MODELLING THE POPULATION DYNAMICS OF AN INSECT PEST

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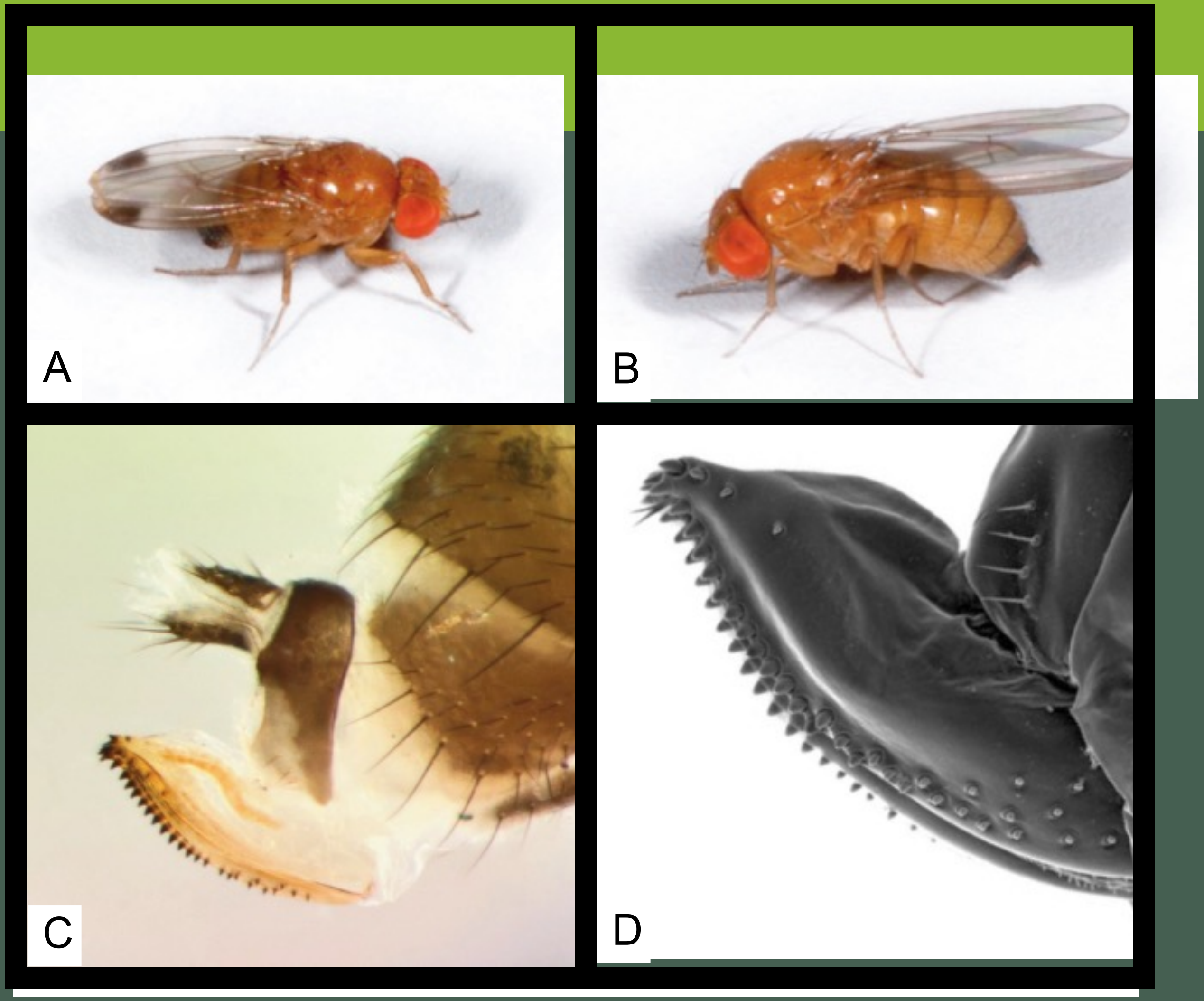
BACKGROUND

DROSOPHILA SUZUKII



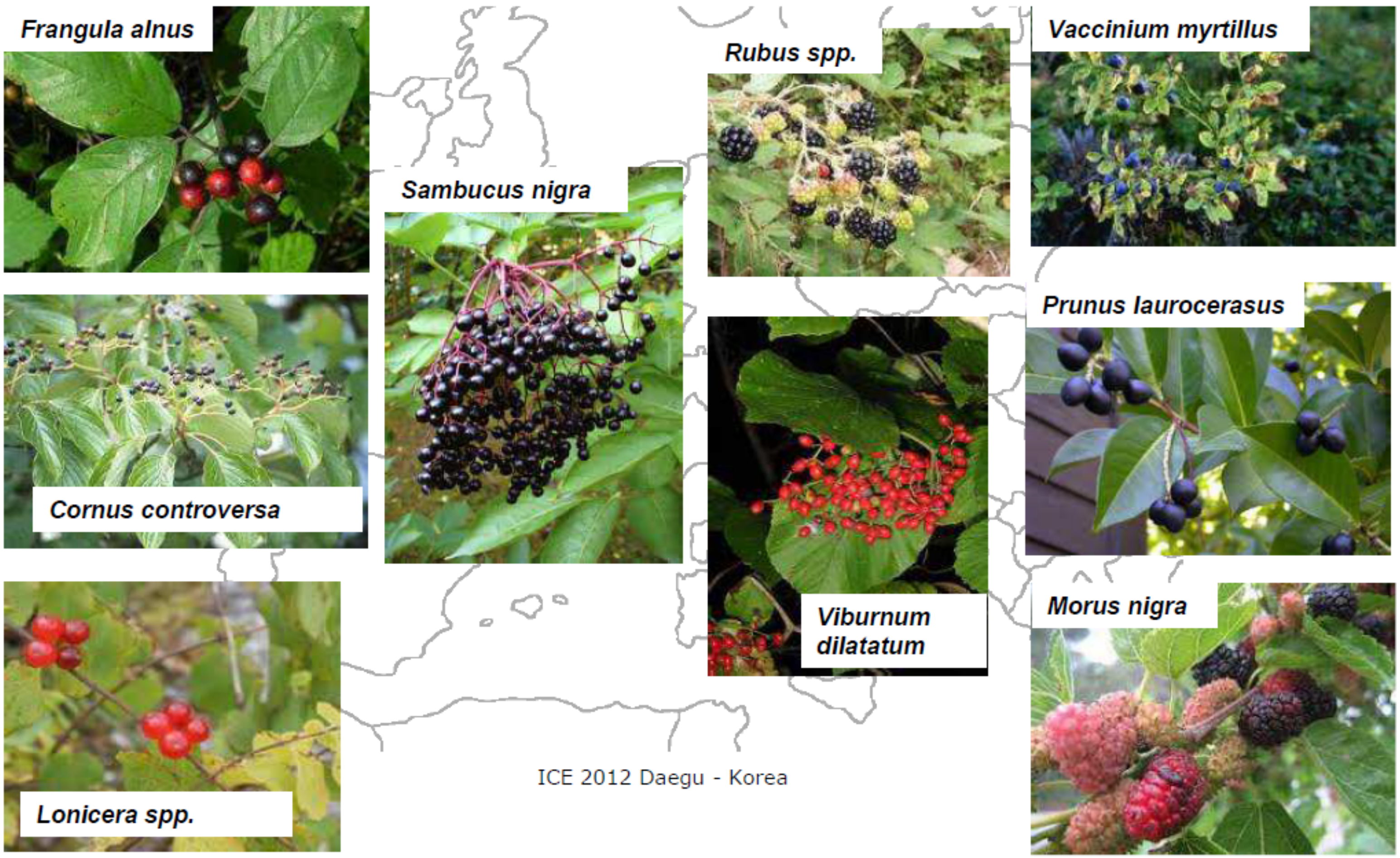
Wide host range

<u>Main host plants</u>:

blackberries, blueberries, cherries, peaches, raspberries, strawberries, grapes (wine and table), kiwis, apricots, figs, pears

