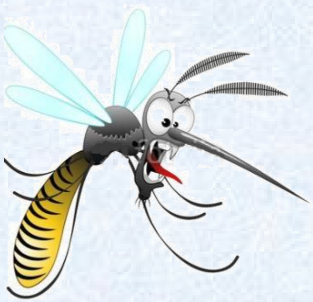
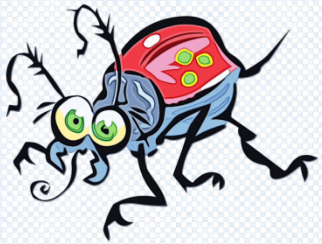
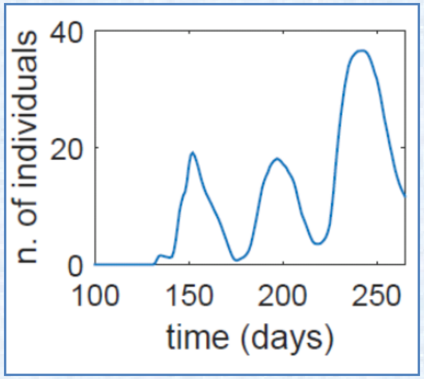
A stage structured demographic model for insect pest dynamics

Sara Pasquali – CNR IMATI Milano







Sustainable pest management






24.11.2009 | EN | Official Journal of the European Union | L 309/71

DIRECTIVES

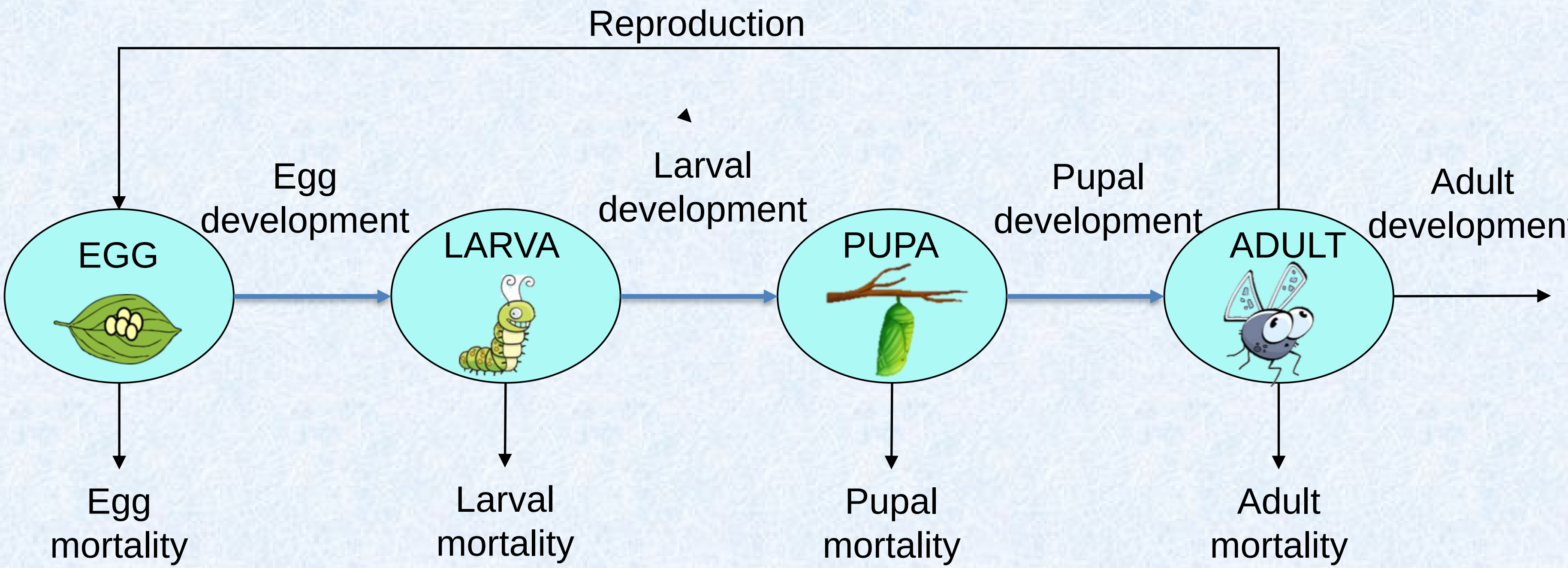
DIRECTIVE 2009/128/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 21 October 2009

establishing a framework for Community action to achieve the sustainable use of pesticides

(Text with EEA relevance)

Stage structured population



Population dynamics models

$$\frac{\partial \phi^i}{\partial t} + \frac{\partial}{\partial x}\left[v^i(t)\phi^i - \sigma^i \frac{\partial \phi^i}{\partial x}\right] + m^i(t)\phi^i = 0, \qquad t > t_0, \qquad x \in (0,1)$$

$$\left[v^i(t)\phi^i(t,x) - \sigma^i \frac{\partial \phi^i}{\partial x}\right]_{x=0} = F^i(t)$$

$$\left[-\sigma^i \frac{\partial \phi^i}{\partial x}\right]_{x=1} = 0$$

$$\phi^i(t_0,x) = \hat{\phi}^i(x) \qquad\qquad i = 1,2,\dots,s$$

Fokker-Planck equations

x = physiological age (percentage of development in a stage)

$v^i(t)$ = development rate function in stage i

$m^i(t)$ = mortality rate function in stage i

Population dynamics models

$$\frac{\partial \phi^i}{\partial t} + \frac{\partial}{\partial x}\left[v^i(t)\phi^i - \sigma^i \frac{\partial \phi^i}{\partial x}\right] + m^i(t)\phi^i = 0, \qquad t > t_0, \qquad x \in (0,1)$$

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Fokker-Planck equations

$\phi^i(t,x)dx$ = number of individuals in stage i with age in $(x, x+dx)$

$N^i(t) = \int_0^1 \phi^i(t,x)dx$ n. of individuals in stage i at time t

$F^1(t) = \int_0^1 b(t)f(x)\,\phi^s(t,x)dx$ egg production flux

$F^i(t) = v^{i-1}(t)\phi^{i-1}(t,x)$ $\quad$ $i > 1$ flux from a stage to the next

σ^i constant diffusion coefficients $\quad$ $\hat{\phi}^i(x)$ initial distributions

Population dynamics models

$$\frac{\partial \phi^i}{\partial t} + \frac{\partial}{\partial x}\left[v^i(t)\phi^i - \sigma^i \frac{\partial \phi^i}{\partial x}\right] + m^i(t)\phi^i = 0,$$

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Buffoni and Pasquali, 2007
Structured population dynamics: continuous size and discontinuous stage structure
J. Math. Biol. 54: 555-595

$v^i(t), m^i(t)$ development and mortality rate functions

$b(t)f(x)$ fecundity rate function

Biodemographic functions

Good estimate of biodemographic functions → **Reliable population dynamics model**

