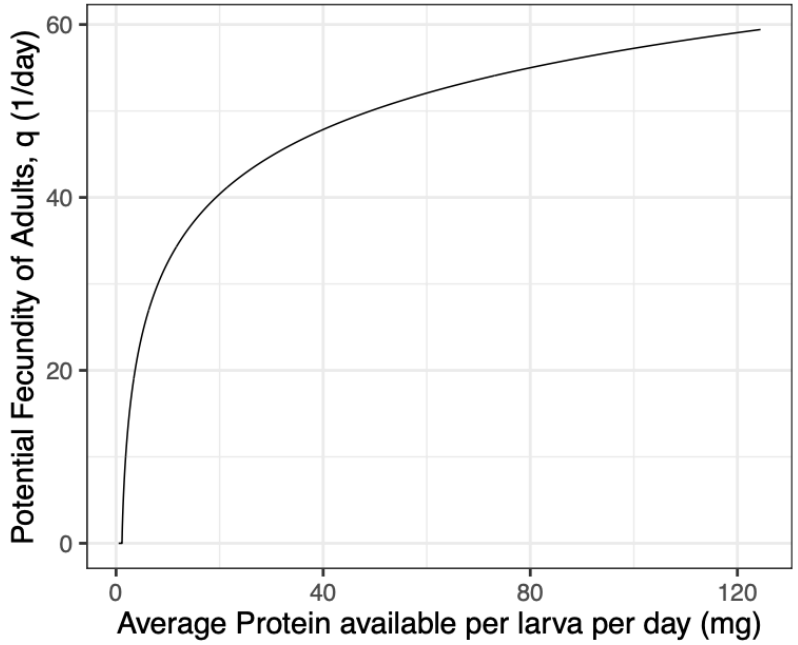
Model that ignores phenotypic plasticity

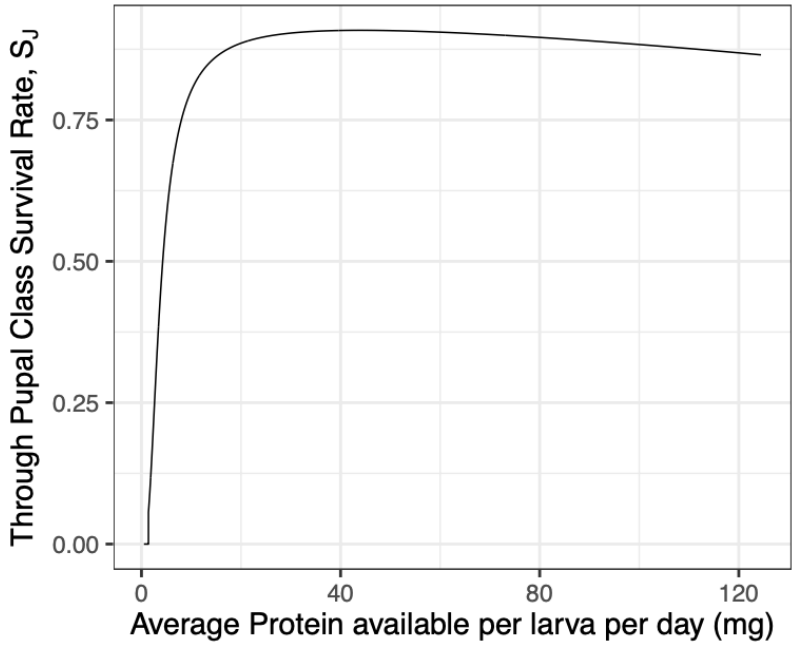
Nicholson's data – hypothesis: due to phenotypic plasticity

DELAYED PHENOTYPIC PLASTICITY

Reaction norms:

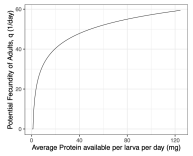
Fix total larval food, so food per larvae is determined by the number of larvae

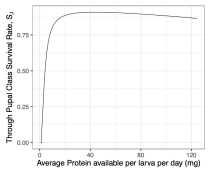


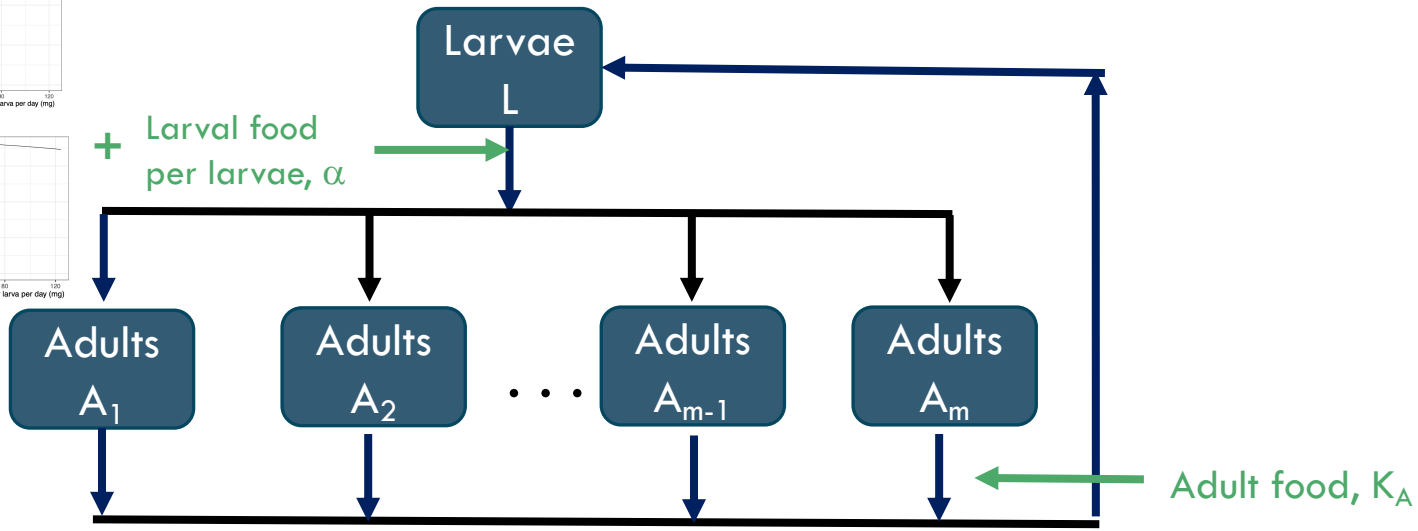


NICHOLSON'S BLOWFLIES

Reaction norms







Small adults:

- low maximum fecundity, q_1
- low pupal survival, S_{J1}

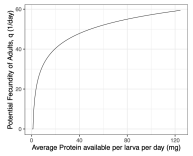
Large adults:

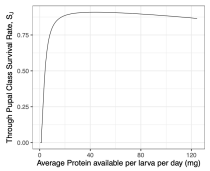
- high maximum fecundity, q_m
- high pupal survival, S_{Jm}

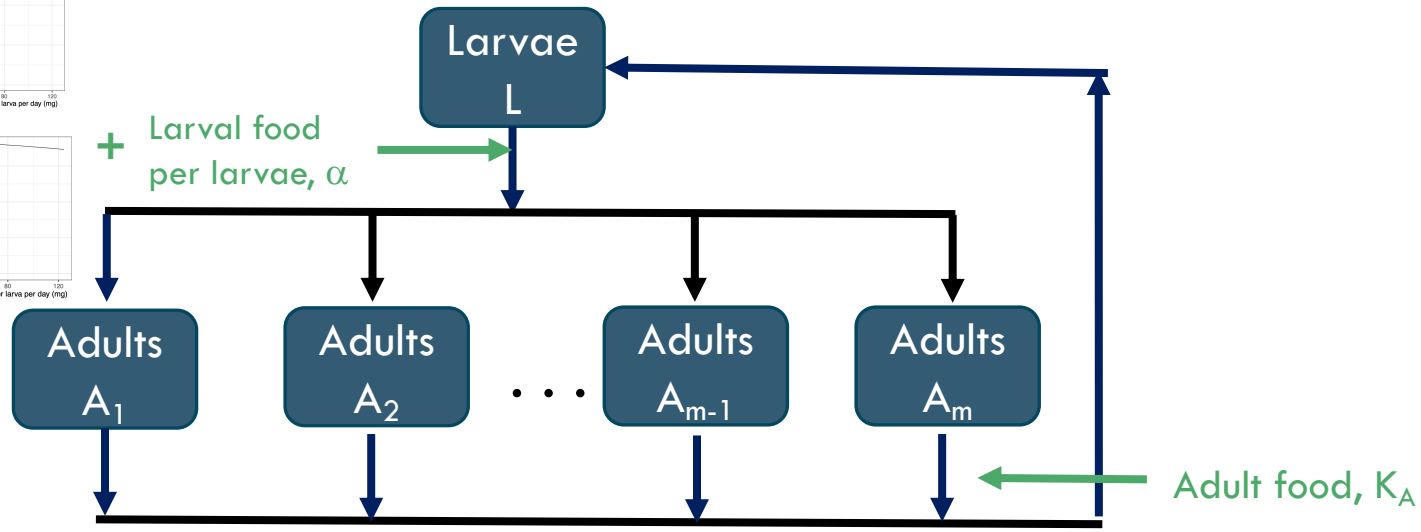
Brass et al. 2021 Ecol Letters

NICHOLSON'S BLOWFLIES

Reaction norms







Small adults:
- low maximum fecundity, q_1
- low pupal survival, S_{J1}

Large adults:
- high maximum fecundity, q_m
- high pupal survival, S_{Jm}

Recruitment – Maturation - Death

$$\frac{\mathrm{d}L(t)}{\mathrm{d}t} = R_L(t) - R_L\left(t-\tau_L\right)S_L - \delta_L L(t),$$

$$\frac{\mathrm{d}A_j(t)}{\mathrm{d}t} = R_{A_j}(t) - \delta_A A_j(t) \quad \text{for} \quad j \in 1,\ldots,m,$$

Recruitment

$$R_L(t) = \left[\sum_{j=1}^{m} q_j A_j(t-\tau_E) e^{-A_{\mathrm{Tot}}(t-\tau_E)/K_A} + I(t-\tau_E)\right] S_E,$$