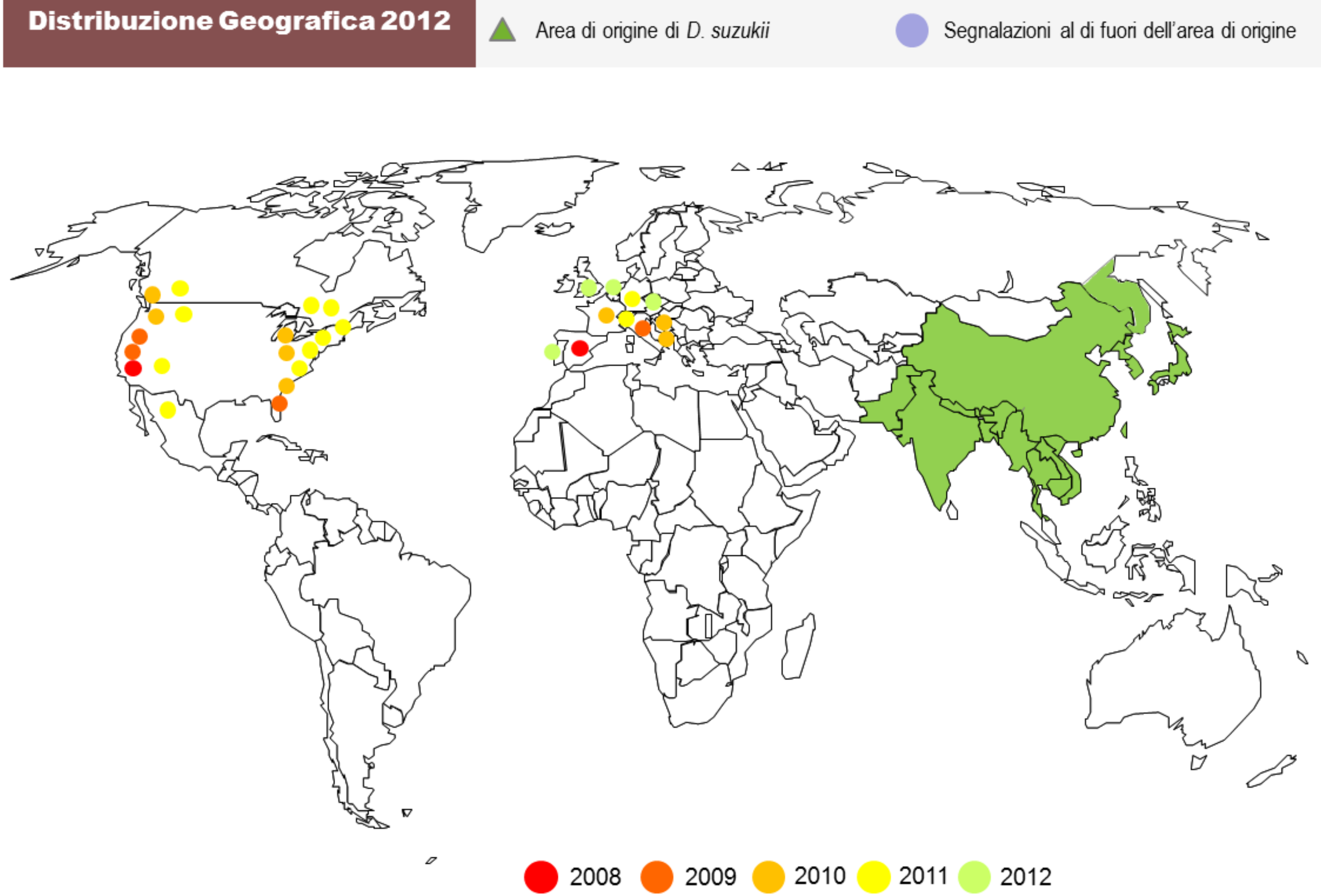
<u>Several alternative wild hosts</u>

Wild host plant

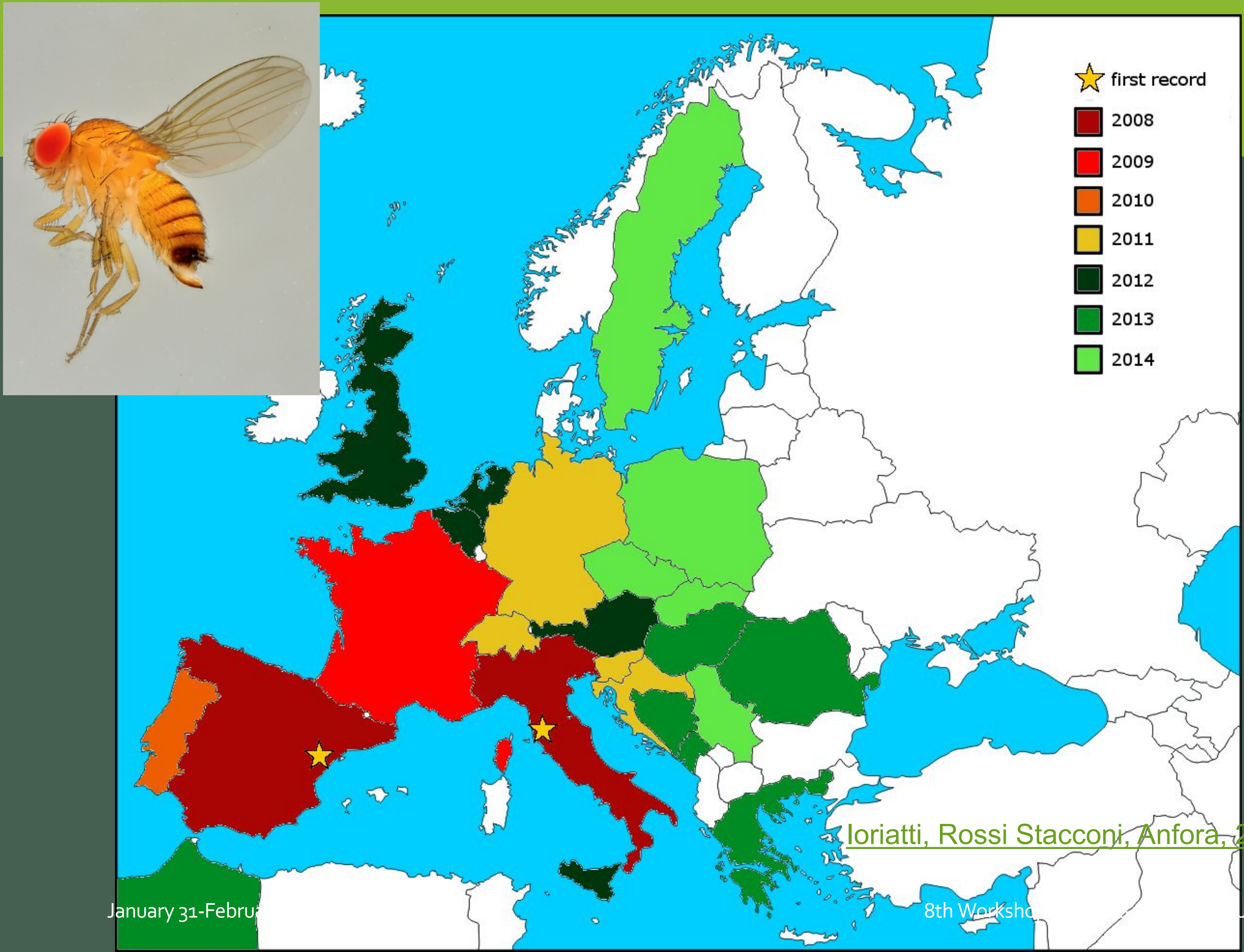


Drosophila zusukii
Distribuzione Geografica 2012

Distribuzione mondiale



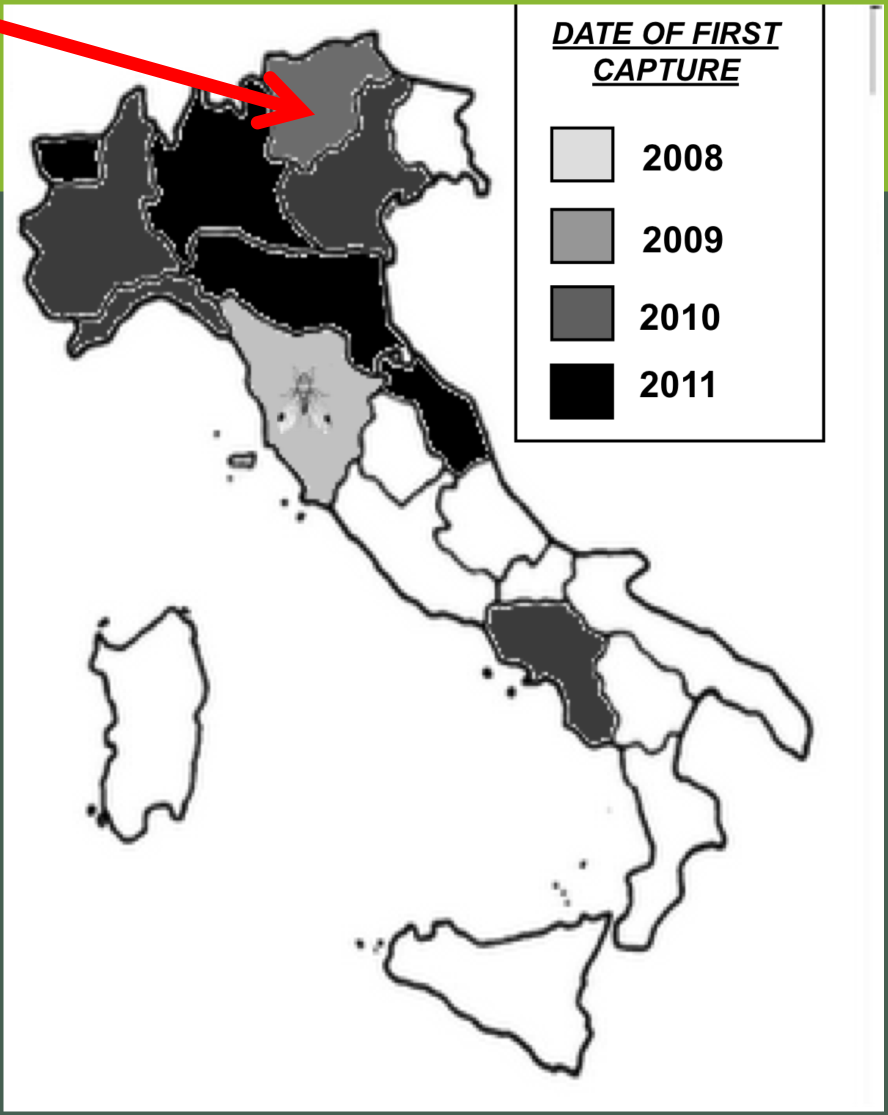
The escalating outbreak in Europe



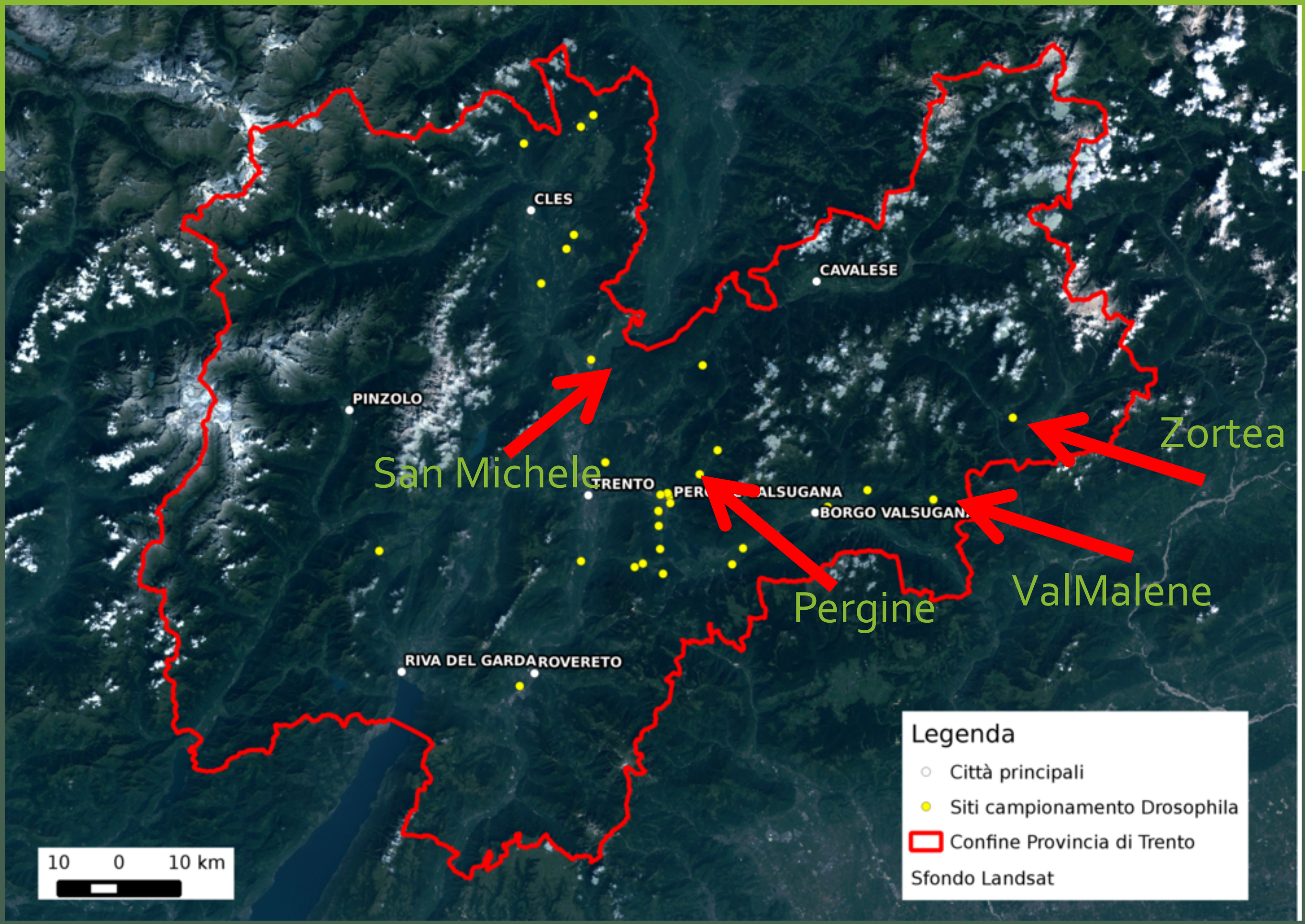
Ioriatti, Rossi Stacconi, Anfora, 2014. CABI