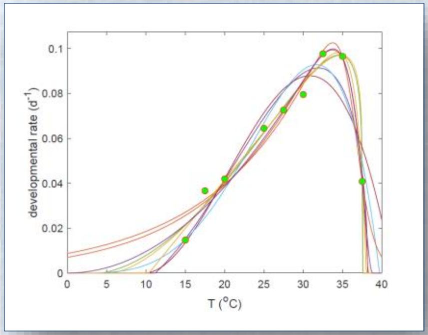
Biodemographic functions

$v^i(t), m^i(t)$ development and mortality rate functions

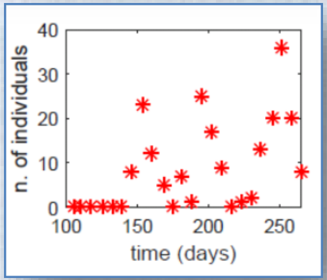
$b(t)f(x)$ fecundity rate function

Biodemographic functions

Data on the biology of the species available → Least square method



Data on the biology of the species NOT available → Statistical estimation method based on population dynamics data



In the following we focus on the estimation of the mortality using population dynamics data

Mortality estimation

CASE 1

$m^i(t)$ of known functional form

least square method

Bayesian method

Gilioli, Pasquali , Marchesini, 2016
A modelling framework for pest population dynamics and management: An application to the grape berry moth - Ecol. Model. 320: 348-357

Lanzarone, Pasquali, Gilioli ,Marchesini, 2017
A Bayesian estimation approach for the mortality in a stage-structured demographic model
J. Math. Biol. 75: 759-779

Mortality estimation

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CASE 2

$$m^i(t) = \sum_{j=1}^{n_i} \alpha_{ij}\xi_{ij}(t)$$

$\xi_{ij}(t)$ suitable basis (ex. splines)

α_{ij} parameters to be estimated

Wood, 2001
Partially specified ecological models
Ecol. Monograph. 71(1): 1-25

Pasquali and Soresina
Estimation of the mortality rate functions from time series field data in a stage-structured demographic model for *Lobesia botrana* - Submitted

Mortality estimation

$$m^i(t) = \sum_{j=1}^{n_i} \alpha_{ij}\xi_{ij}(t)$$ $\xi_{ij}(t)$ suitable basis

w_k weight

Objective: minimize $q(\boldsymbol{p}) = \sum_{k=1}^{d} w_k\left(N^k(\boldsymbol{p}) - Y^k\right)^2$

Y^k observation

d total n. of observations

$N^k(\boldsymbol{p})$ simulated abundance for vector $\boldsymbol{p}$ collecting all parameters α_{ij}

1. Given a guess of $\boldsymbol{p}$ solve system to obtain $N^k(\boldsymbol{p})$
2. Slight changes in parameter to approximate

$$J_{kh} = \frac{\partial N^k}{\partial p_h} \sim \frac{N^k(\boldsymbol{p} + \delta_h e_h) - N^k(\boldsymbol{p} - \delta_h e_h)}{2\delta_h}$$ $\{e_h\}$ canonical basis

3. Construct a quadratic model approximating the fitting objective

$$q(\boldsymbol{p}) \sim (\boldsymbol{Y} - \boldsymbol{N} + \boldsymbol{J}\boldsymbol{p})^T W (\boldsymbol{Y} - \boldsymbol{N} + \boldsymbol{J}\boldsymbol{p})$$ where $W_{kk} = w_k$

4. Minimize $q(\boldsymbol{p})$ and then repeat steps 1 – 4 until convergence and obtain $\overline{\boldsymbol{p}}$

Confidence bands

$$m^i(t) = \sum_{j=1}^{n_i} \alpha_{ij}\xi_{ij}(t)$$ $\xi_{ij}(t)$ suitable basis

The method allows to obtain confidence bands for the mortality rate function

Denoting by $\boldsymbol{P} = argmin_{\boldsymbol{p}}(q(\boldsymbol{p}))$ the estimator, the parameter covariance matrix is given by

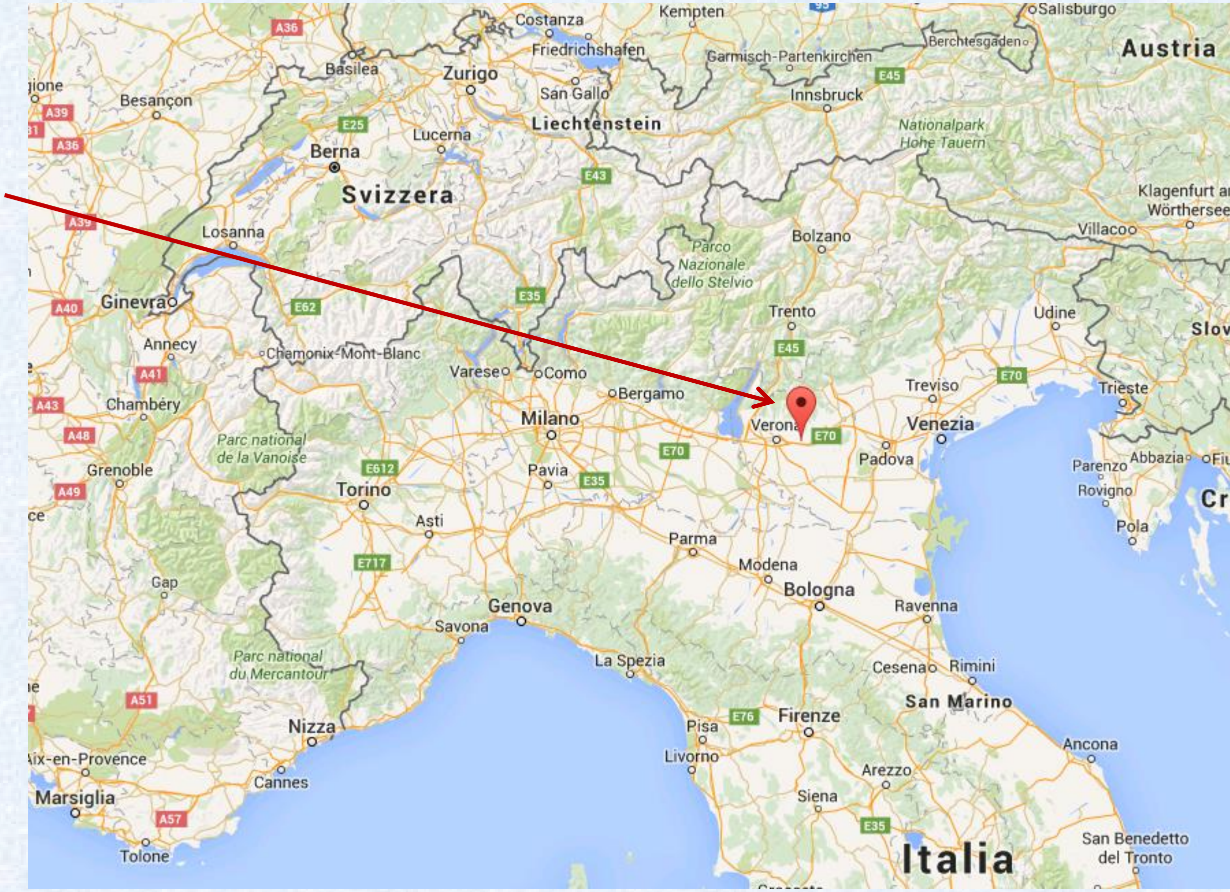
$$C_J(\boldsymbol{P}) = \frac{q(\boldsymbol{P})}{d - n_p}(\boldsymbol{J}^Y W^{-1}\boldsymbol{J})^{-1}$$

For large samples, $\boldsymbol{P}$ has approximately a multivariate normal distribution with mean $\overline{\boldsymbol{p}}$ and covariance matrix $C_J(\overline{\boldsymbol{p}})$

To obtain confidence bands for mortality we draw a certain number of values for $\boldsymbol{p}$ from this distribution and then compute confidence bands

Case study: the grape berry moth

Estimate the mortality in order to fit the abundance data collected in a vineyard in Colognola ai Colli (Italy) for three years (2008, 2009 and 2011)



Data collected for the cultivar Garganega, from April to September (grape harvest).
Immatures: on a sample of 100 bunches of grapes.
Adults: pheromone traps.