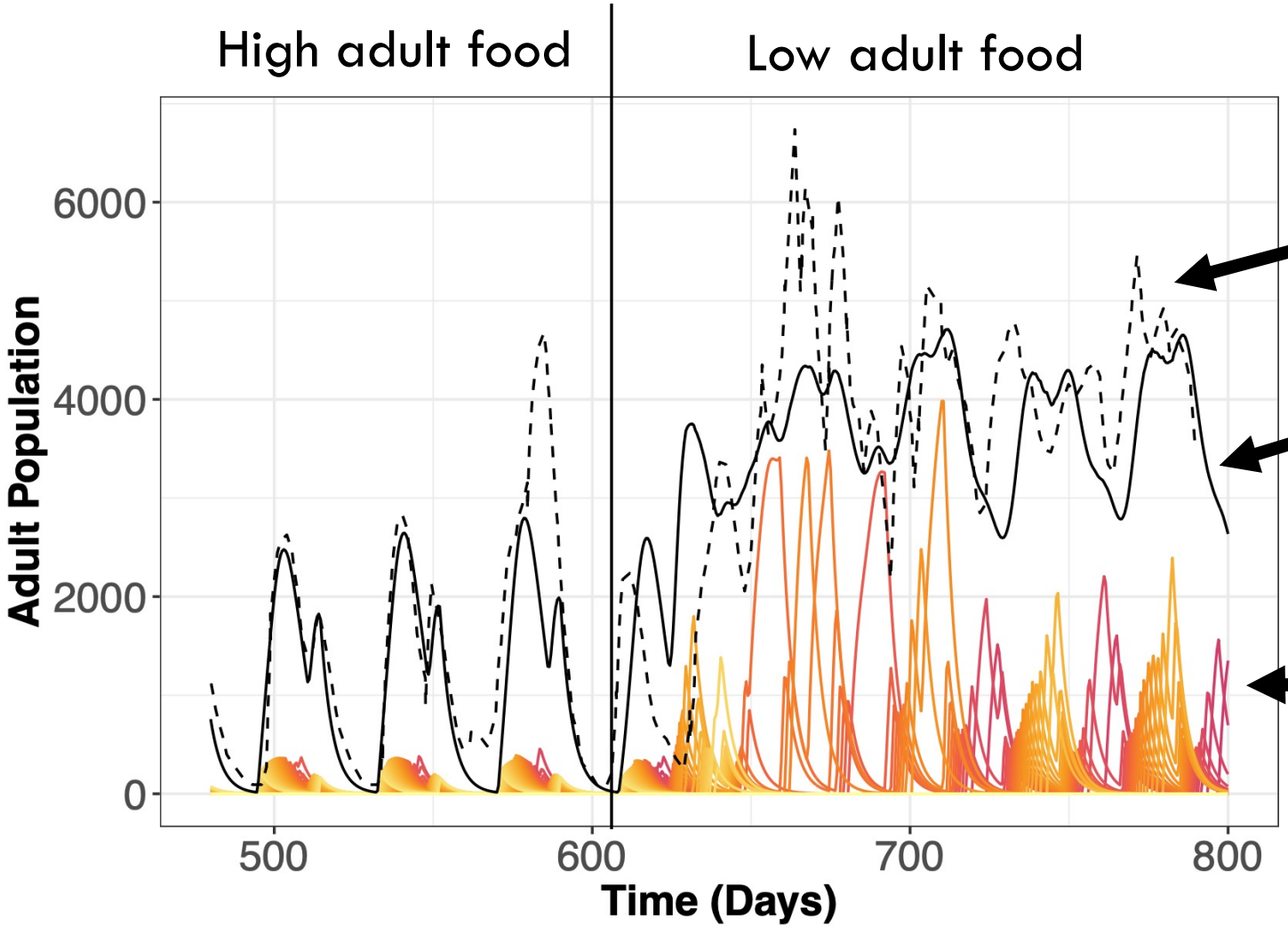
$$R_{A_i}(t) = \omega_i(\alpha(t-\tau_J))R_L(t-\tau_L-\tau_J)S_L S_{Ji}$$

Larval food per larvae

$$\alpha(t) = \frac{K_L \tau_L}{\int_{t-\tau_L}^{t} L(s)\mathrm{d}s}$$

Brass et al. 2021 Ecol Letters

NICHOLSON'S BLOWFLIES



Nicholson's data – hypothesis: due to phenotypic plasticity

Model: adult abundance

Individual traits: max. adult fecundity, q_i

OVERVIEW

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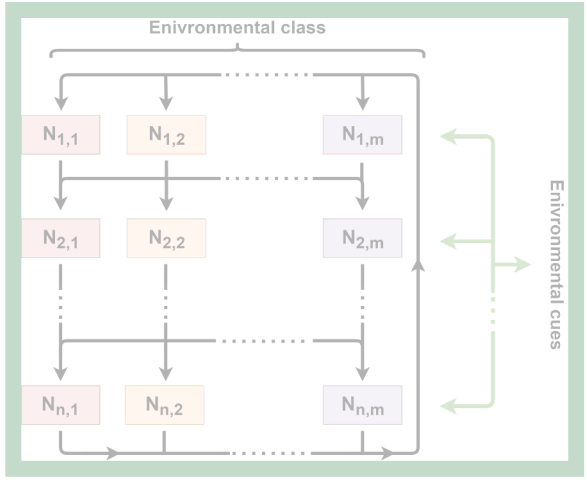
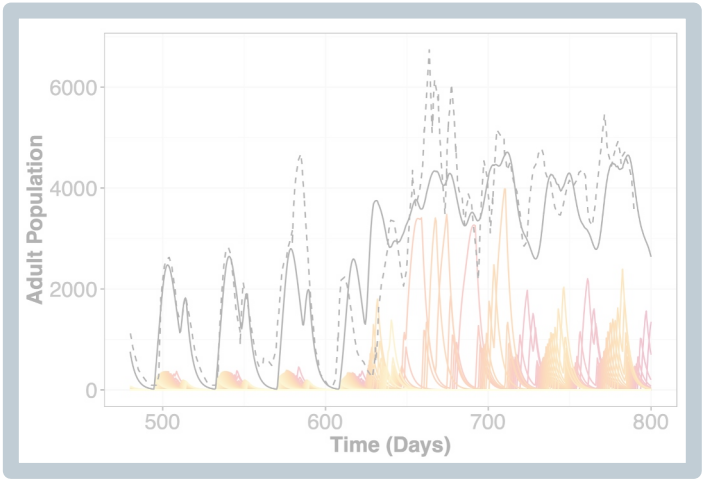
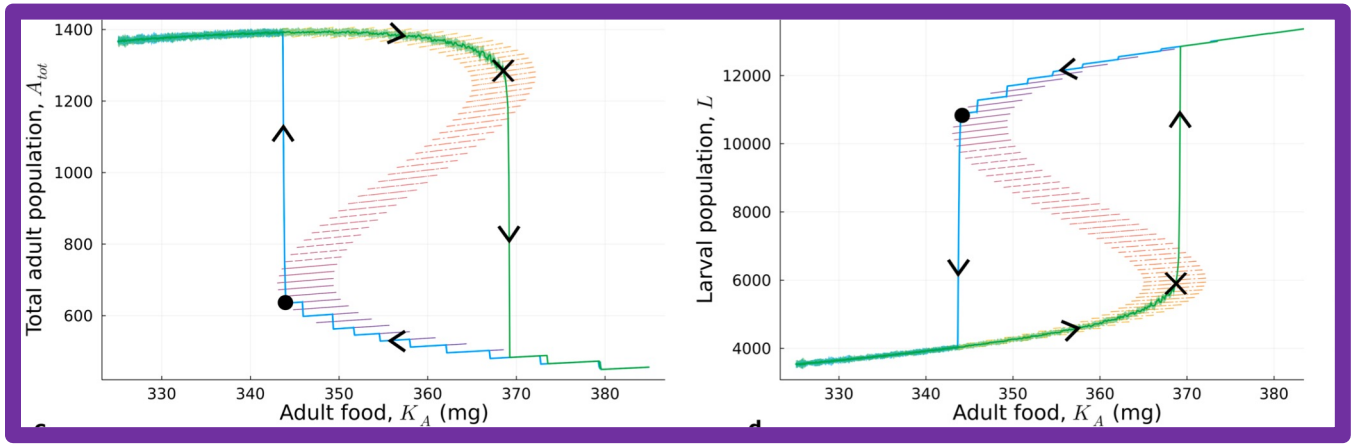
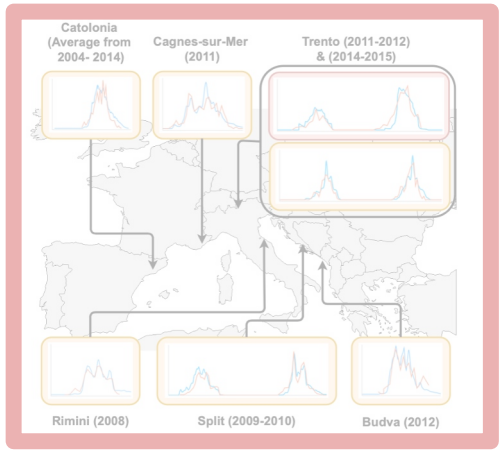