D. SUZUKII IN ITALY

Study area



FIELD DATA IN TRENTO PROVINCE



33 trapping sites with weekly sampling since 2011; **68** since 2013

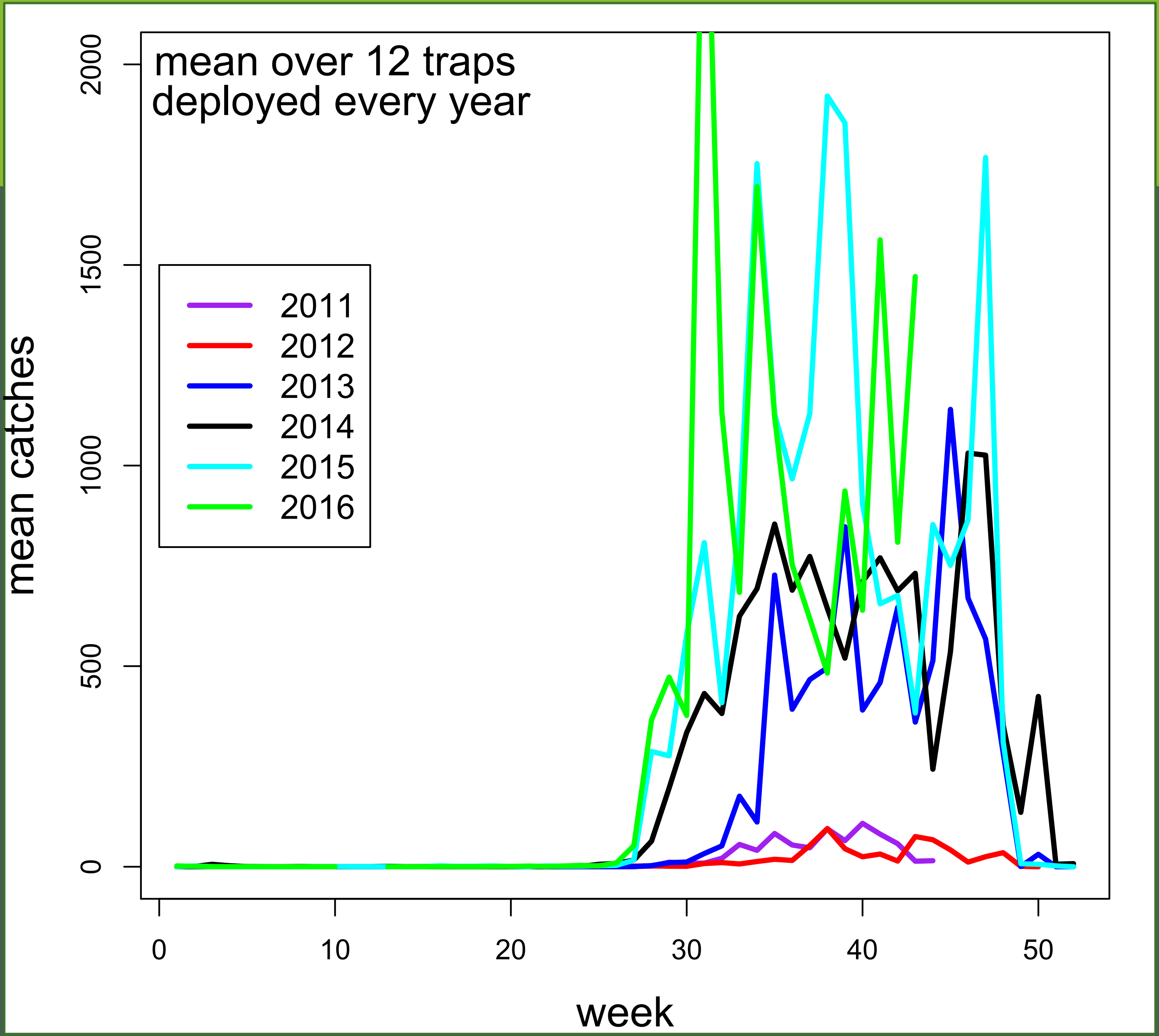
TRAPPING DROSOPHILA

Traps were serviced once a week starting from the half of April, until the end of October .

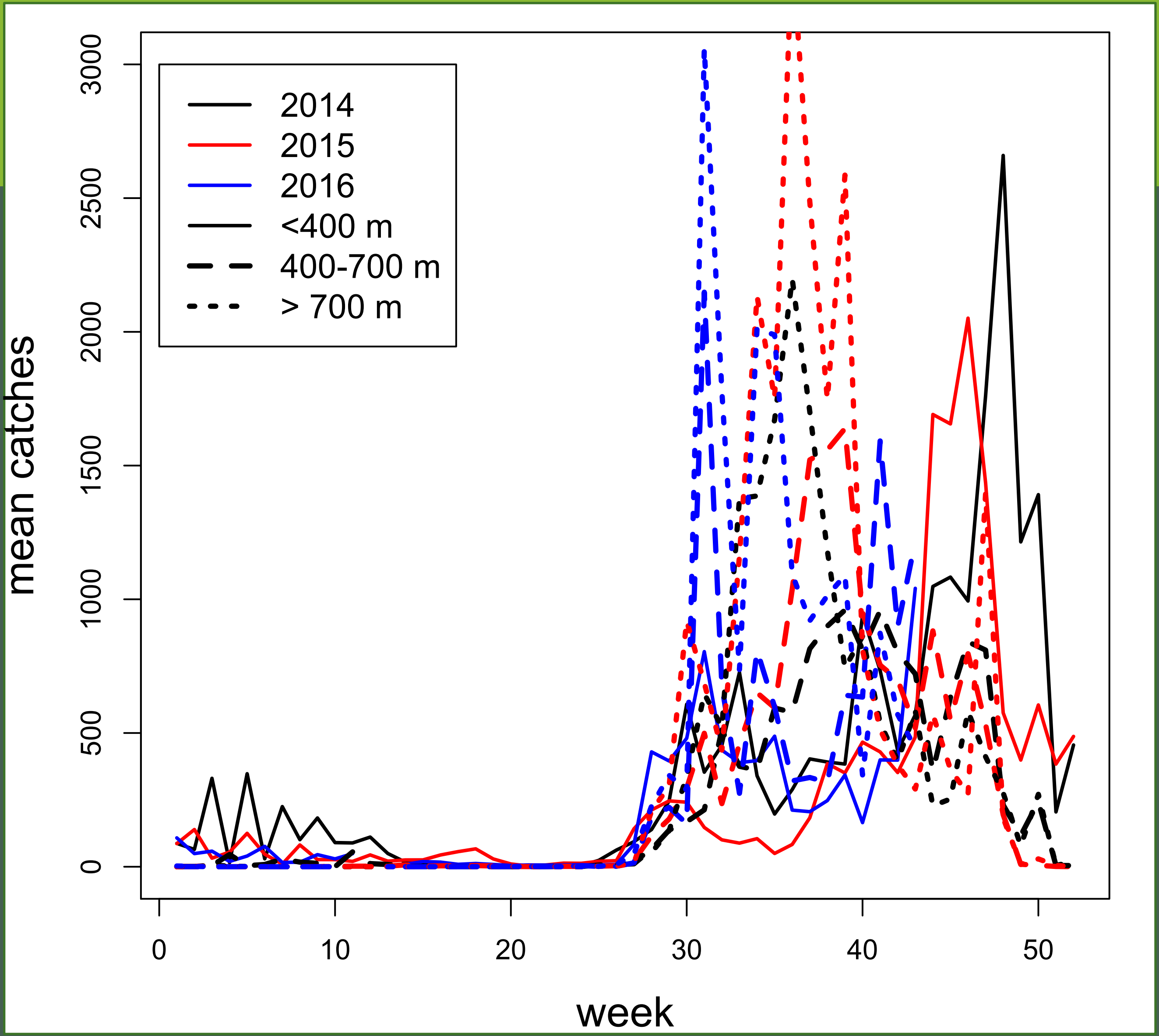
Rossi Stacconi *et al.*, 2013. Entomologia

Since 2013, many traps have been maintained all year round.