Data on grape berry moth

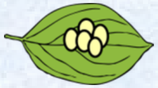
INPUT DATA FOR MODEL SIMULATION

- Temperatures recorded by a meteorological station placed nearby the vineyard

- N. of adults catches per week until larvae of the first generation are detected

FURTHER DATA FOR MORTALITY ESTIMATION

Weekly data for



- eggs

- larvae

- pupae

- adults

L. botrana biodemographic functions

$v^i(T),\ b(T)f(x)$ development and fecundity rate functions

estimated from literature data (laboratory experimental data)

- Baumgärtner and Baronio, 1988

Modello fenologico di volo di Lobesia relativo alla situazione ambientale della Emilia-Romagna - Boll. Ist. Entom. Univ. Bologna 43, 157–170

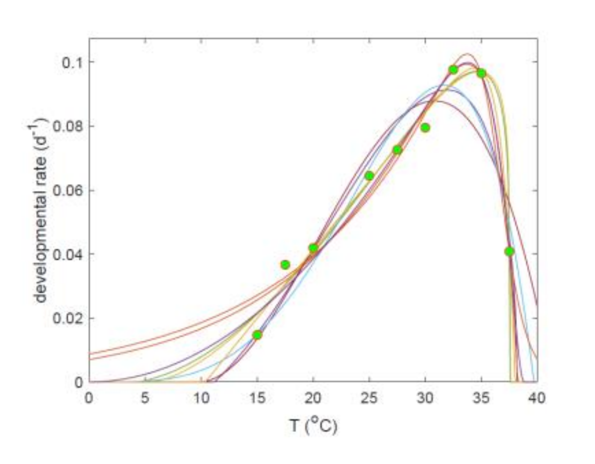
- Brière and Pracros, 1998

Comparison of temperature dependent growth models with the development of *Lobesia botrana* (Lepidoptera: Tortricidae) - Environ.Entomol. 27, 94–101

Functional forms for the development rate function

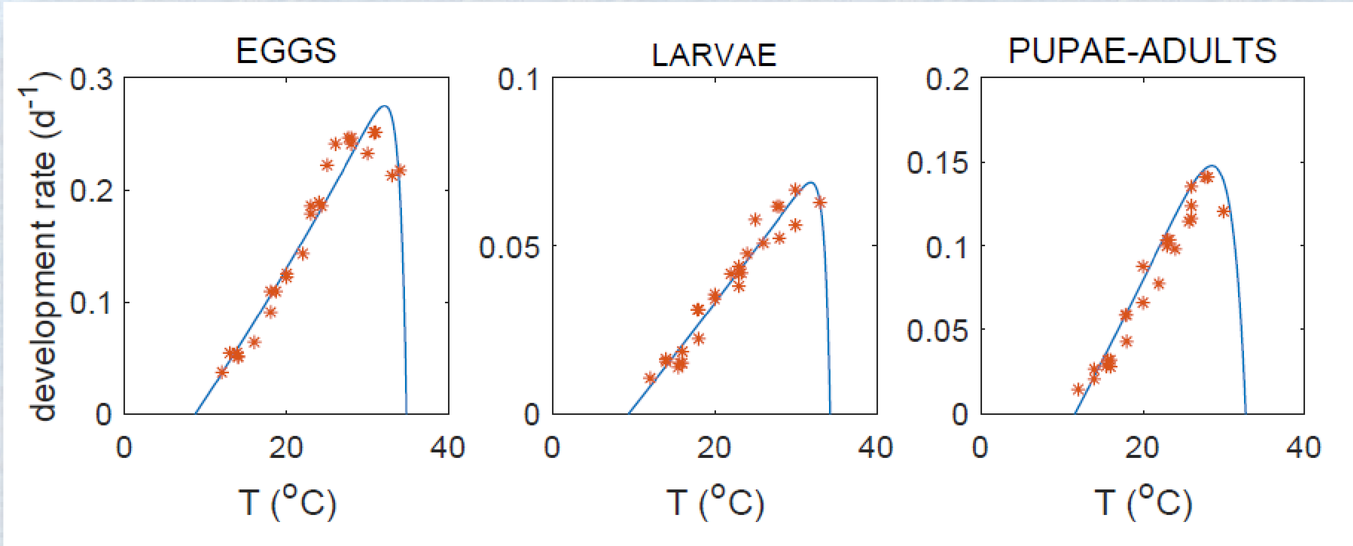
good review

Kontodimas, Eliopoulos, Stathas and Economou, 2004
Environ. Entomol. 33 (1), 1–11