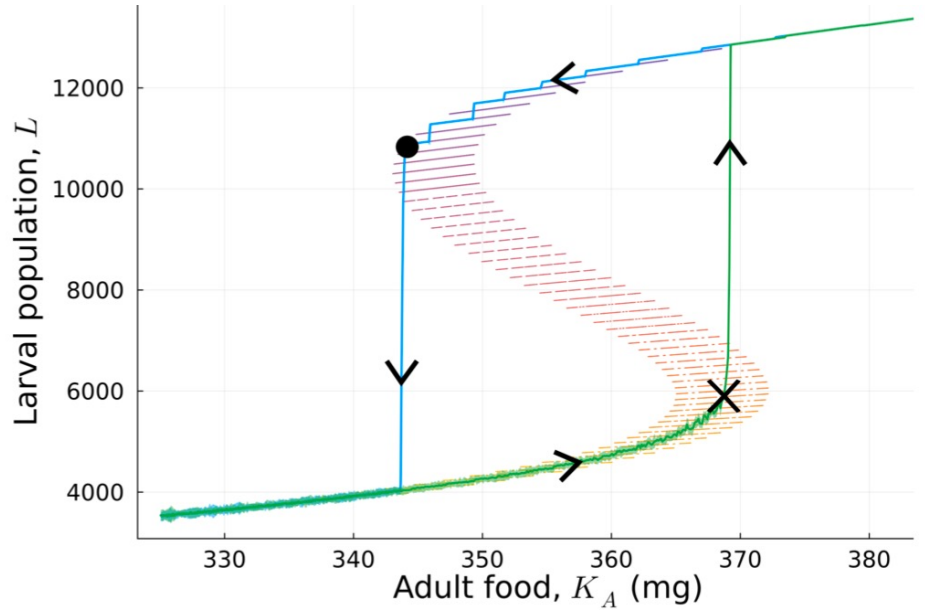


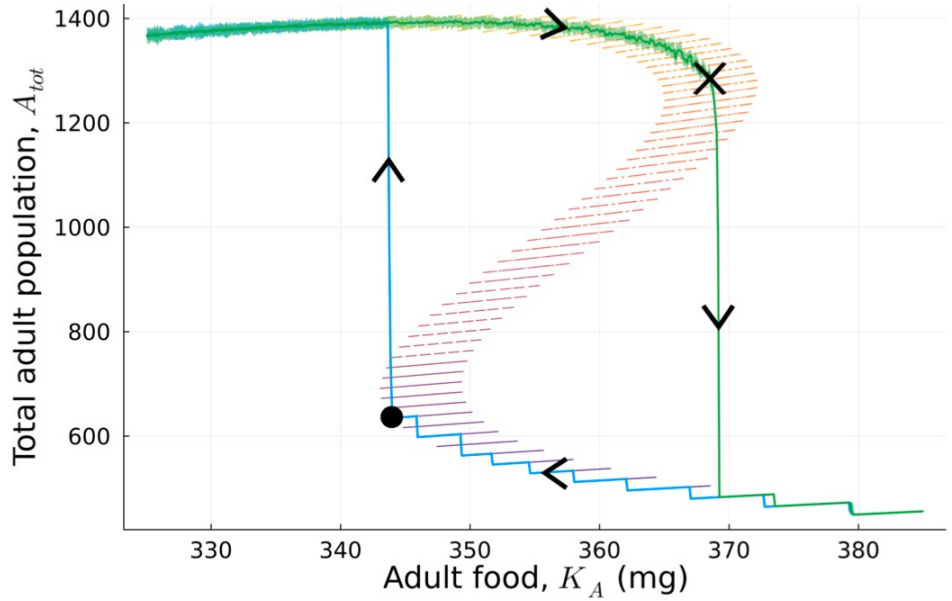




HYSTERESIS

Opposing effects of changing adult food





HYSTERESIS

Decreased adult food

↓

Fewer eggs laid

↓

Reduced larval competition

↓

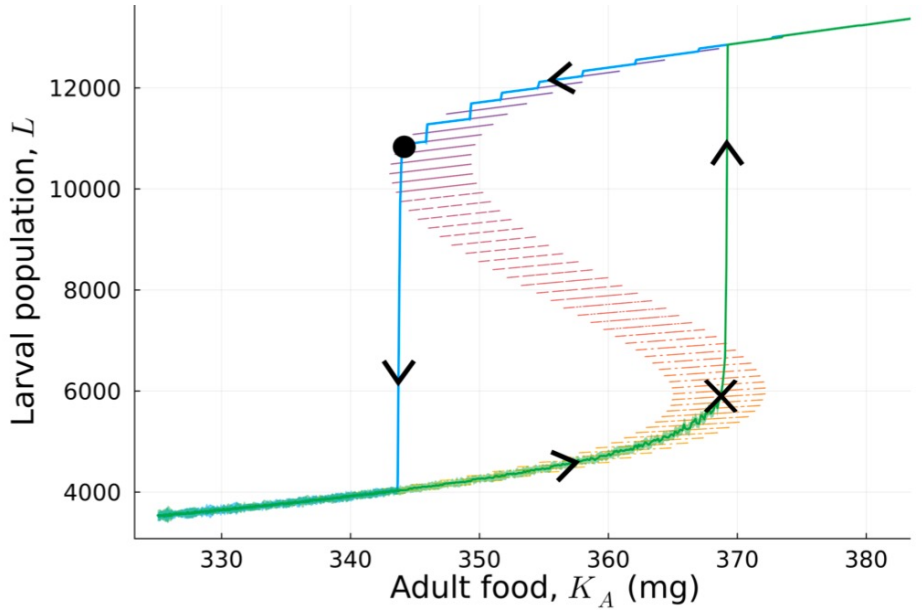
Larger adult size

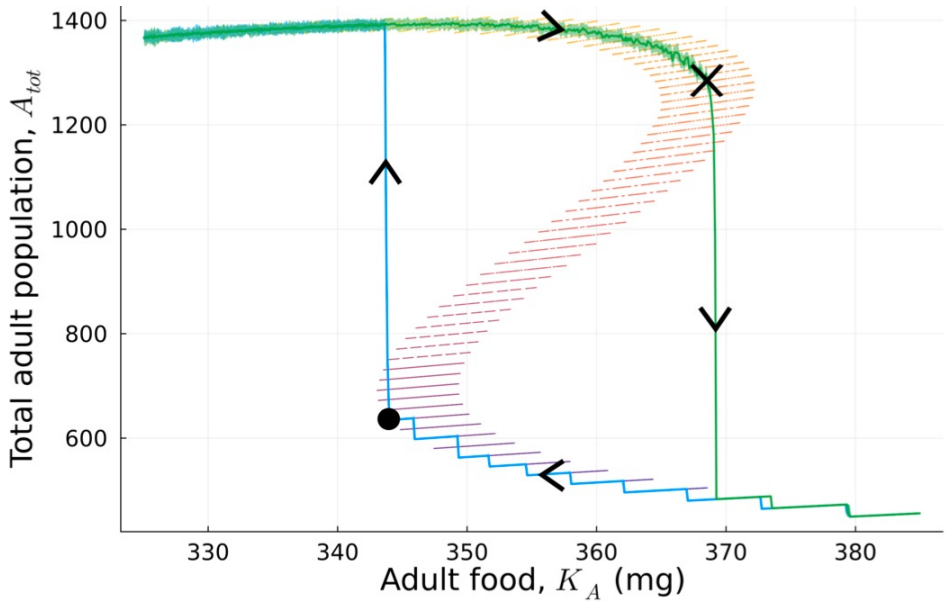
↓

Lower pupal mortality

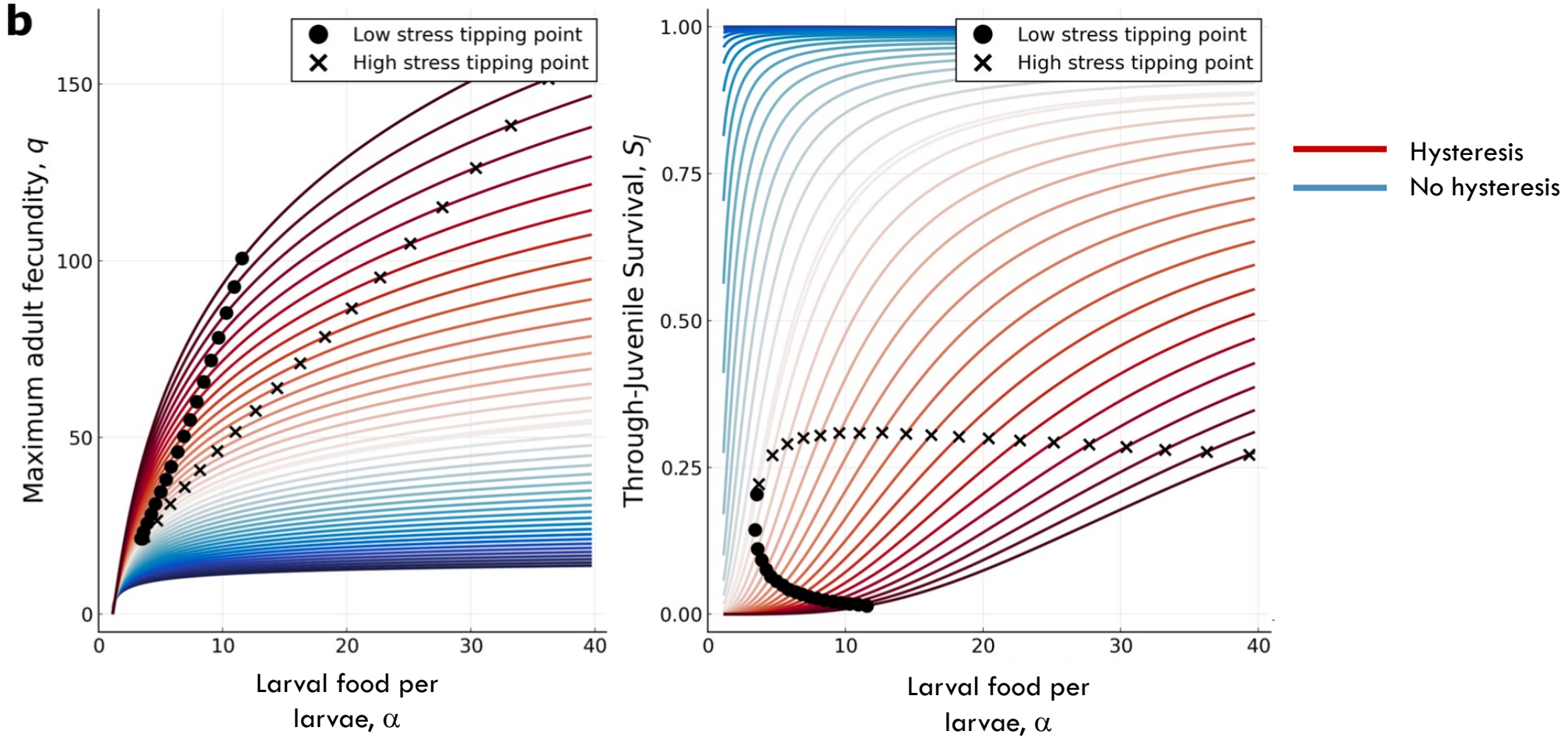
↓

More blowflies reach adulthood





ROLE OF THE REACTION NORMS



OPEN QUESTIONS

- Will maternal effects also generate hysteresis?

- What happens for more complex life-cycles with more environmental cues?

- Can we start disentangling longstanding ecological debates about the role of plasticity?

  E.g. Evidence for and against plasticity aiding persistence under climate change?