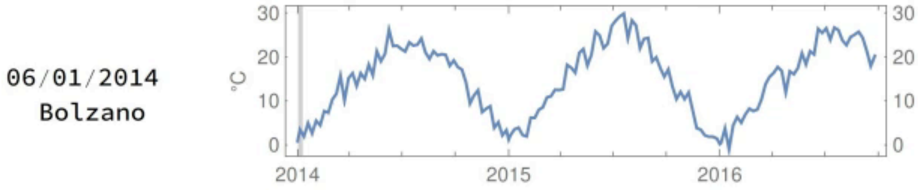
OVERALL TREND OF FIELD DATA

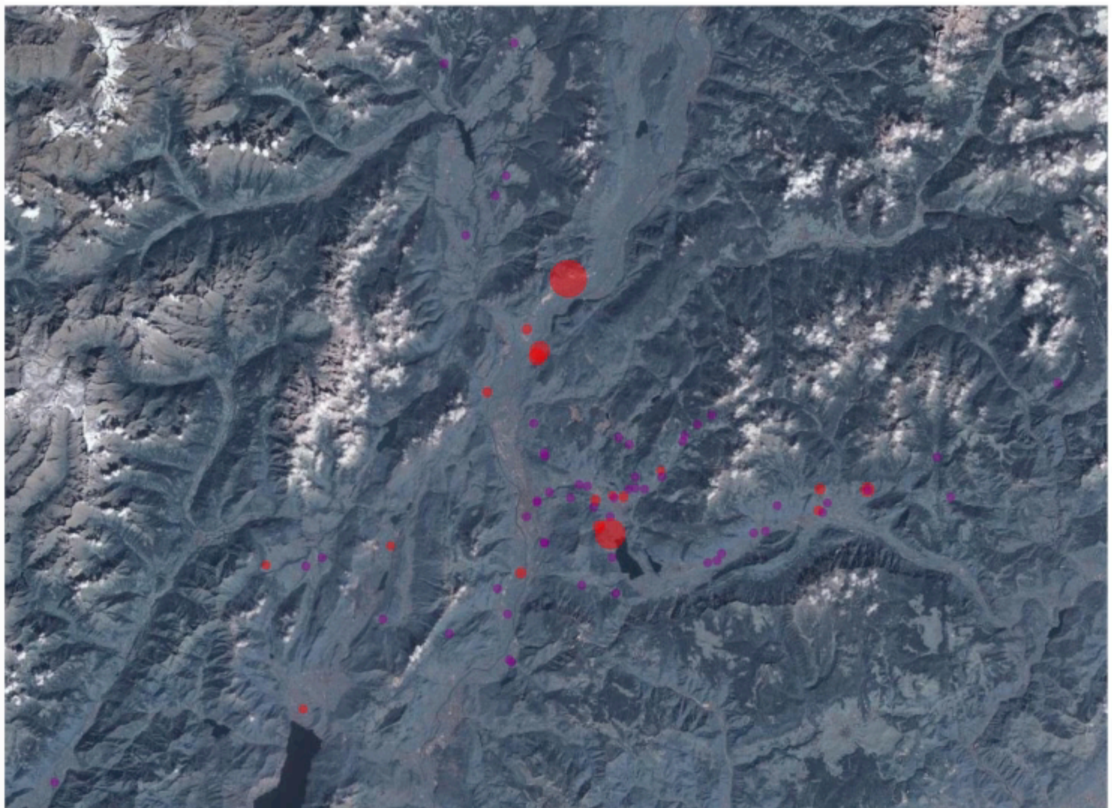


BUT PATTERNS DEPEND ON ELEVATION



FIELD DATA IN TRENTO PROVINCE





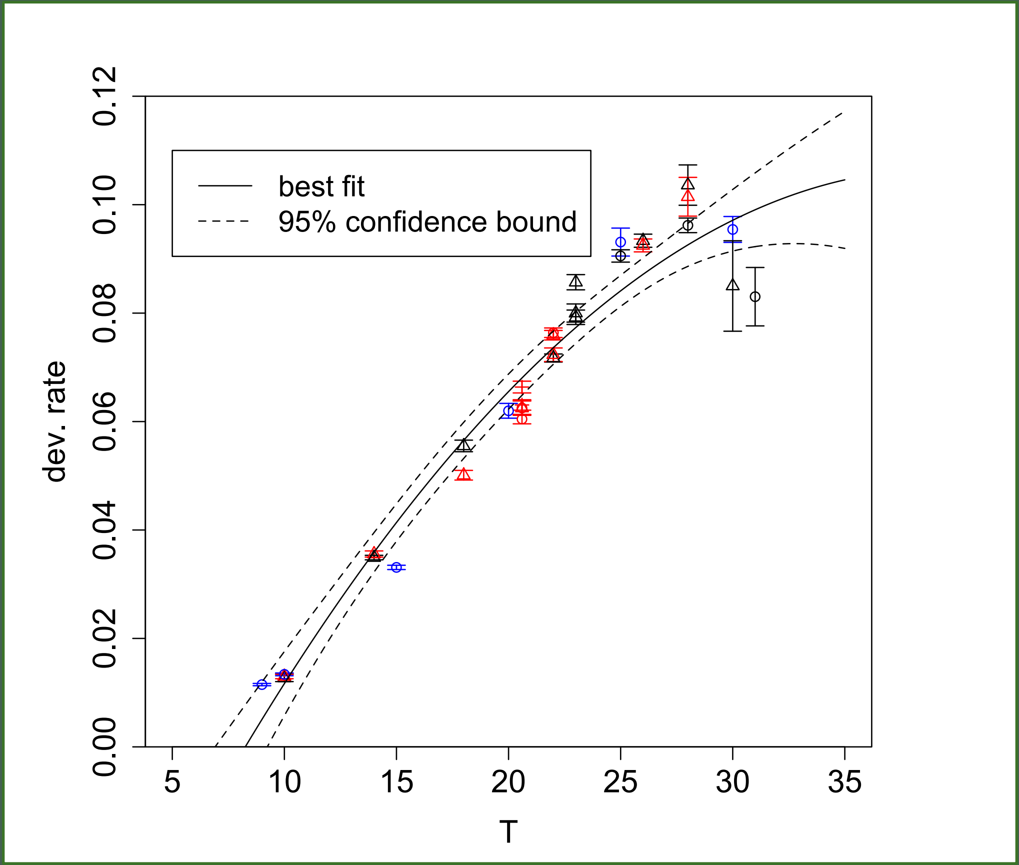
location	owner	type	m	pop.
Riva	Az.Mosca	cil., frag.,lamp.,mora	77.	8.
Aldeno	Az.Delaiti Luca	ciliegio	189.	na
Romagnano	Az.Caldonazzi	ciliegio	198.	2.
Trento	parco al Fersina	parco + torrente	195.	na
Zambana V.	Az.Osti Aldo	ciliegio	203.	1.
Besenello	Az.Adami	ciliegio	207.	na
Mezzocorona	fam.Mattedi	giardino (cil., vite)	213.	1.
Roverè d.Luna	Az.Keller	bosco al vigneto	234.	612.
Besenello	Az.Calavin	lampone unif.	234.	na
Trento	ponte al Galilei	bosco + torrente	242.	na
S.Michele	FEM	imp.compostaggio	249.	17.
Pergolese	Az.Gobber	ciliegio	258.	8.
Trento	abit.Tommaso	giardino domestico	252.	na
S.Michele	FEM	vigneto	272.	28.
Trento	Orrido	bosco + torrente	347.	na
S.Rocco	az.Gamper	bosco	357.	na
S.Rocco	az.Gamper	lampone,mora	357.	na
Storo	Az.Armanini	fragola	377.	na
Civezz./Slacche	cava	bosco + torrente	395.	na
Civezz./Slacche	Az.Laner	fragola	482.	na
Telve	Az.Trentinaglia	mirtillo	411.	na
Telve	Az.Trenti G.	ciliegio	421.	1.
Roncegno	Az.Baitella	lampone	430.	na
Levico	Az.Giovannini	fragola	430.	na
Roncegno	Az.Ueller/Montibeller	mirtillo	430.	na
Levico	Az.Pintarelli	lampone	448.	na
Castelnuovo	Az.Capra T.	fragola	467.	na
Vigalzano	Az.Beber	ciliegio	472.	na
Drena	Az.Zanetti	mora	472.	na
Roncogno	Az.Giovannetti	ciliegio	475.	1.
Vigalzano	FEM	diversi pf	487.	8.
Zivignago	Az.Bortolotti	ciliegio	489.	1.
Canale	Az.Gretter	ciliegio	506.	184.
Susà	Az.Bertoldi Mauriz.	ciliegio	506.	na
Vigo Meano	strada sotto paese	ciliegio selv.	523.	na
Dasindo	az.Dalponte	ciliegio	528.	na
Poia	az.Bonavida	ciliegio	529.	na
Campiello	Az.Giongo C.	mirtillo	538.	na
Denno		ciliegio	572.	na
S.Caterina	Az.Biasi	albicocco	579.	na
Villa Moretta	Az.Puecher	ciliegio	618.	na
Viarago	Az.Zampedri D.	lampone	656.	na
Cimirlo	Az.Valerani	ciliegio	657.	na
Canezza/Giare	Az.Bertoldi	fragola	657.	na
Serso		bosco	664.	na
Serso	Az.Bianchi	ciliegio	676.	na
Susà/sopra paese	Az.Bertoldi Marco	ciliegio	682.	4.
Vattaro	Az.Micheloni	mirtillo	691.	na
Tres	Az.Maccani	ciliegio	709.	na
Garniga	Az.Delaiti Guido	ciliegio	719.	na
Telve	Az.Pecoraro	cil., mirt., frag., mora	722.	2.
V.Vattaro	Az.Debiasi	fragola	729.	na
Montevaccino2	Az.Pontalti M.	ciliegio	737.	na
Montevaccino	Az.Pallaver	ciliegio	781.	na
Mala	Az.Franchini	ciliegio, mirtillo	787.	8.
Samone	Az.Tiso	mirtillo	798.	na
Balbido	Az.Crosina S.	ciliegio, albicocco	792.	8.
Maso Sasso	Az.Dalsasso	mirtillo	795.	na
Samone	Az.Tiso	bosco	796.	7.
Castel Tesino	Az.Fabbro	mora	835.	na
Rumo	Az.Nardelli	ciliegio, lampone	868.	na
Smarano	Az.Brentari	ciliegio	897.	na
Cei	Az.Galvagni	ciliegio	901.	na
Laghestel	Az.Mattivi F.	fragola	927.	na
Prada	Az.Tessadri	fragola	936.	na
loc.Terabi		bosco	966.	na
Salobbi	Az.Corazza	ciliegio, albicocco	1085.	na
Zortea	Az.Romagna	mirtillo, fragola	1057.	na
Val Malene	Az.Granello	fragola	1067.	na
S.Orsola	Az.Paoli	lampone u., mora	1091.	na
Masi Alti S.Orsola		bosco	1252.	na
P.sso Redebus		bosco	1493.	na
Palù d.Fersina		bosco	1795.	na

DEMOGRAPHIC LABORATORY DATA

- Tochen et al. (2014) at various temperature (on cherries and blueberries)
- Tochen et al. (2015) at various humidity levels (on blueberries)
- Data collected in LeXeM project at tempearture 23 °C and humidity 70% *(cherries)*
- Data collected in LeXeM project at temperature 22 °C and humidity 35% and 75% *(blueberries)*
- Kinjo et al. (2015): temperatures 25-33 °C   *(some under varying temperatures)*
- Dalton et al. (2011): survival at 1-10 °C *(also after freeze exposure)*
- Chabert et al. (2013): several treatments
- Emiljanowicz et al. (2014); Gray et al. (2016) at several temperatures and treatments (on diet)
- Shearer et al. (2016) survival of winter and summer morphs at different temperatures
- **Large consistency in data about larvae survival and development, much less about adults.**

FITTING ENVIRONMENT VARIABLES DEPENDENT FUNCTIONS

Larval development rate = 1/(Time from adult to egg)



Shape and colour of points correspond to different humidity levels and raising media.

Development = 0 at T=8.3 °C

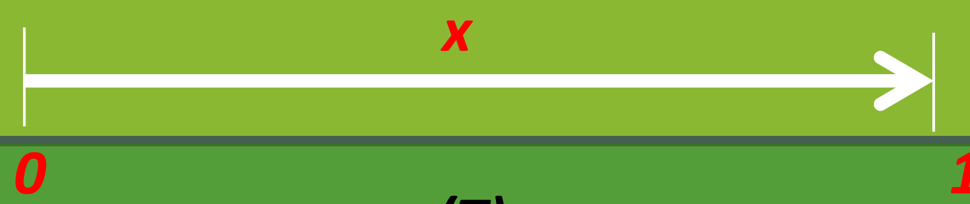
OBJECTIVES OF MODELLING THE POPULATION DYNAMICS OF *D. SUZUKII*

- [Big economic relevance of the pest]
- Understanding main factors affecting its population dynamics
- Providing *short-term* predictions on abundance and spatial distribution
- Assessing potential control measures (mass captures, insecticides, parasitoids) and developing guidelines on their implementation

MODEL STRUCTURE: POSSIBLE CHOICES

- **ODE** formulation with compartments (eggs, larvae, pupae, adults) and rates=1/(development time)
- **Age-structured** models (Tochen et al, 2014; Wiman et al, 2014)
- **Physiologically-structured** model: immatures (and adults) denoted by a maturity variable *x (may correspond to instar stage),* with development depending on temperature and other environmental variables.
  - Mathematically equivalent (as for immatures) to models with **temperature-dependent delays** (Langille et al, 2016), and extending **degree-days models**
  - It seems to be the most flexible approach to variable environment.