L. Botrana biodemographic functions

Development:
Lactin functions

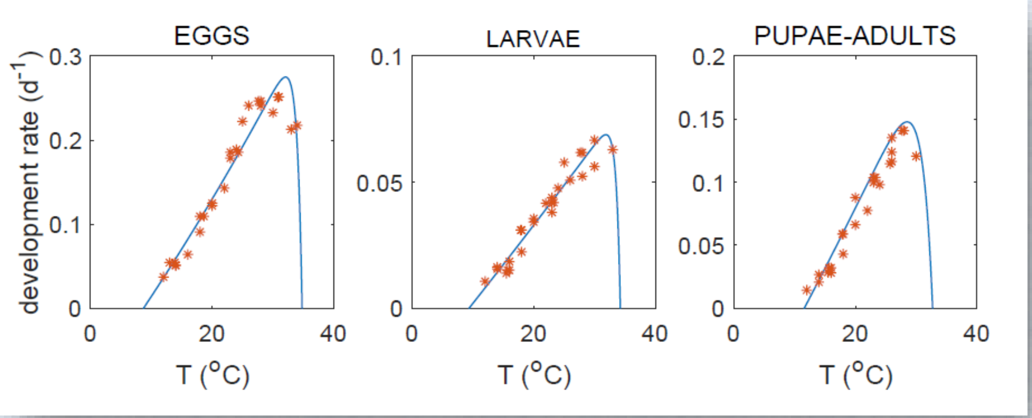


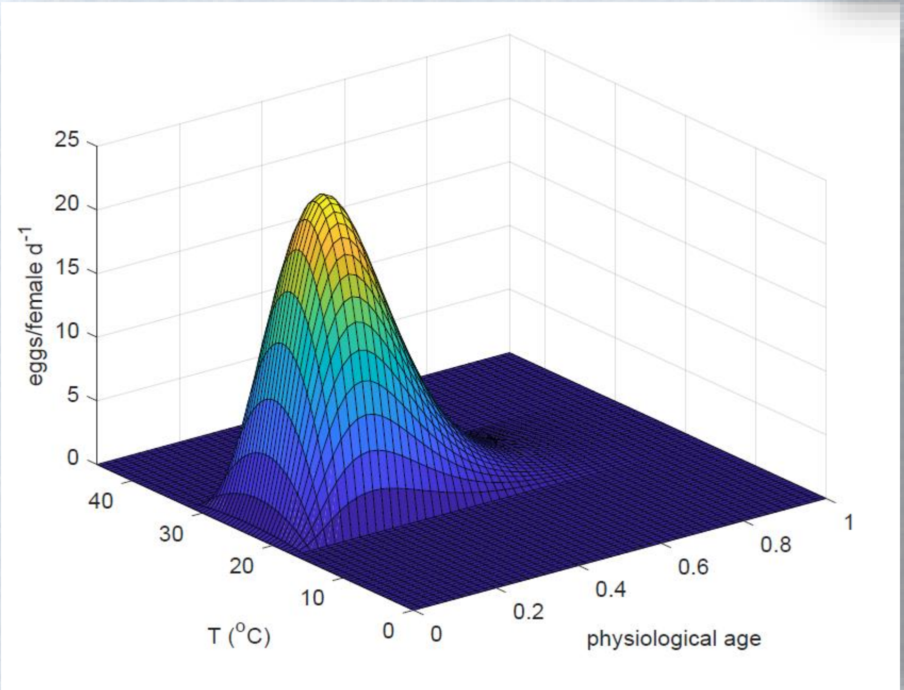
Same development rate function for pupae and adults

Gutierrez, Ponti, Cooper, Gilioli, Baumgärtner, Duso, 2012
Prospective analysis of the invasive potential of the European grapevine moth *Lobesia botrana* (De & Schiff.) in California. Agr. Forest Entomol. 14, 225–238.

L. Botrana biodemographic functions

Development:
Lactin functions





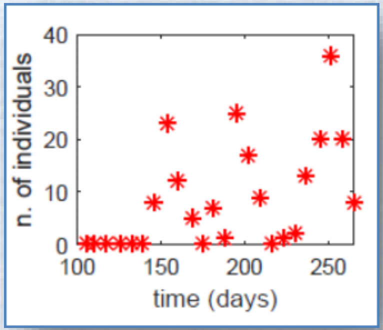
Fecundity function

$$ax^b e^{-cx}\left[1-\left(\frac{T-T_L-T_0}{T_0}\right)^2\right]$$

L. Botrana mortality rate function

$m^i(T)$ mortality rate function

??? No literature data



Data on population dynamics to estimate mortality rate function

$$m^i(t) = \sum_{j=1}^{7} \alpha_{ij} \xi_{ij}(t)$$

α_{ij} parameters to be estimated

$\xi_{ij}(t)$ cubic spline basis built on the nodes $[0,10,20,30,40]$

Constraints:

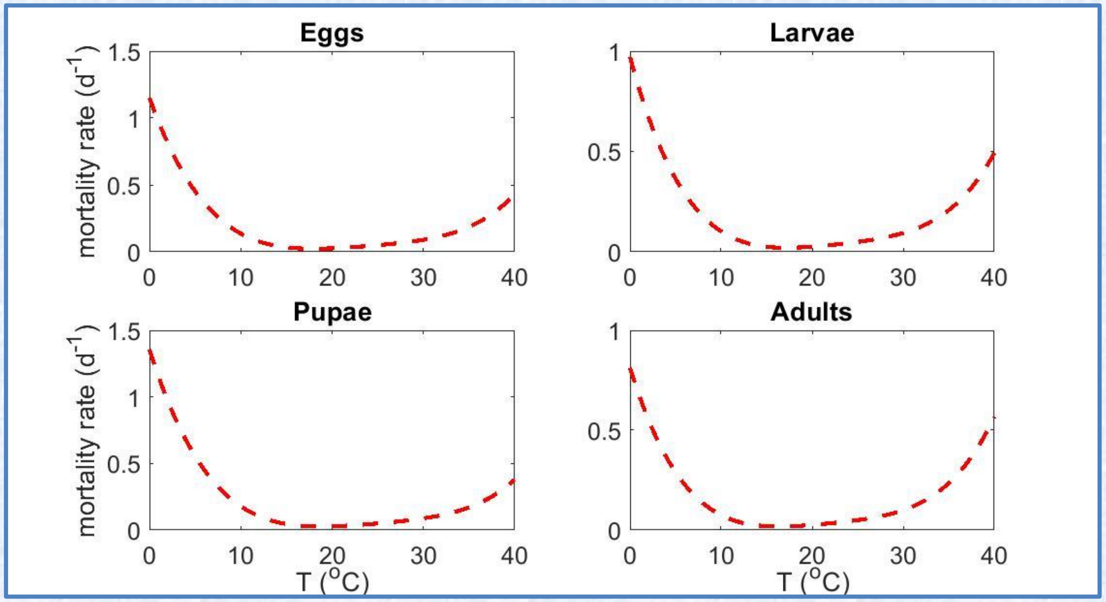
- $m^i(t)$ non negative continuous function
- $m^i(0) > 0$ and $m^i(40) > 0$