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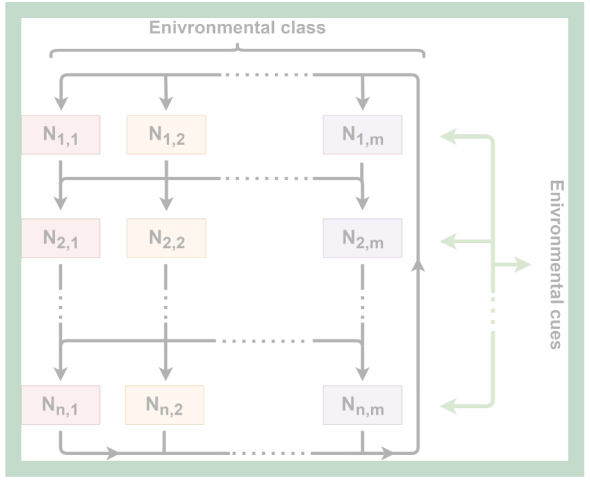
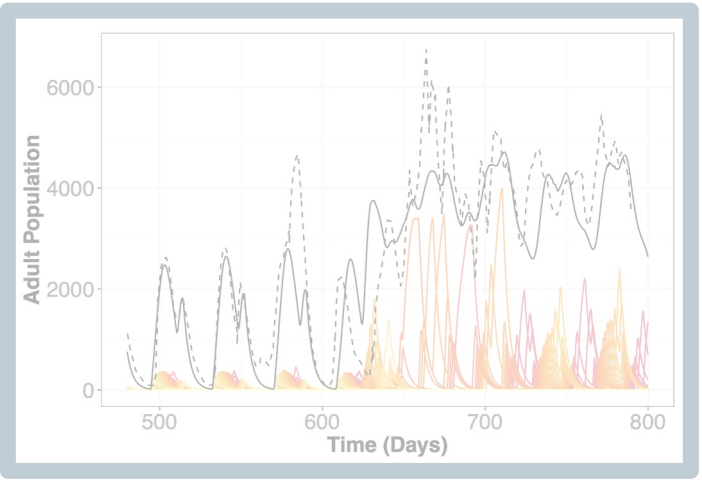
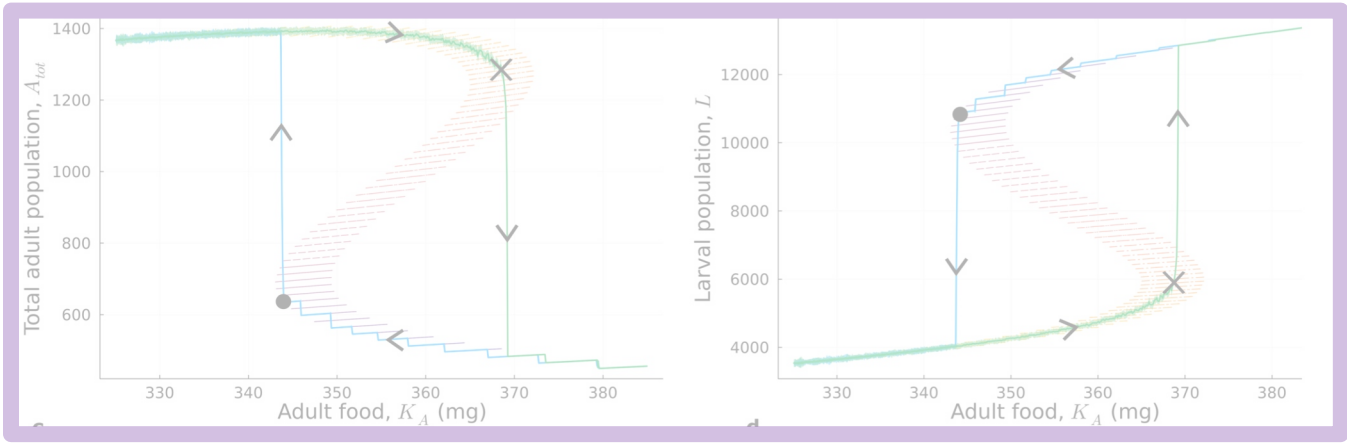
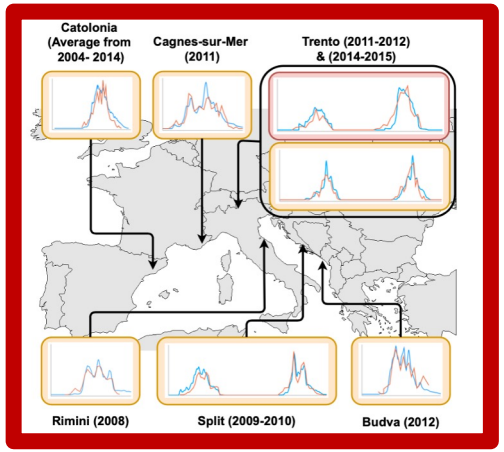






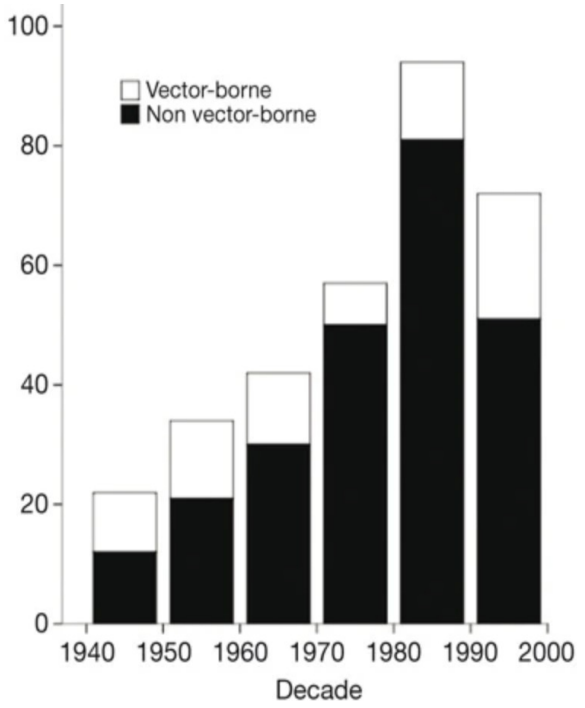


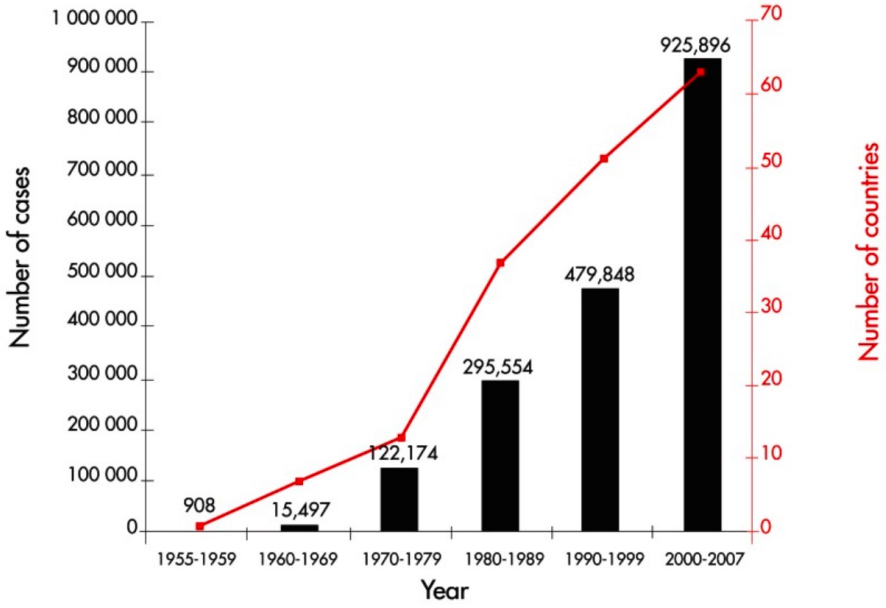
CLIMATE AND MOSQUITO BORNE DISEASE

Anthropogenic factors are driving a global rise in vector borne disease

Vectors and diseases are sensitive to environmental variation

Mosquitoes vector two of the most prevalent diseases (malaria, dengue)