MODEL STRUCTURE



start stage

g(T) speed

maturation

$$\frac{\partial L}{\partial t} + \frac{\partial}{\partial x}(g_L(T(t))L(t,x)) = -\mu_L(T(t))L(t,x)$$

Development rate

Density of larvae at time *t* and maturity *a*

Death rate

Temperature

B.C. at *a = 0*

$$g(T(t))L(t,0) = b(T(t)) \int_0^{a_{max}} \nu(x)A(t,x)\,dx$$

Birth rate

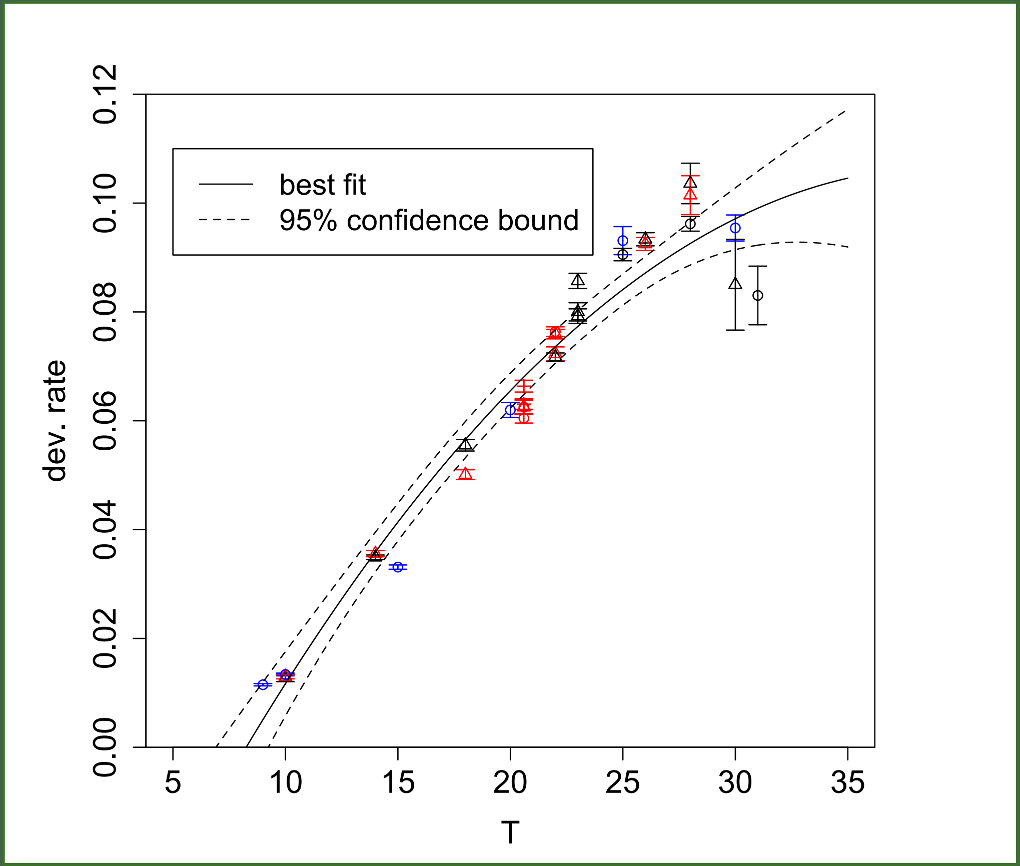
Adults

COMPLETE MODEL

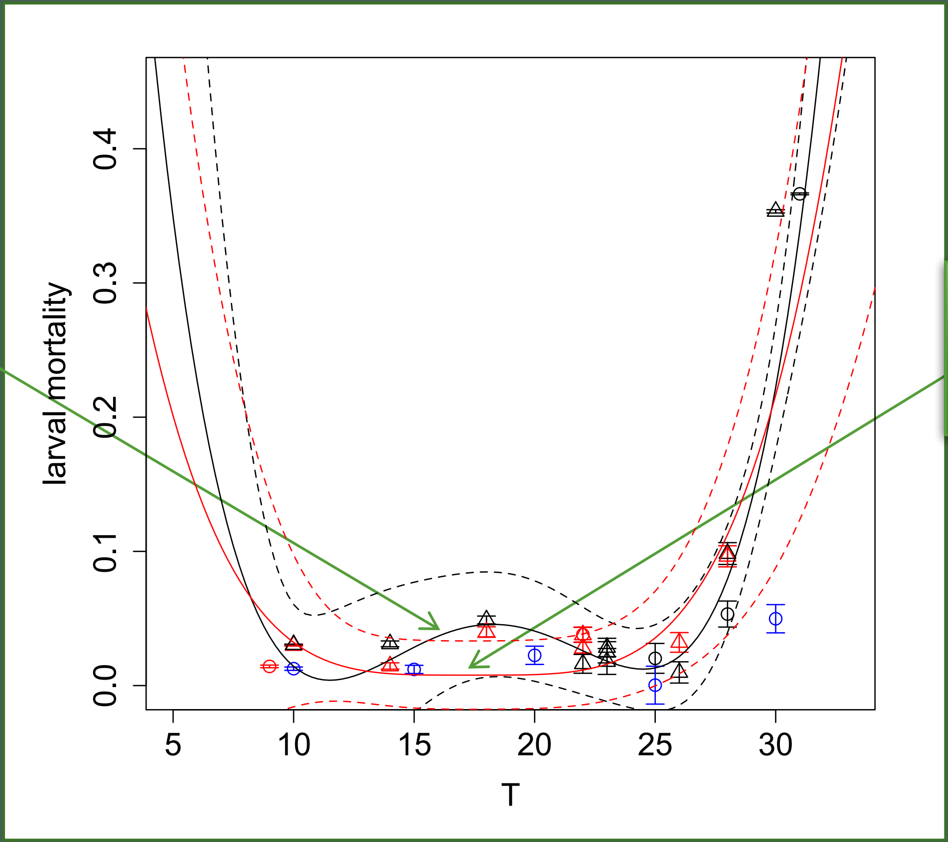
$$
\begin{aligned}
\frac{\partial L}{\partial t} + \frac{\partial}{\partial x}(g_L(E(t))L(t,x)) &= -\mu_L(E(t))L(t,x) && x \in (0,1) \\
\frac{\partial A}{\partial t} + \frac{\partial}{\partial x}(g_A(E(t))A(t,x)) &= -\mu_A(E(t), x)A(t,x) && x > 0 \\
g_L(E(t))L(t,0) &= \int_0^\infty b(E(t), x)A(t,x)\,da \\
g_A(E(t))A(t,0) &= g_L(E(t))L(t,1)
\end{aligned}
$$

- *E(t)*: environmental conditions (temperature, humidity…)
- $1/g_L(E)$: developmental time (egg -> adult)
- $1/g_A(E)$: mean life of an adult
- Assumptions: $\mu_A(E,x) = g_A(E)\nu(x)$ $b(E,x) = b(E)\phi(x)$

USE OF LABORATORY DATA TO ESTIMATE MODEL FUNCTIONS



Larval mortality rate



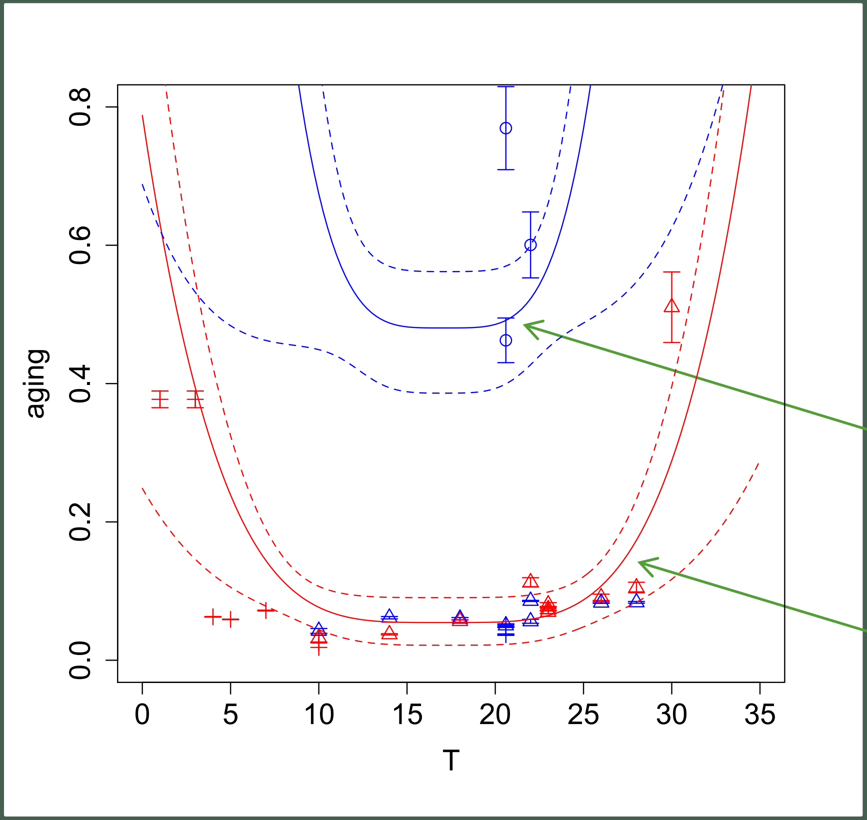
4th deg

4th deg a(x-b)^4 + c

ADULT MORTALITY

Parsimonious form:

$$g_A(E)$$



$$\mu_A(E, x) = g_A(E)\nu(x)$$

Speed of aging

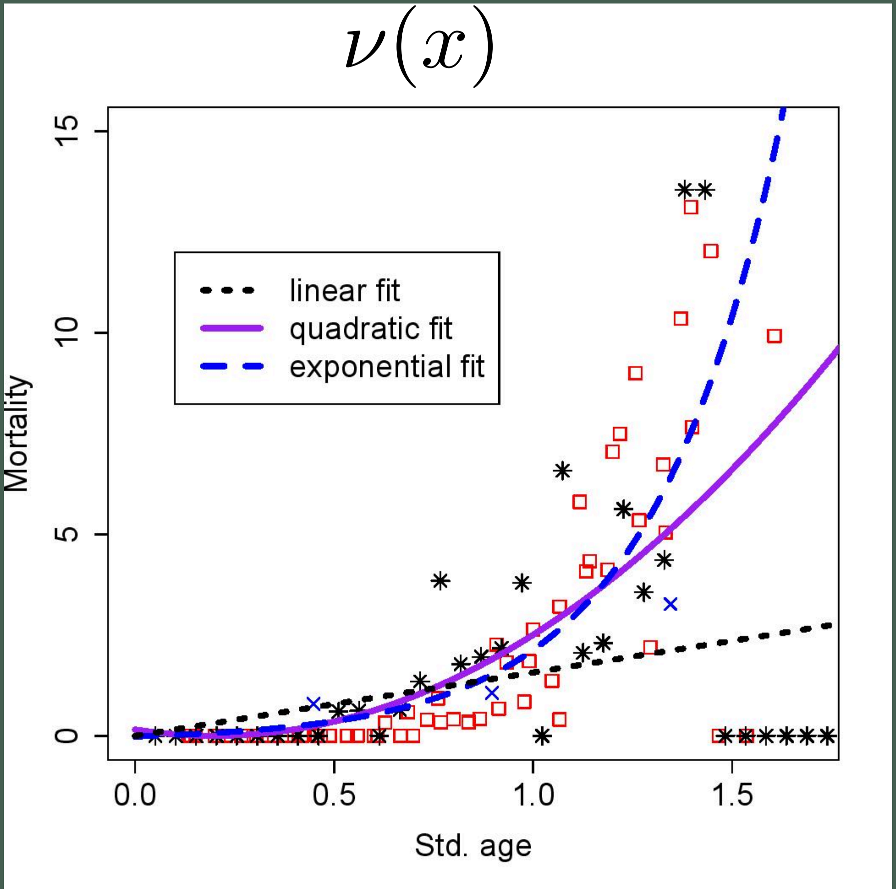
Mortality with (normalized) age

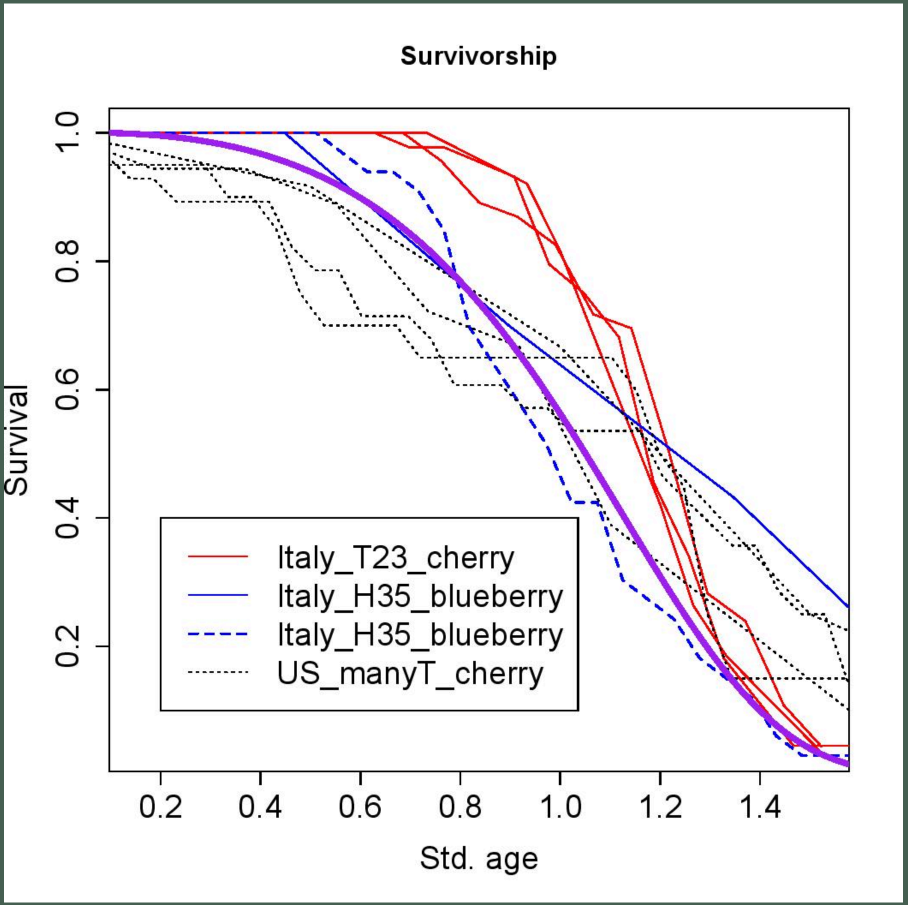
30% hum

70% hum

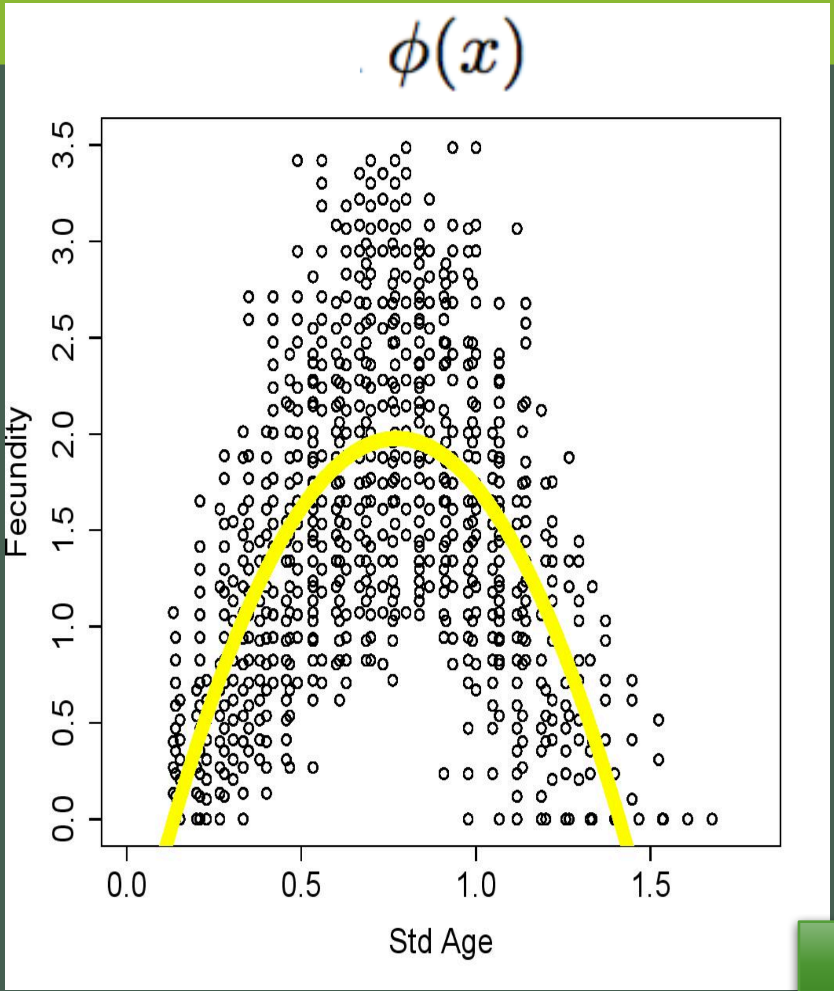
ADULT MORTALITY

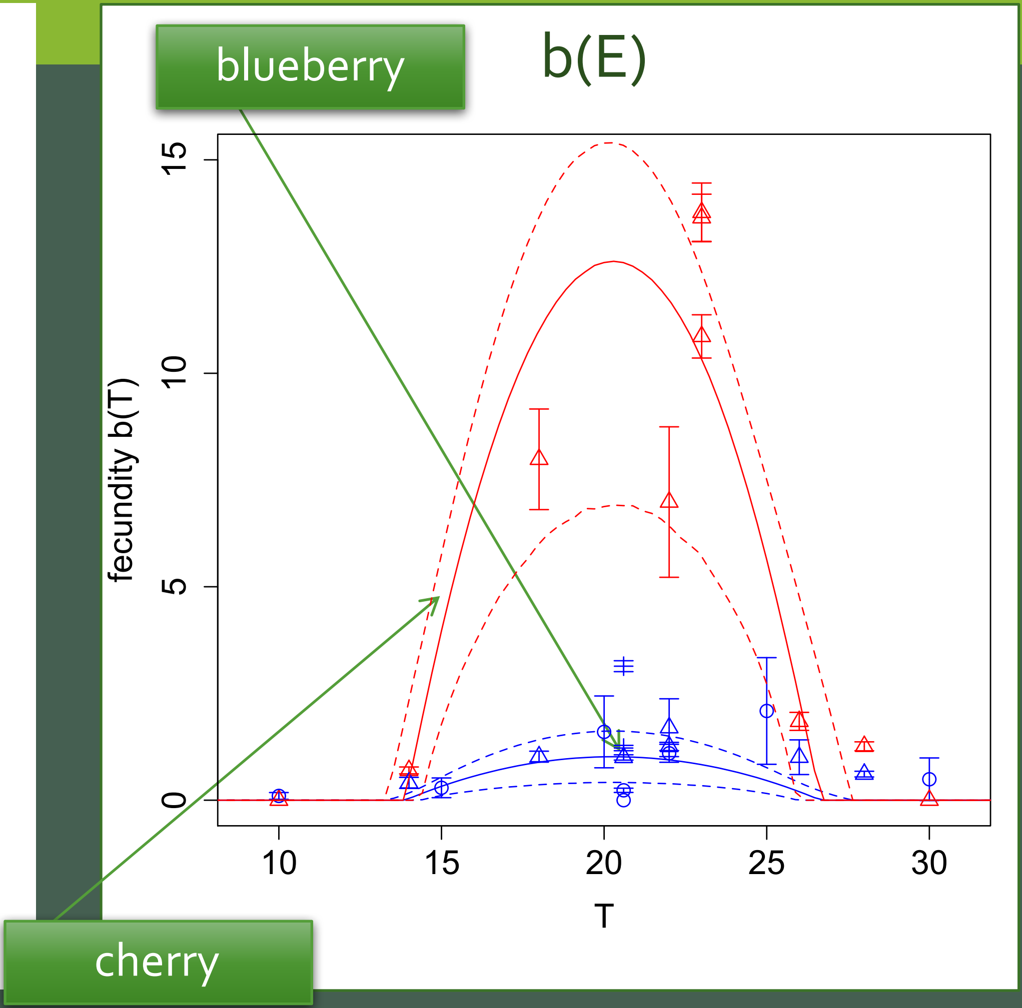
only from Lexem data $\mu_A(E, x) = g_A(E)\nu(x)$





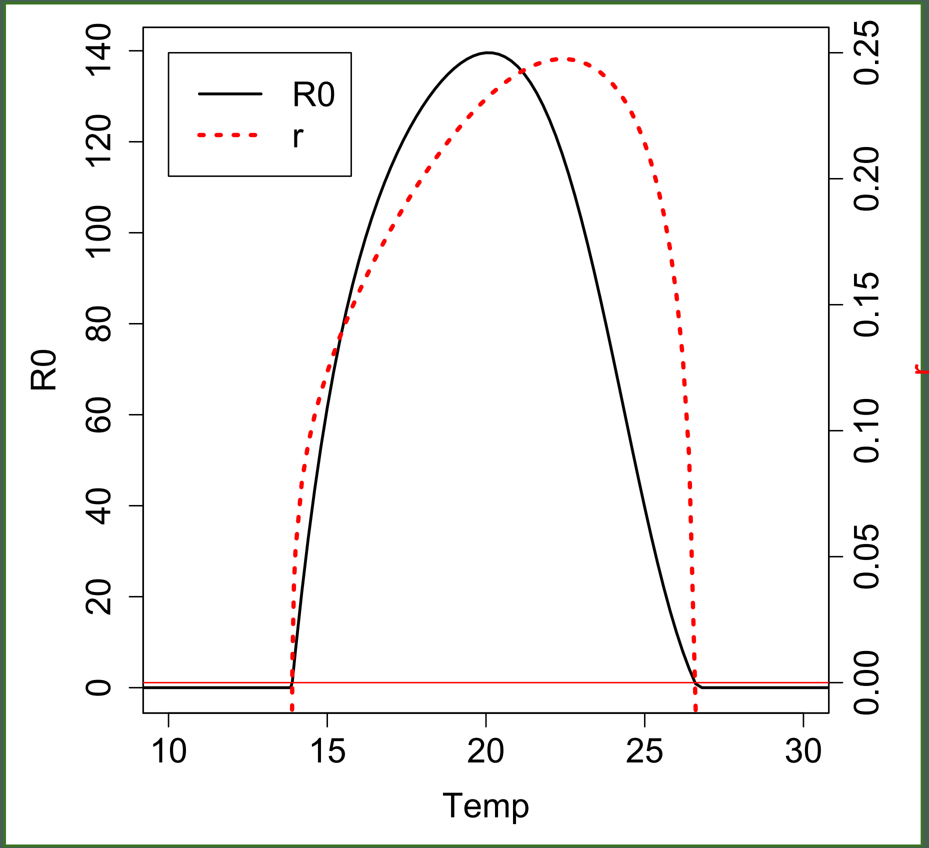
FECUNDITY   b(E)ϕ(x)