L. Botrana: generated data

Generate data for 3 years: 2008 2009 2011

Hourly temperature available for Colognola ai Colli

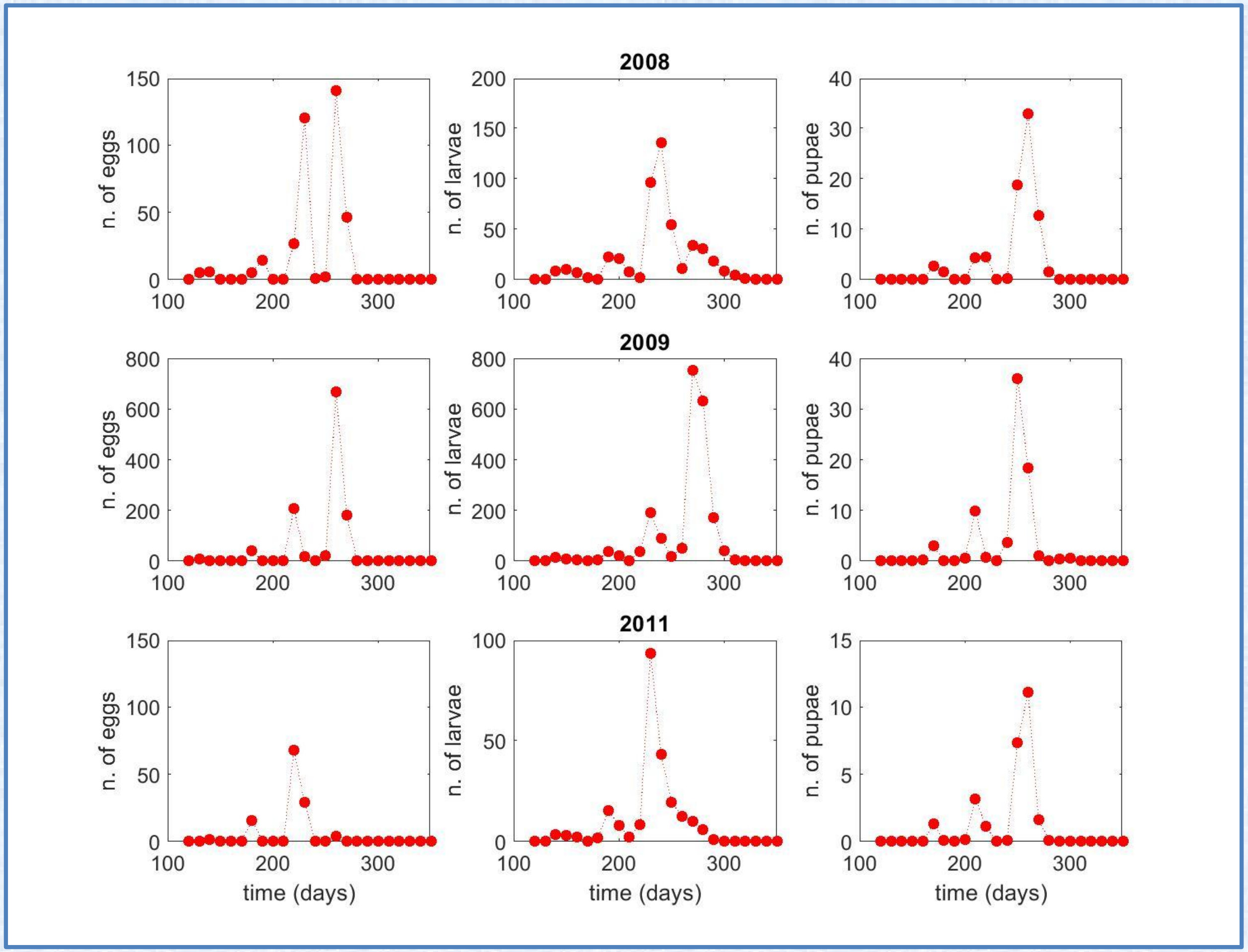
Initial condition: 100 adults with physiological age 0 at May 1st



Mortalities: bath tube shape functions

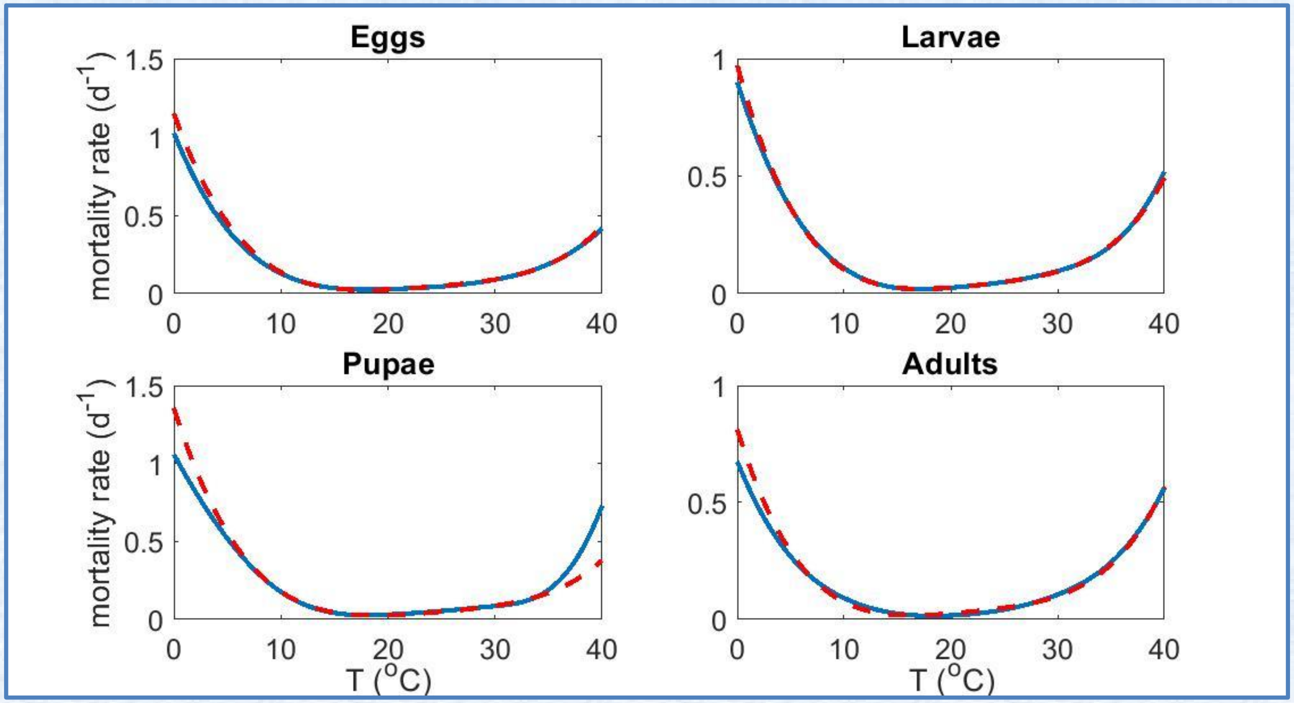
L. Botrana: generated data

We pick a value of abundance each 10 days for all the stages, up to the end of the year