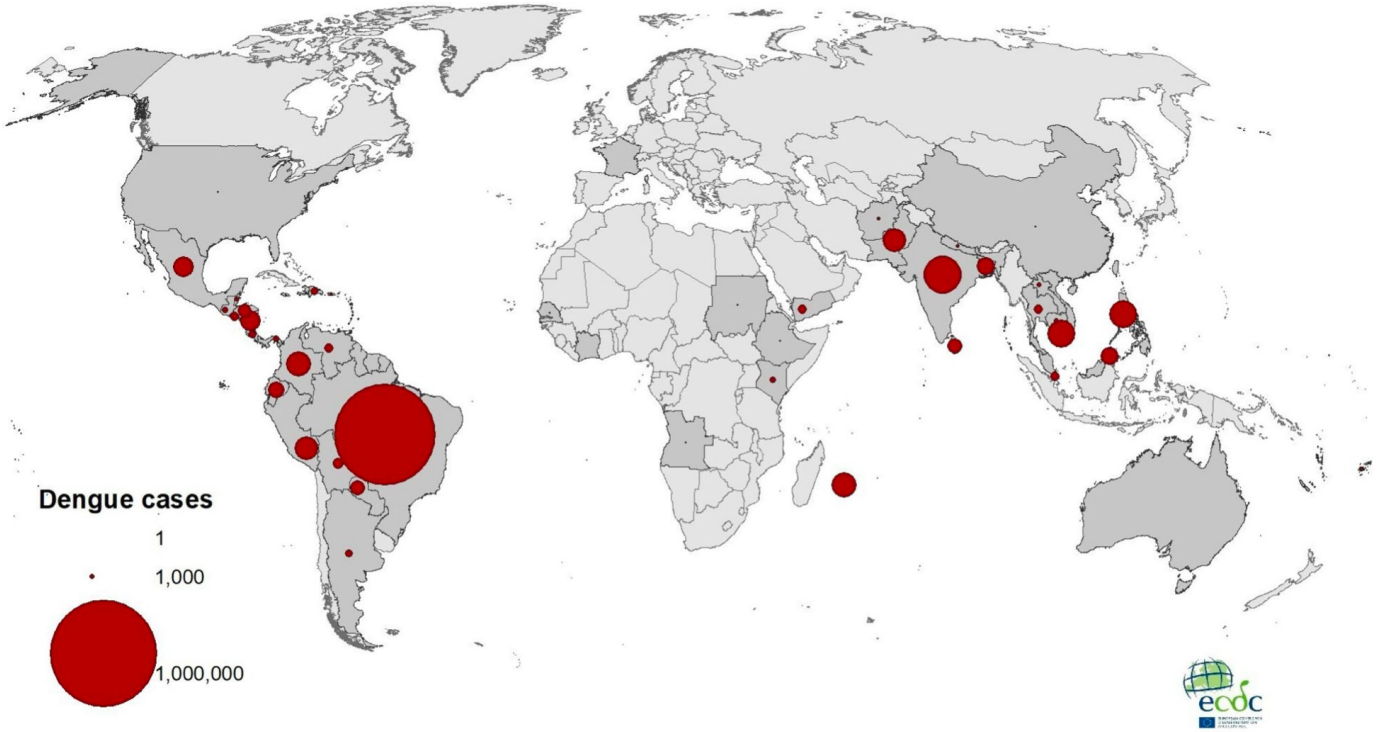


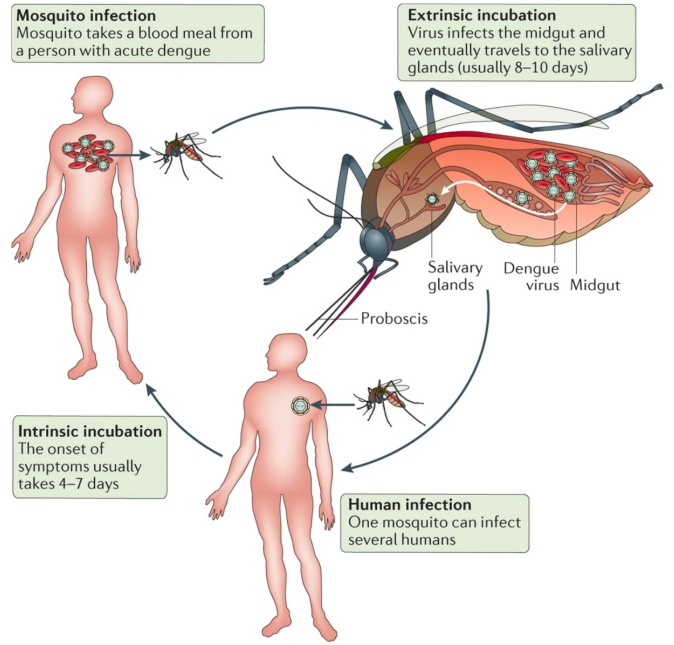
DENGUE FEVER

3.97 billion people at risk

40,467 deaths in 2017

Why do some regions with the vector see regular outbreaks and others do not?