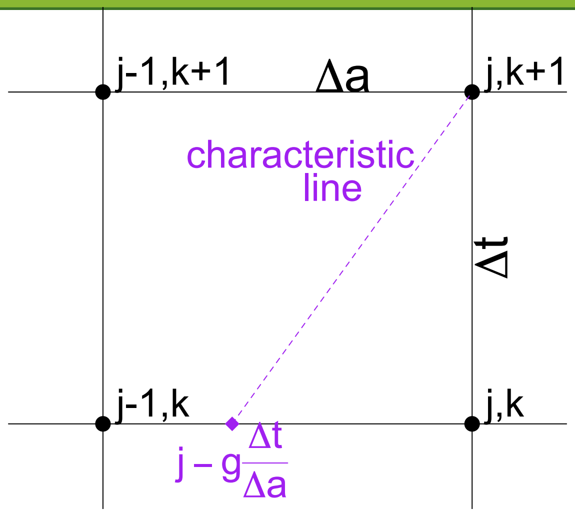
TEMPERATURE AND GROWTH RATE

In constant environment, equivalent to age-structured model



Growth rate *r* peaks at higher temperatures than reproduction number R_0

NUMERICAL SCHEME



$$g(T(t))\frac{\Delta t}{\Delta a} < 1$$

Courant–Friedrichs–Lewy condition

$$\frac{L_j^{k+1} - L_{j-g^k\frac{\Delta t}{\Delta a}}}{\Delta t} = -\mu_L^k L_j^{k+1}$$

$$L_j^{k+1} - \left[\left(1 - g^k\frac{\Delta t}{\Delta a}\right)L_j^k + g^k\frac{\Delta t}{\Delta a}L_{j-1}^k\right] = -\mu_L^k L_j^{k+1}\Delta t$$

NUMERICAL SCHEME VS. PDE MODEL

Finally, we get an explicit scheme:

$$L_j^{k+1} = \frac{L_j^k}{1+\mu_L^k \Delta t}\left[1 - \frac{\Delta t}{\Delta a} g^k\right] + \frac{L_{j-1}^k}{1+\mu_L^k \Delta t}\frac{\Delta t\ g^k}{\Delta a}$$

- **In the PDE, all eggs laid together mature at the same time**
- **In the numerical scheme, a distribution for the time to maturity T_m**
- **If** $g^k \equiv g,\ \Delta a = \frac{1}{N}$ **then**

$$\mathbf{E}(T_m) = \frac{1}{g}, \quad \mathbf{V}(T_m) = \frac{1 - Ng\Delta t}{Ng^2}$$

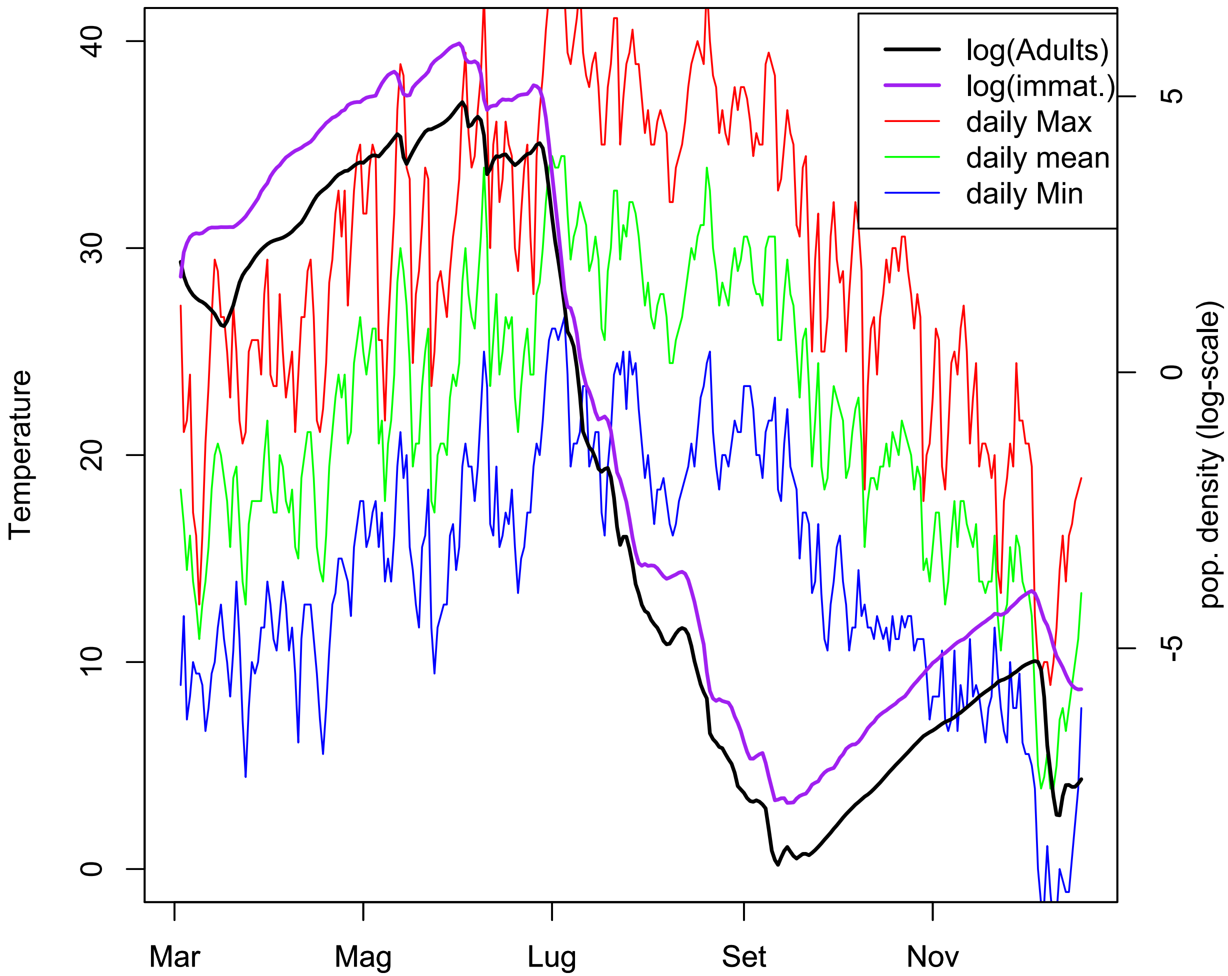
Is the numerical scheme a better model?

PRACTICAL ASPECTS OF SIMULATION

- We set a `biological' time step of 1 day
- We compute all parameters using either the daily mean temperature or daily minimum and maximum;
  - in the latter case, we assume $$T(t) = \frac{T_M + T_m}{2} + \frac{T_M - T_m}{2} \sin(2\pi t)$$ and have for that day similarly for all parameters $$g_L \equiv \int_0^1 g_L(T(s))\, ds$$

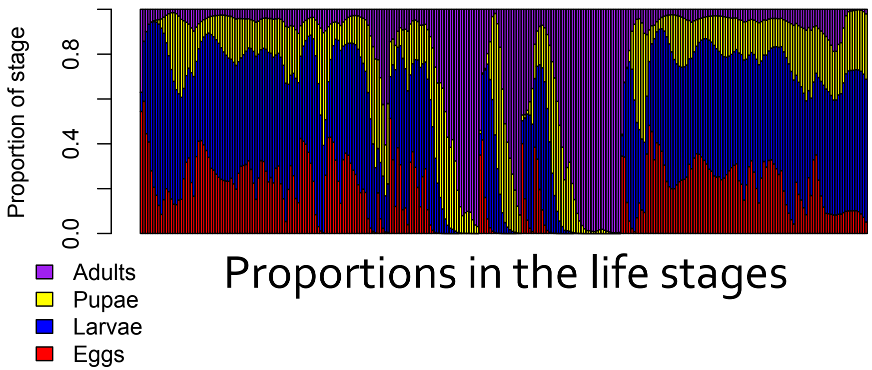
  (the idea is similar to the degree-days, widely used by entomologists)
- If CFL condition is violated for *Δt=1* day, choose *Δt=1/n* and repeat *n* steps.
- Simulations using min and max T are smoother and appear more realistic.

Simulations using daily Min & Max temperatures on Central California data



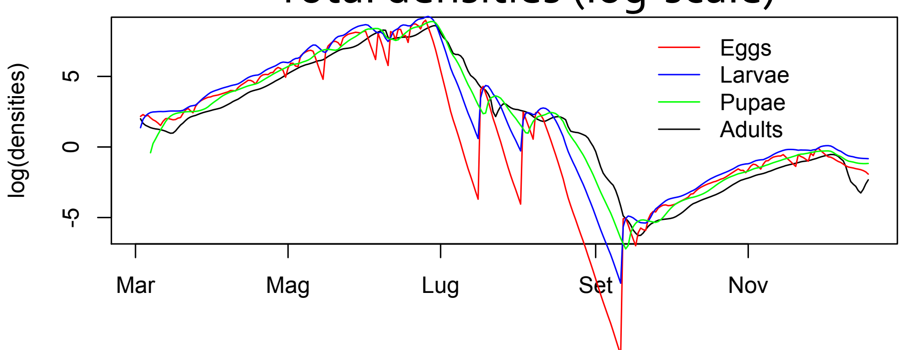
COMPARISON OF SIMULATIONS WITH DAILY MEANS OR MIN-MAX

Using means

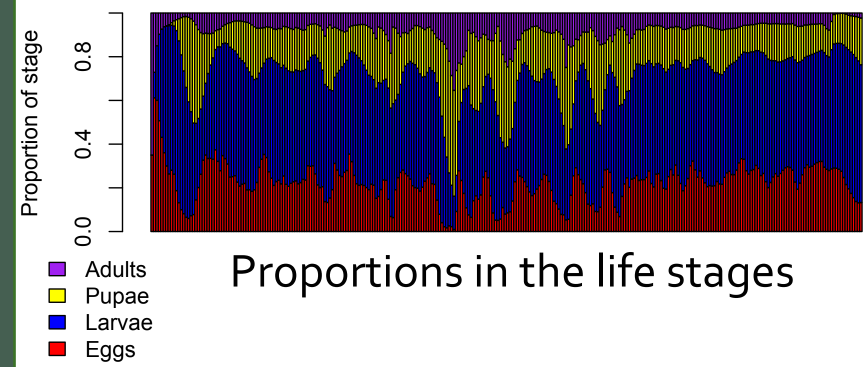


Proportions in the life stages

Total densities (log-scale)