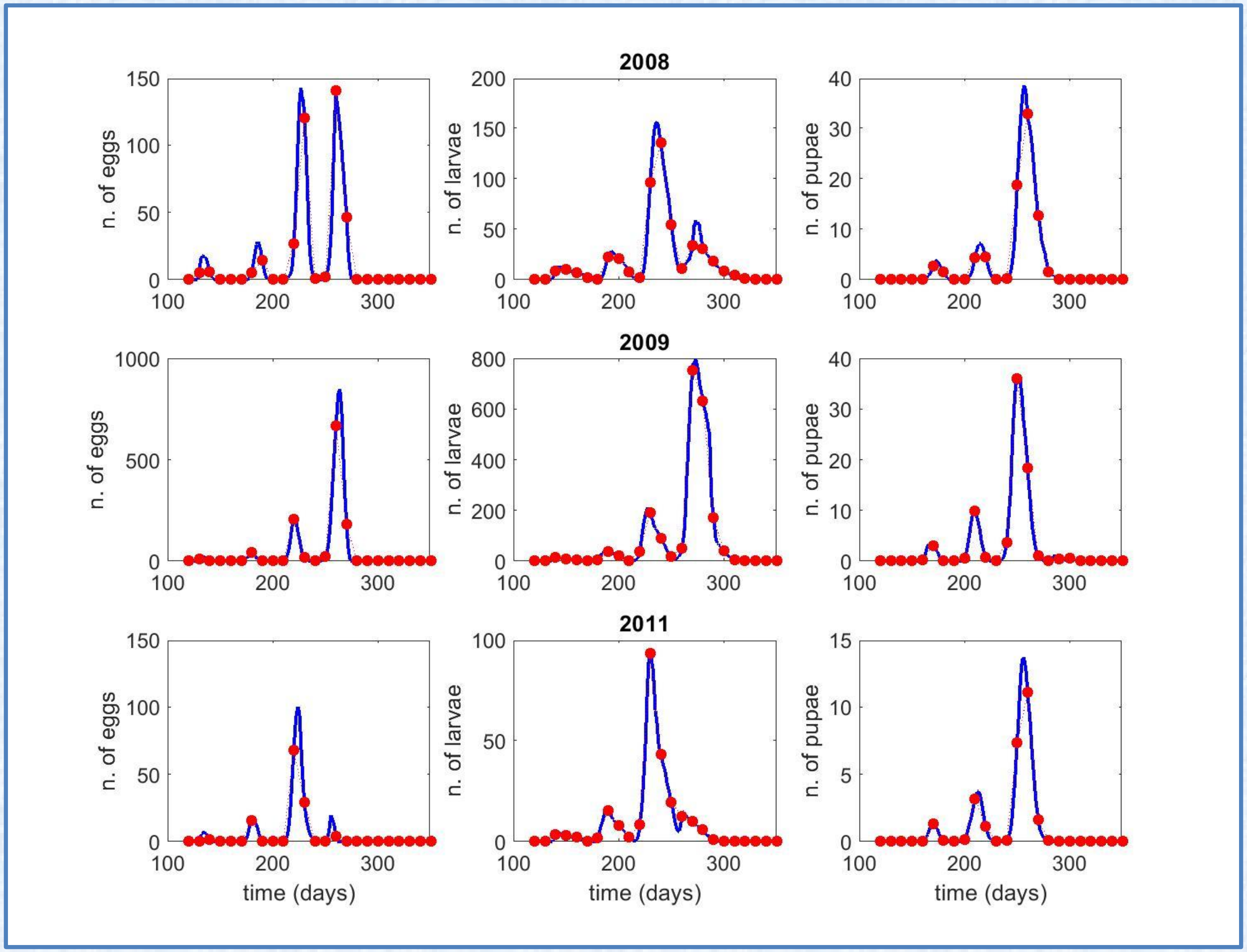
L. Botrana: generated data

To estimate the mortality we consider equal weights for all the data



Blue continuous line: mortality estimate

L. Botrana: generated data

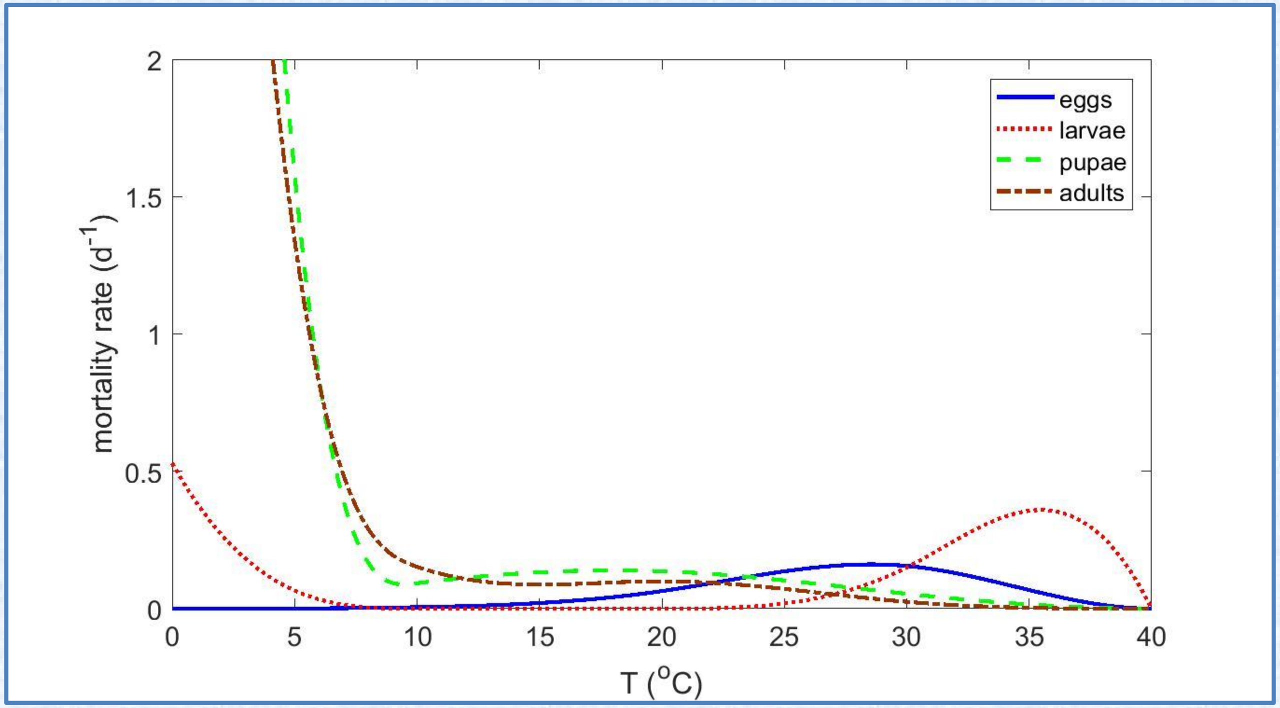


L. Botrana: field data

Use data for 3 years: 2008 2009 2011

Hourly temperature in Colognola ai Colli

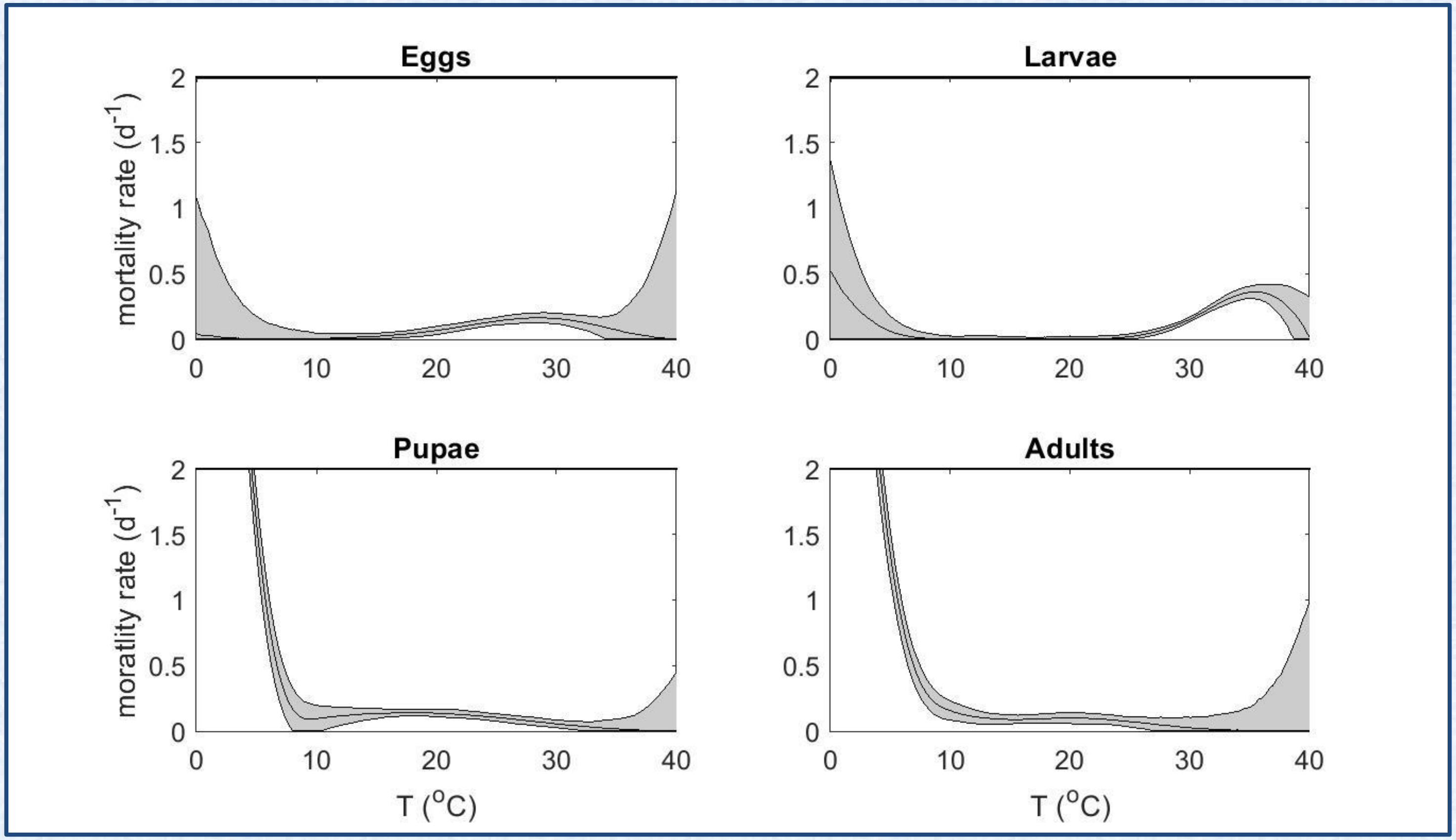