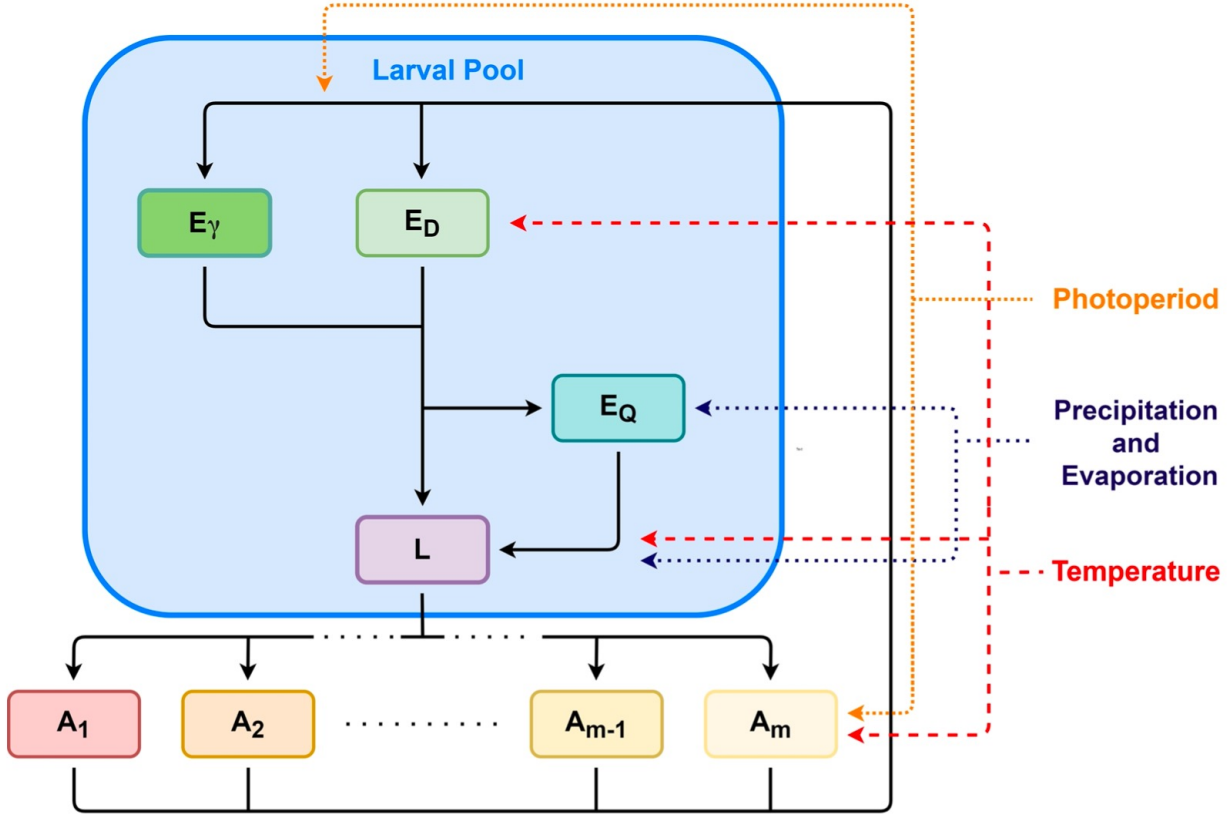




Guzman et al. 2016

MODEL FOR AEDES ALBOPICTUS

Delayed developmental plasticity



Larval conditions

Temperature Competition

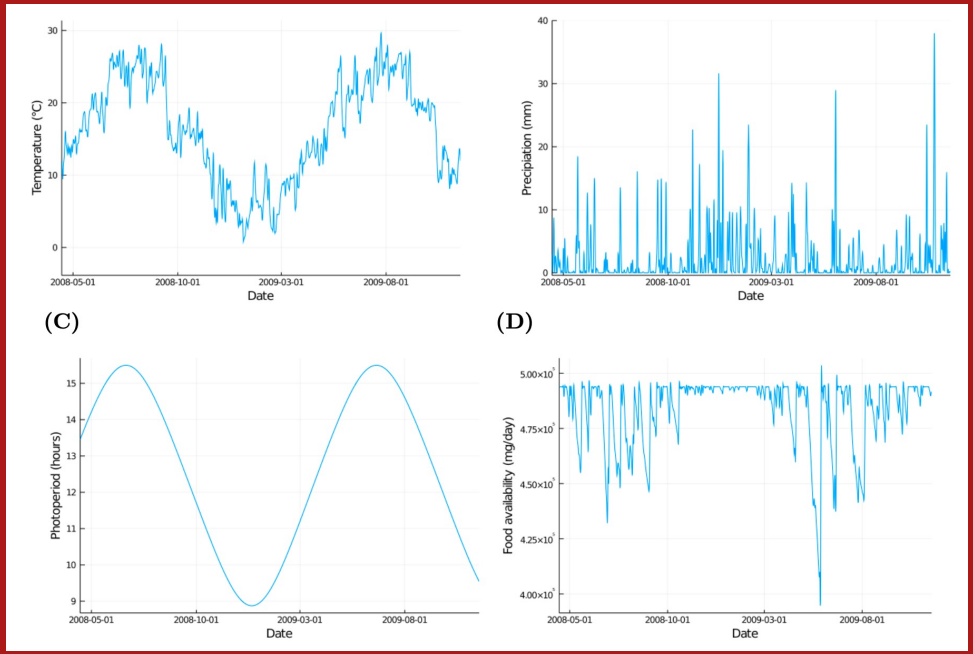
Adult traits

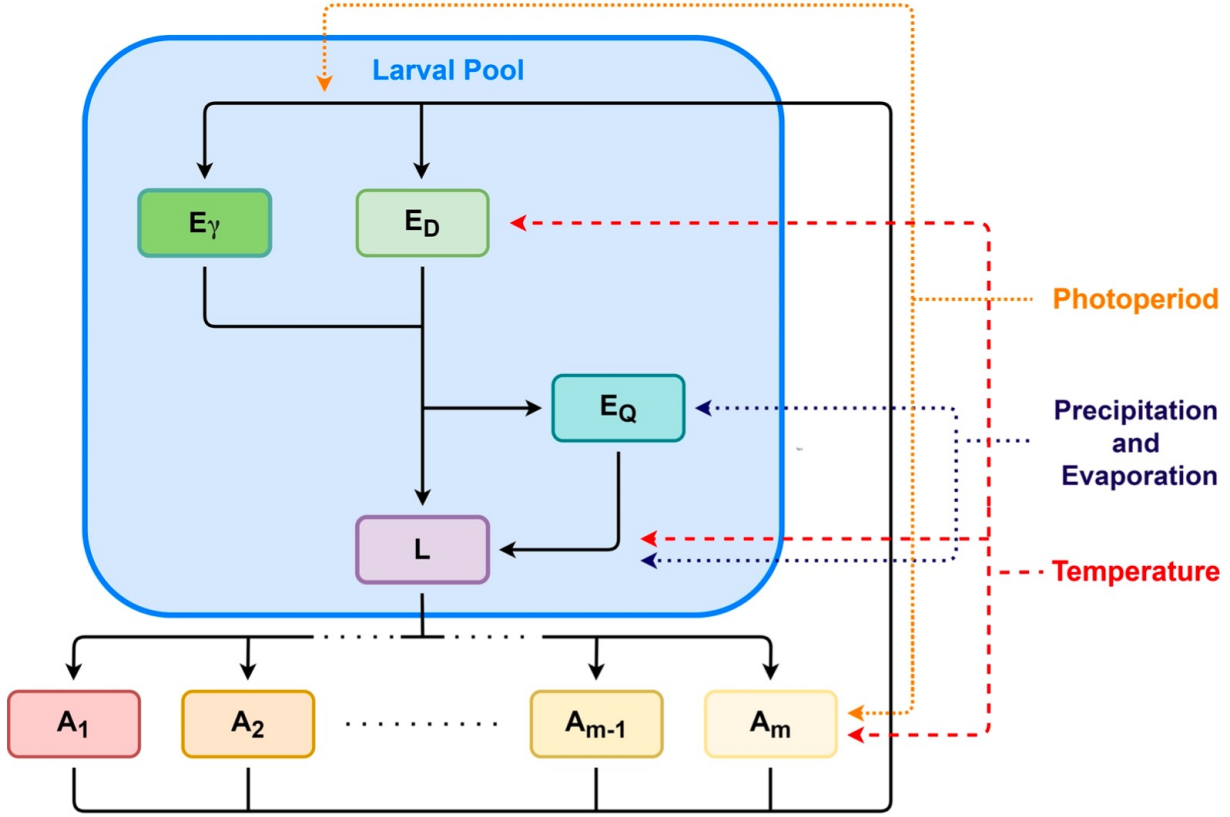
Wing length

Fecundity Survival

MODEL FOR AEDES ALBOPICTUS

Input environmental drivers

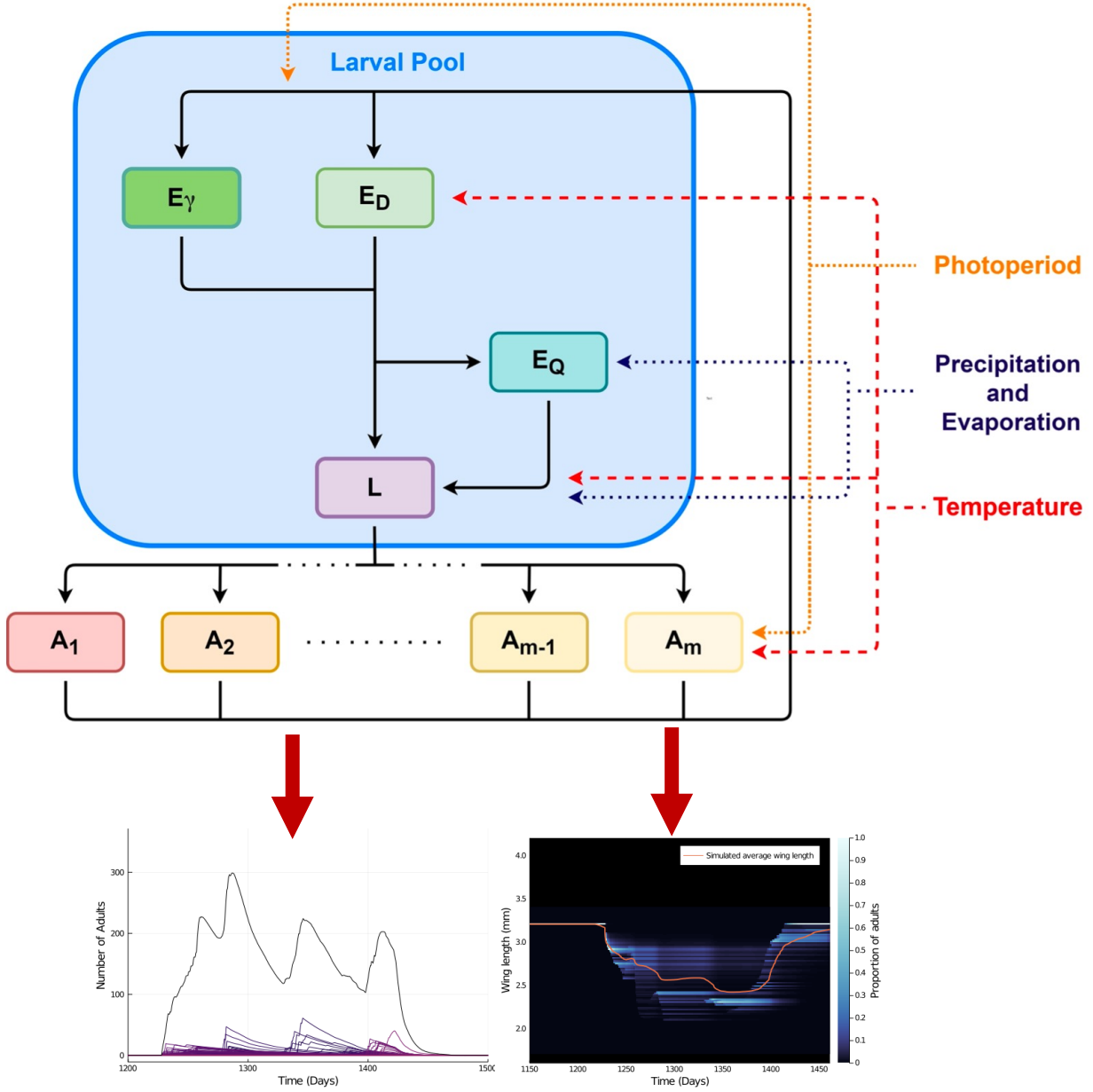




MODEL FOR AEDES ALBOPICTUS

Input environmental drivers

Output population and trait dynamics



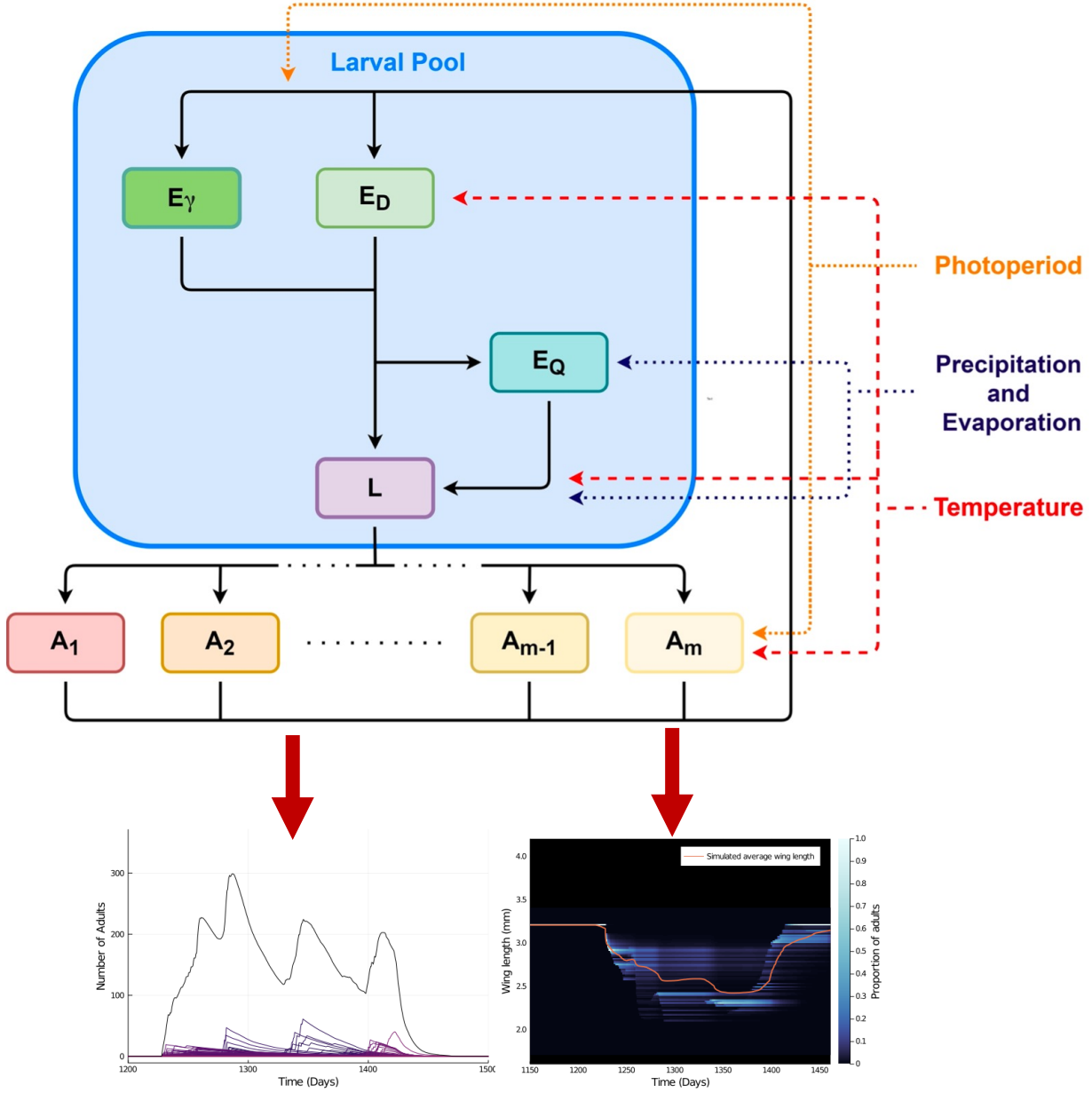
MODEL FOR AEDES ALBOPICTUS

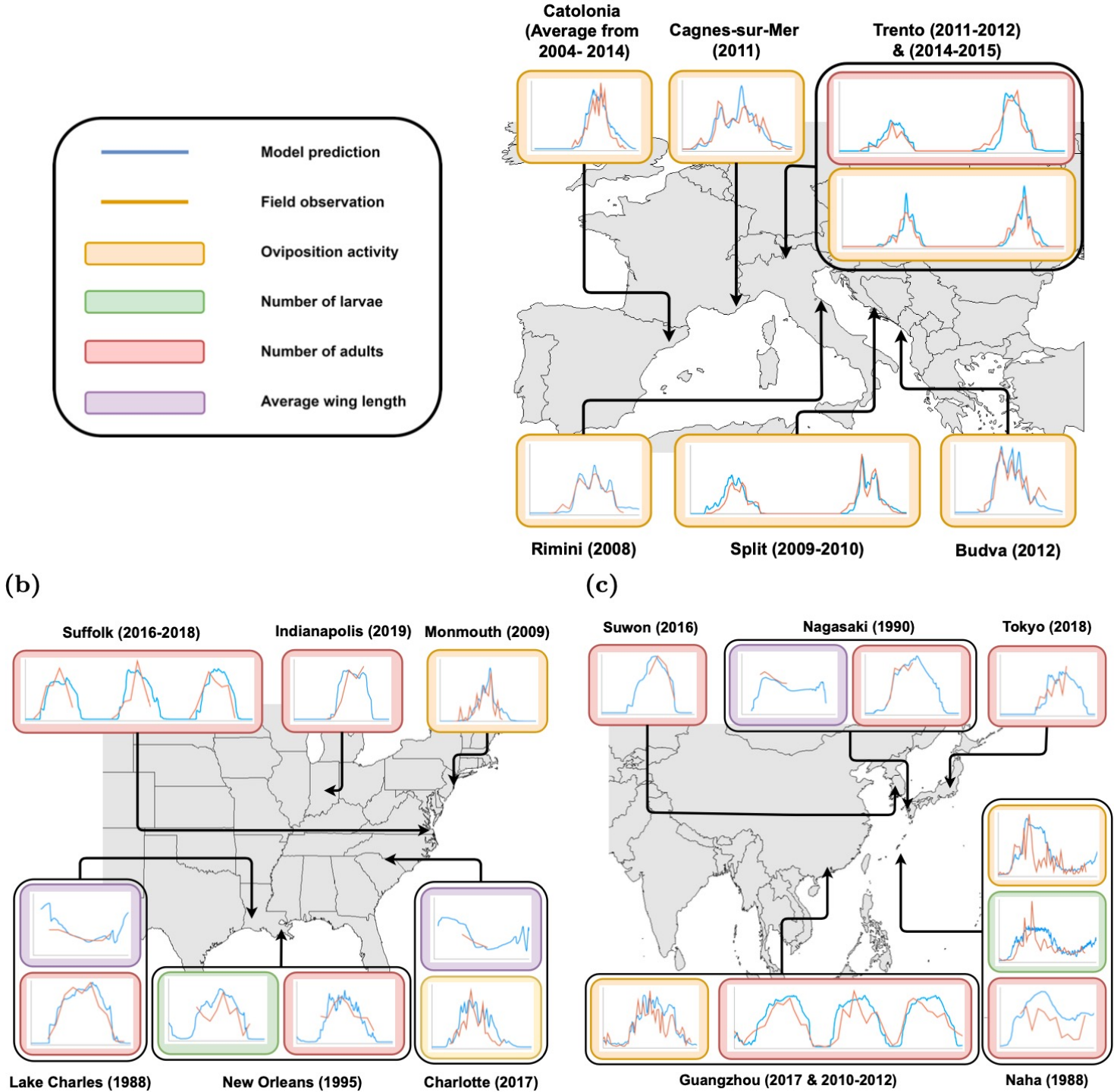
Input environmental drivers

Output population and trait dynamics