Initial condition: n. of adults catches per trap per week until the first larvae of the first generation are observed



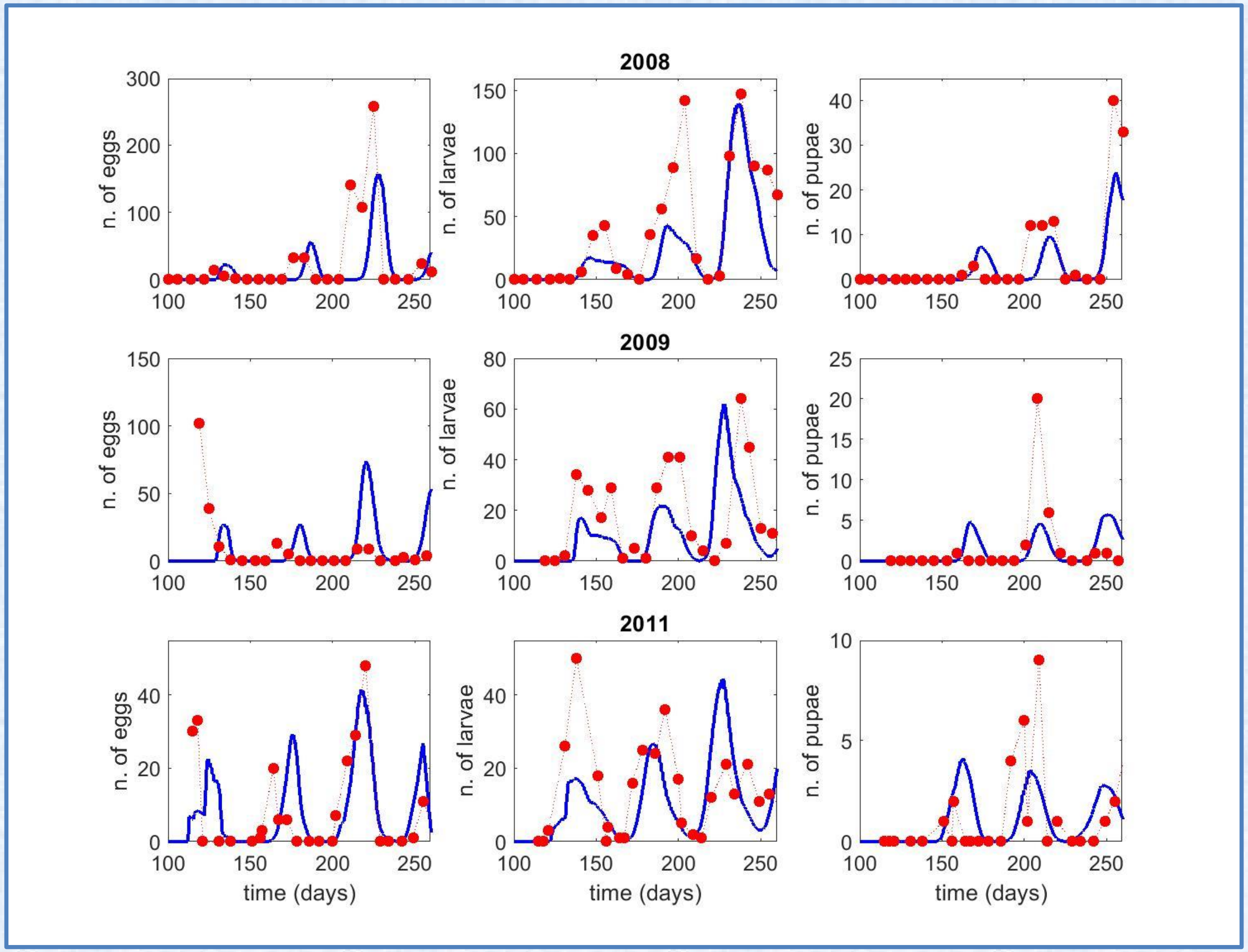
Equal weights for all the data

L. Botrana: field data

95% confidence bands for mortality: obtained drawing 500 values of the parameter vector from its multivariate normal distribution corresponding to 500 mortalities for each stage