Predictions are independently validated against field datasets

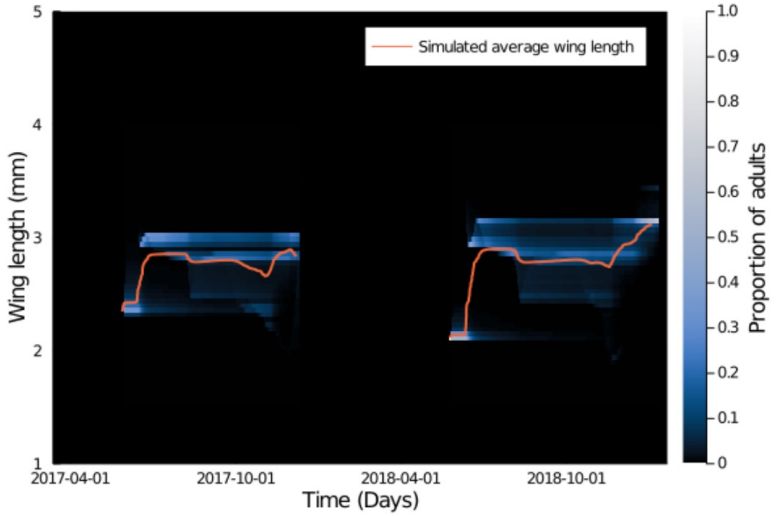
No backfitting

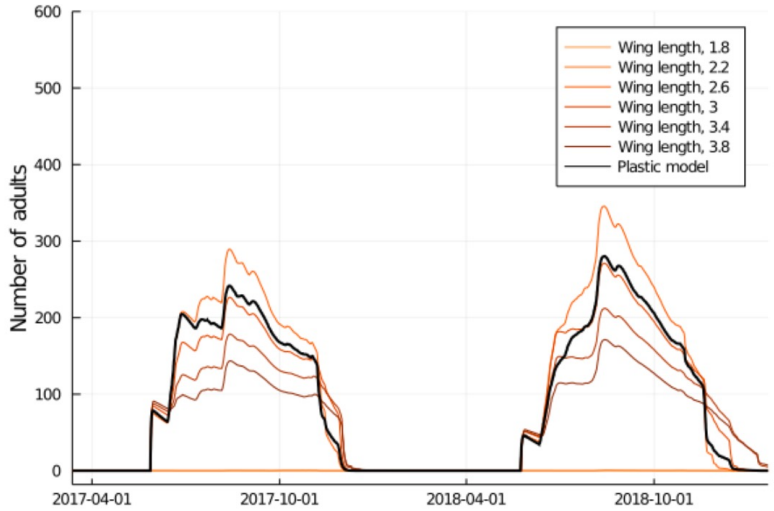




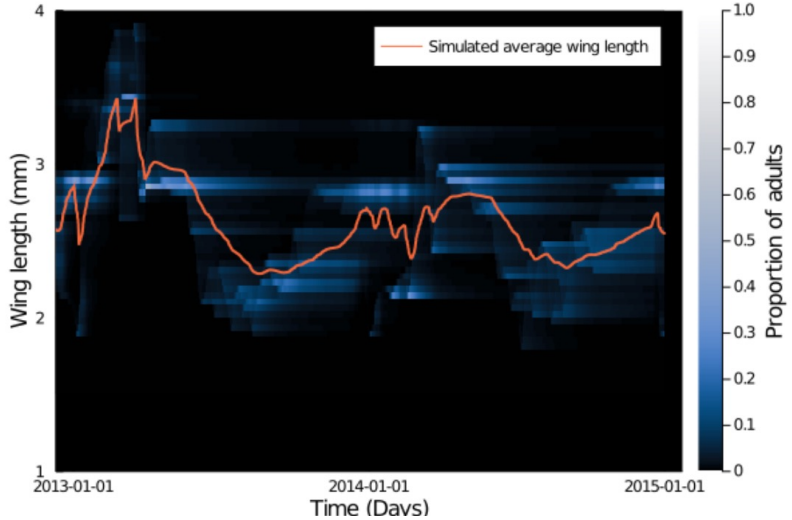
Brass et al. submitted

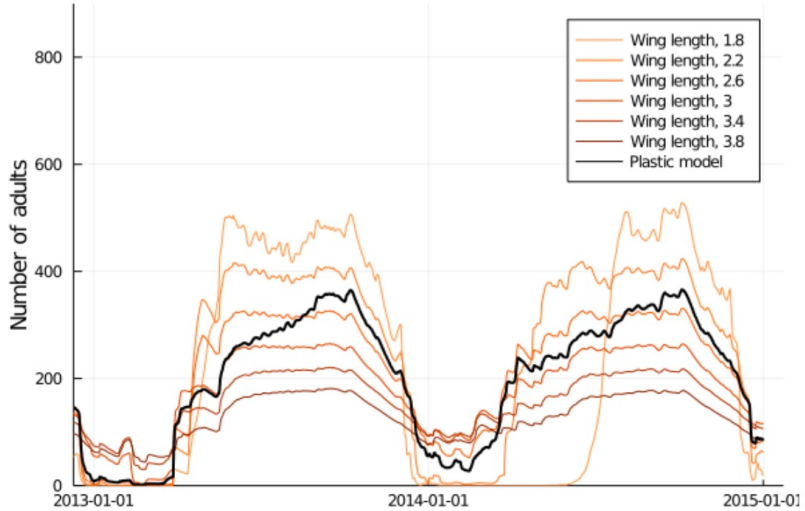
Cagnes-sur-Mer





Guangzhou

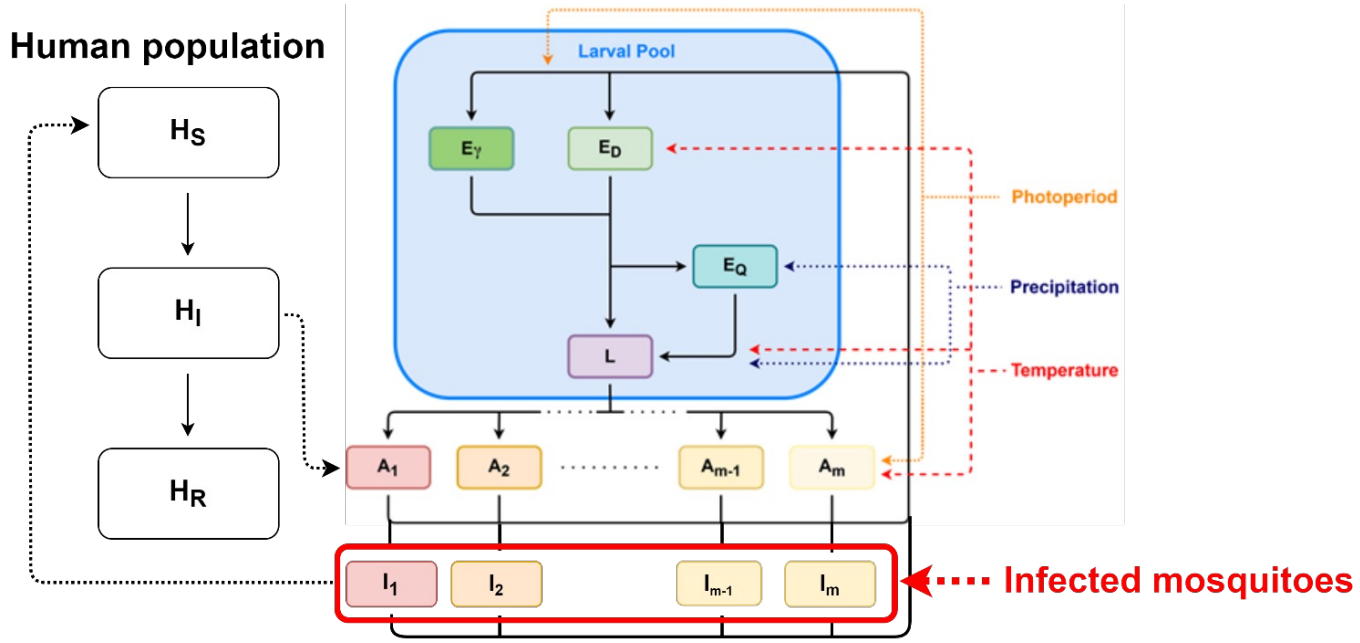




Brass et al. submitted

DENGUE FEVER

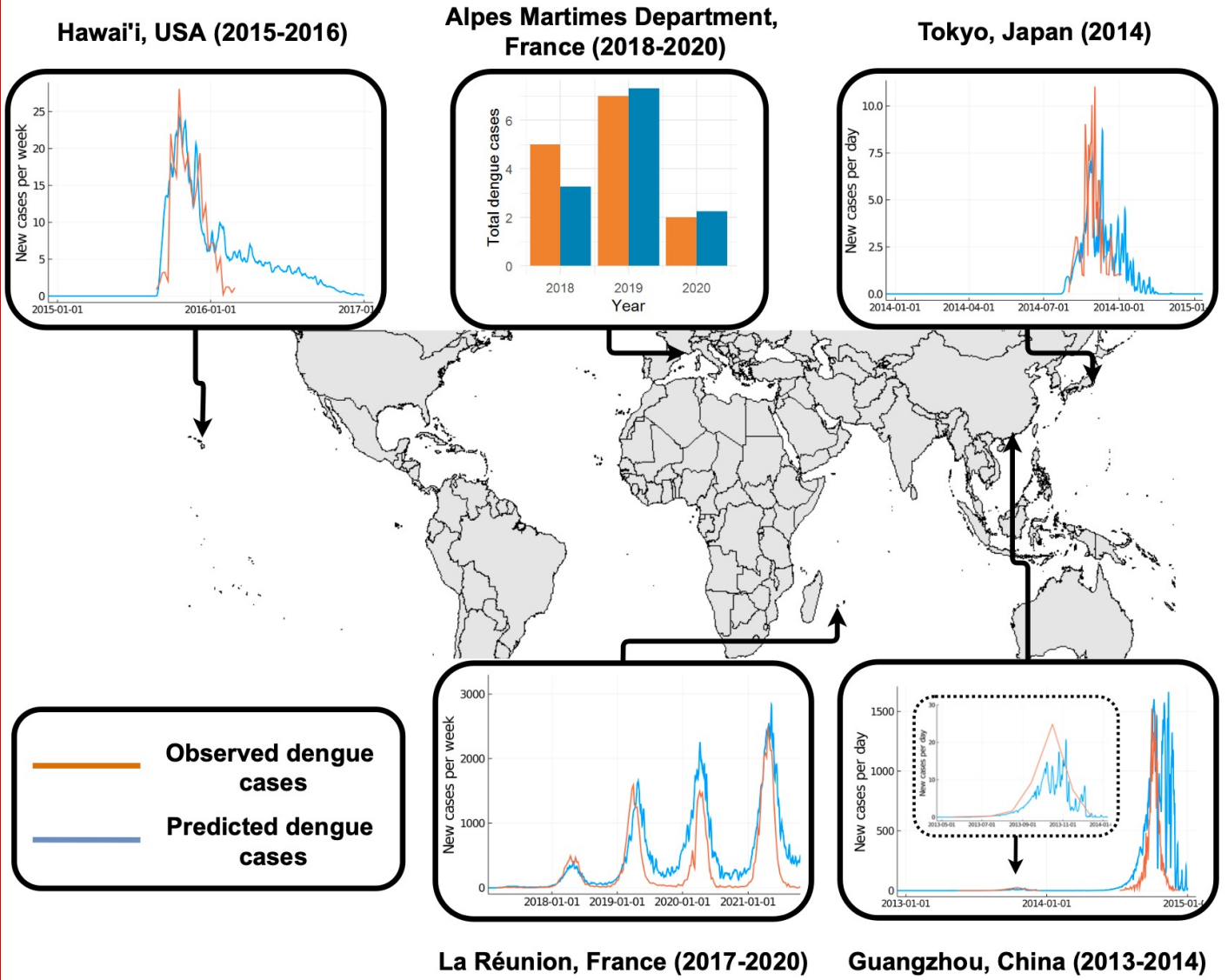
Adapt model to predict dengue fever outbreaks



DENGUE FEVER

Adapt model to predict dengue fever outbreaks

Accurate predictions of timing and magnitude of outbreaks



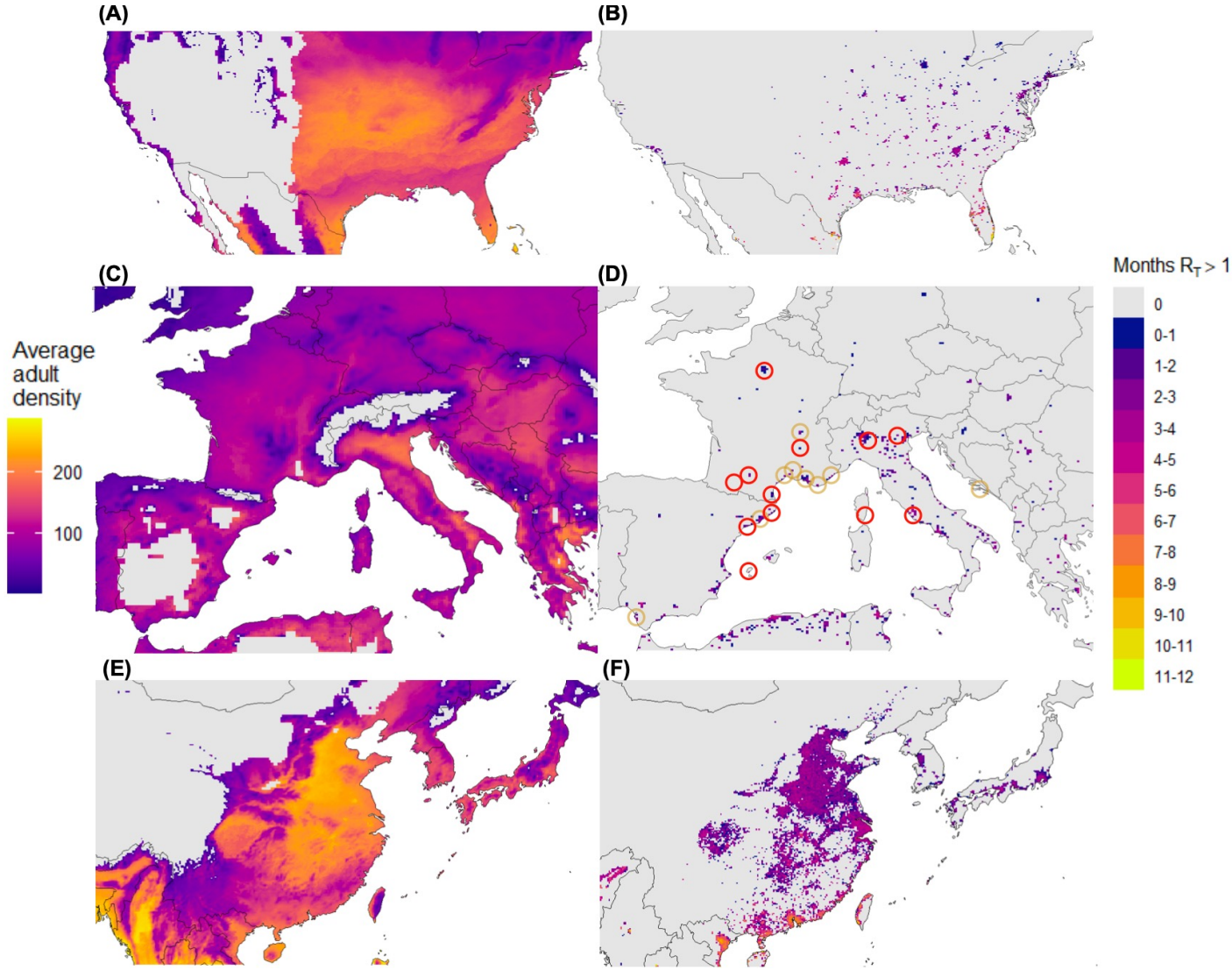
Brass et al. submitted

DENGUE FEVER

Adapt model to predict dengue fever outbreaks