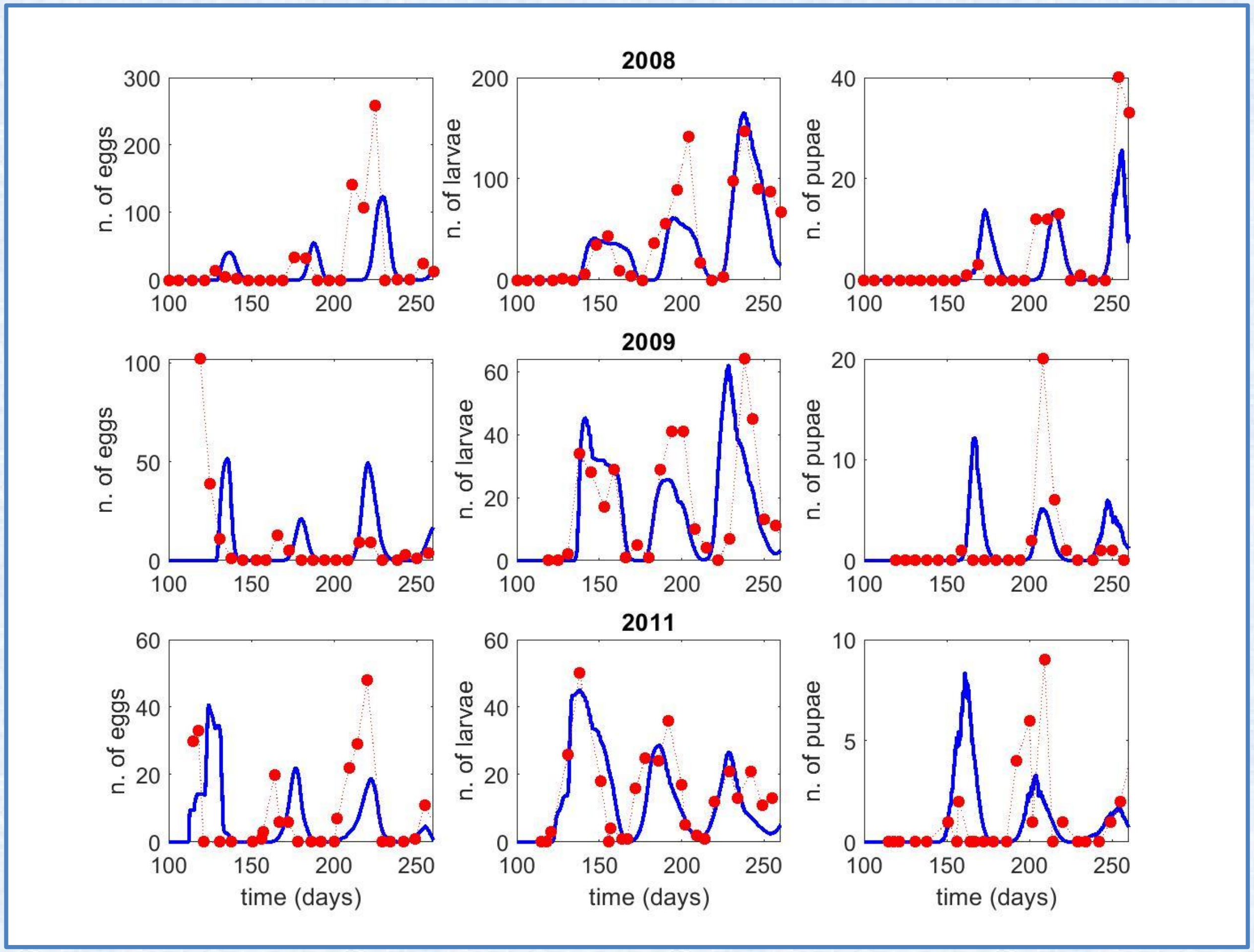


L. Botrana: field data



EQUAL WEIGHTS

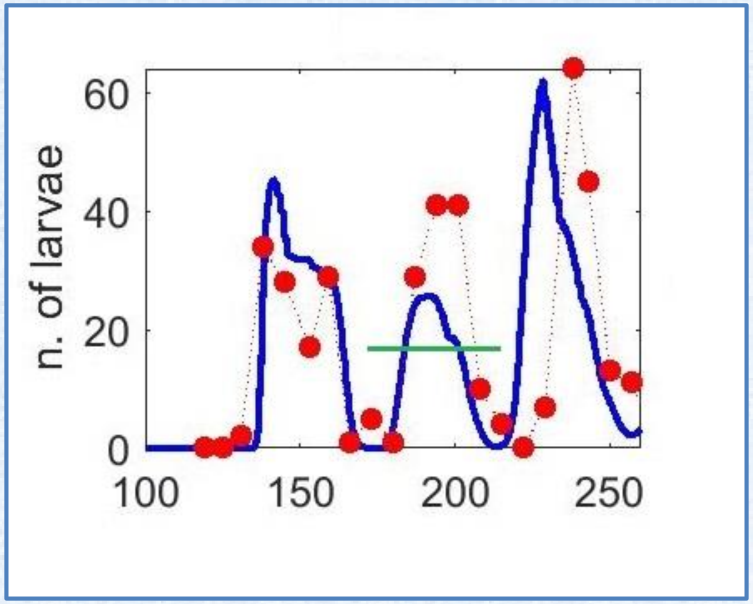
L. Botrana: field data



HIGHER WEIGHTS FOR LARVAE (10 times)

Pest control

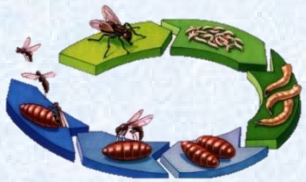
Population dynamics models can be used to forecast the dynamics and control if alert thresholds are crossed.

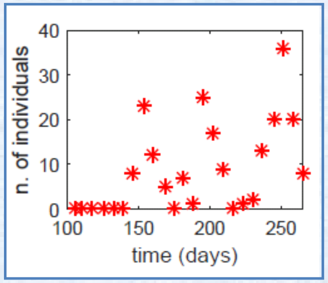


Larvae of 2nd generation: most damaging stage

Red: collected data
Blue: simulated dynamics
Green: control threshold for treatment in 2nd generation

Decision support system





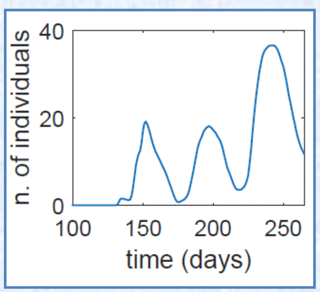
Expert knowledge on treatments

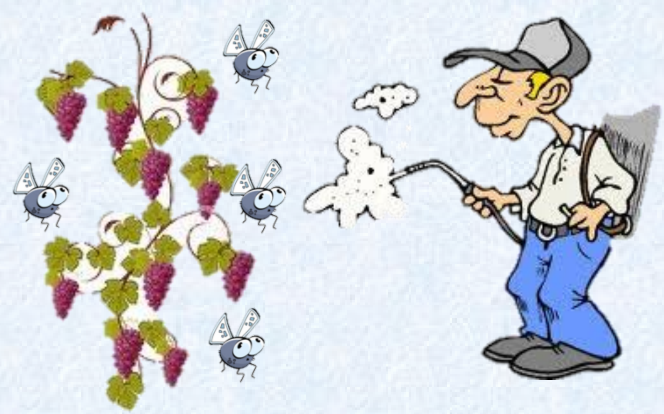
$$
\begin{aligned}
&\frac{\partial \phi^i}{\partial t} + \frac{\partial}{\partial x}\left[v^i(t)\phi^i - \sigma^i \frac{\partial \phi^i}{\partial x}\right] + m^i(t)\phi^i = 0,\\
&\left[v^i(t)\phi^i(t,x) - \sigma^i \frac{\partial \phi^i}{\partial x}\right]_{x=0} = F^i(t), \quad t > t_0, \; x \in (0,1)\\
&\left[-\sigma^i \frac{\partial \phi^i}{\partial x}\right]_{x=1} = 0\\
&\phi^i(t_0,x) = \hat{\phi}^i(x) \qquad\qquad i = 1,2,3,4
\end{aligned}
$$

Methods of parameter estimation

MODELS

DECISIONS






THANK YOU!