Accurate predictions of timing and magnitude of outbreaks

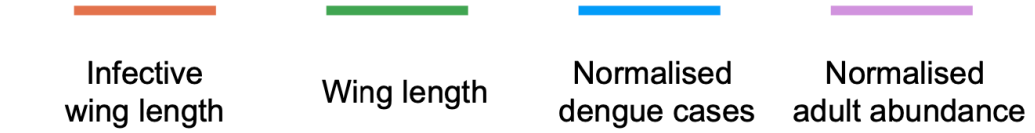
Predict locations of autochthonous transmission

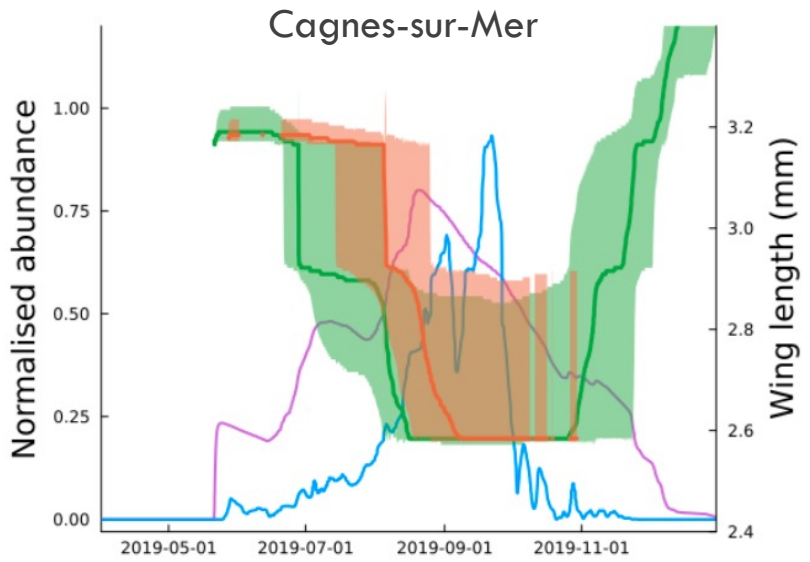


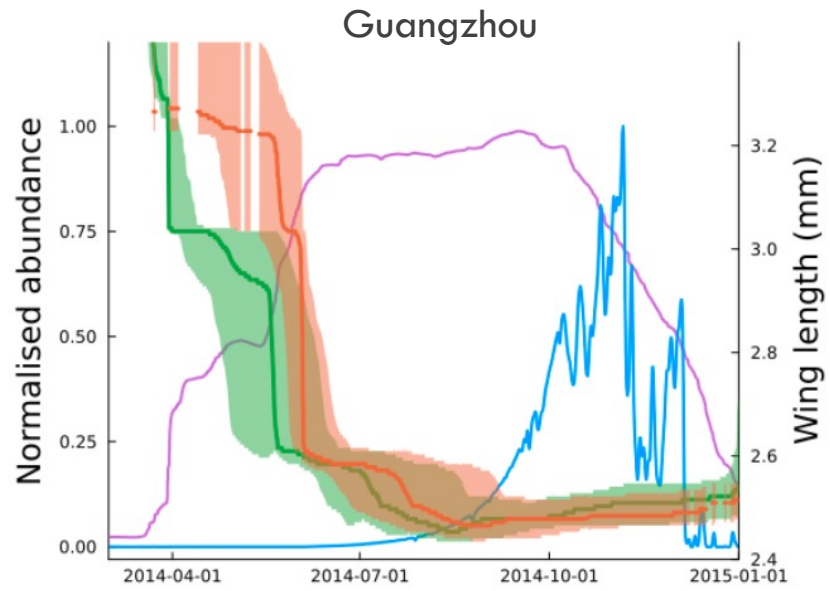
Brass et al. submitted

DENGUE FEVER

Early in the outbreak the majority of transmission is attributed to large, long lived individuals







Brass et al. submitted

CONCLUSIONS

Modelling the traits-population-environment feedback can explain population dynamics

Emergence of novel dynamics and new mathematical questions

Vector-trait dynamics explain the timing, magnitude, and location of dengue outbreaks

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