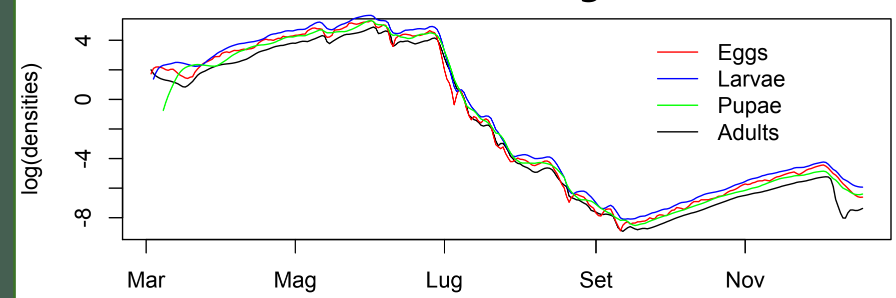


Using min-max



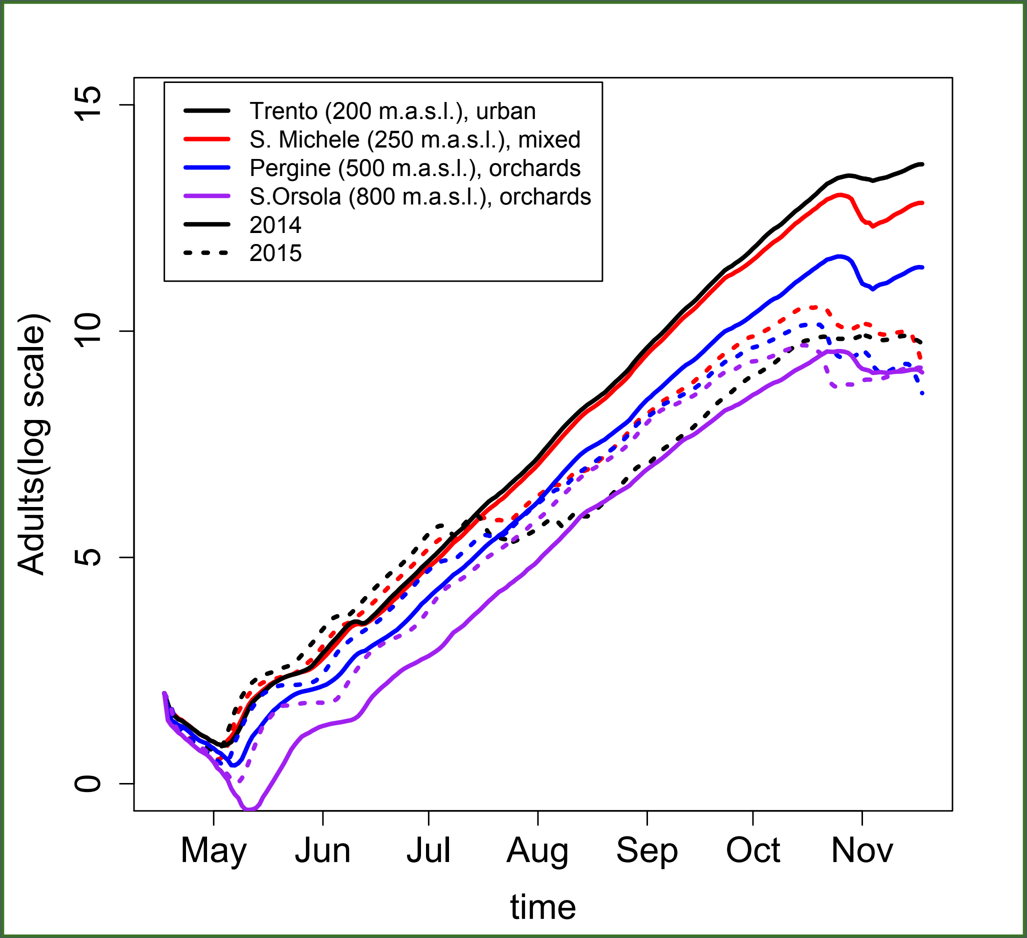
Proportions in the life stages

Total densities (log-scale)



LABORATORY MODEL WITH FIELD TEMPERATURES OF TRENTINO

Simulations starting with 100 adults on April 15

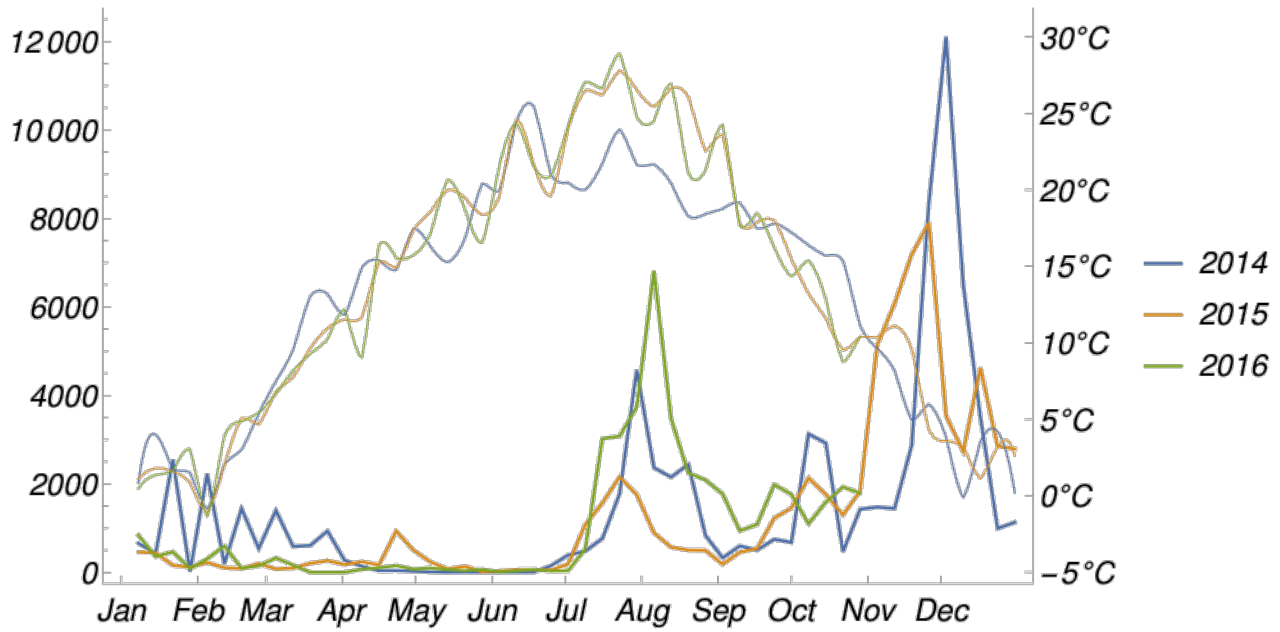


2015 was the hottest summer since 2003;
2014 was one of the coldest.
Predictions: lower densities in 2015 for the low-altitude sites; higher densities in 2015 at high elevations.

Simulations based only on ***daily*** min and max temperatures; no humidity or rainfall.

CATCHES 2014-16

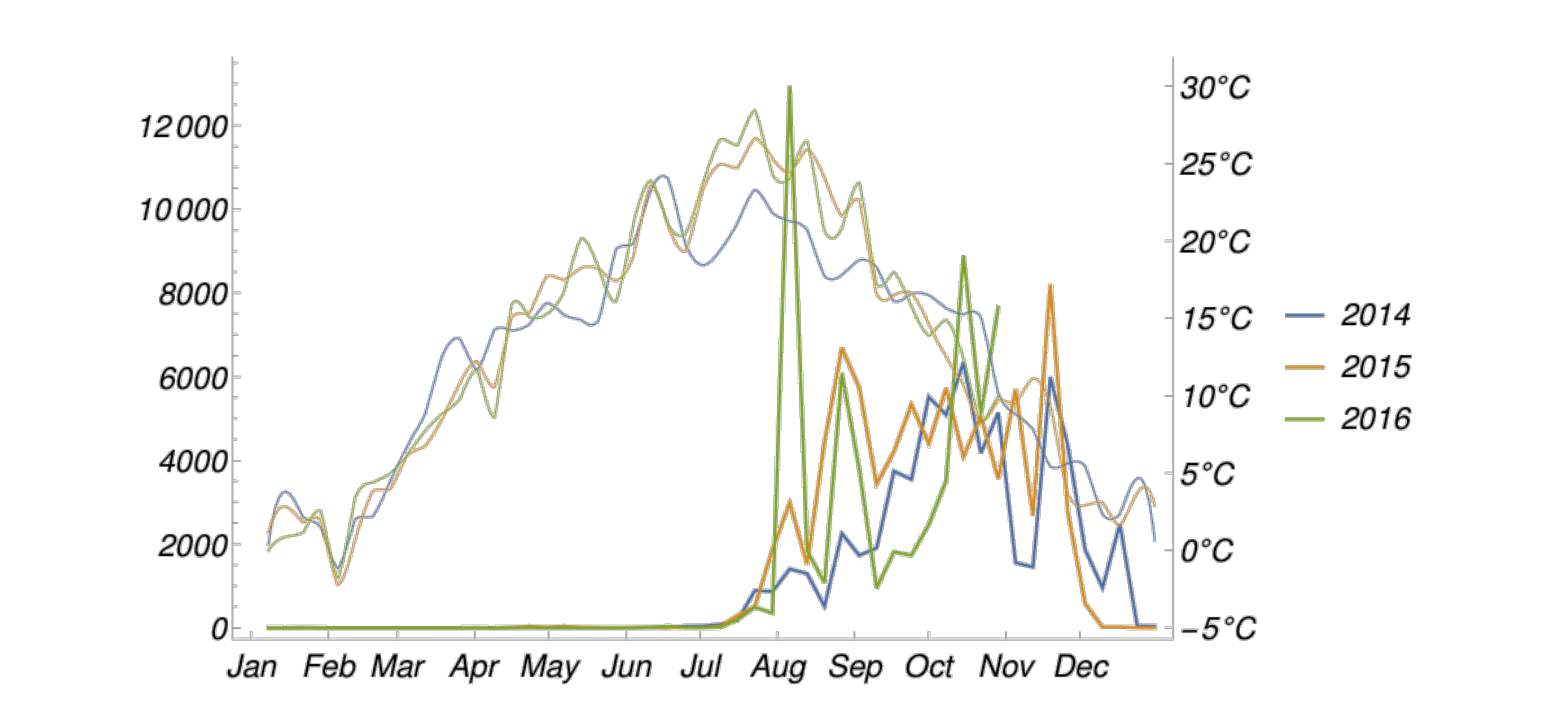
Traps around San Michele



- Summer densities were lower in 2015
- Very sharp increases in densities in November
- Significant catches also in winter (especially in 2014)

CATCHES 2014-16

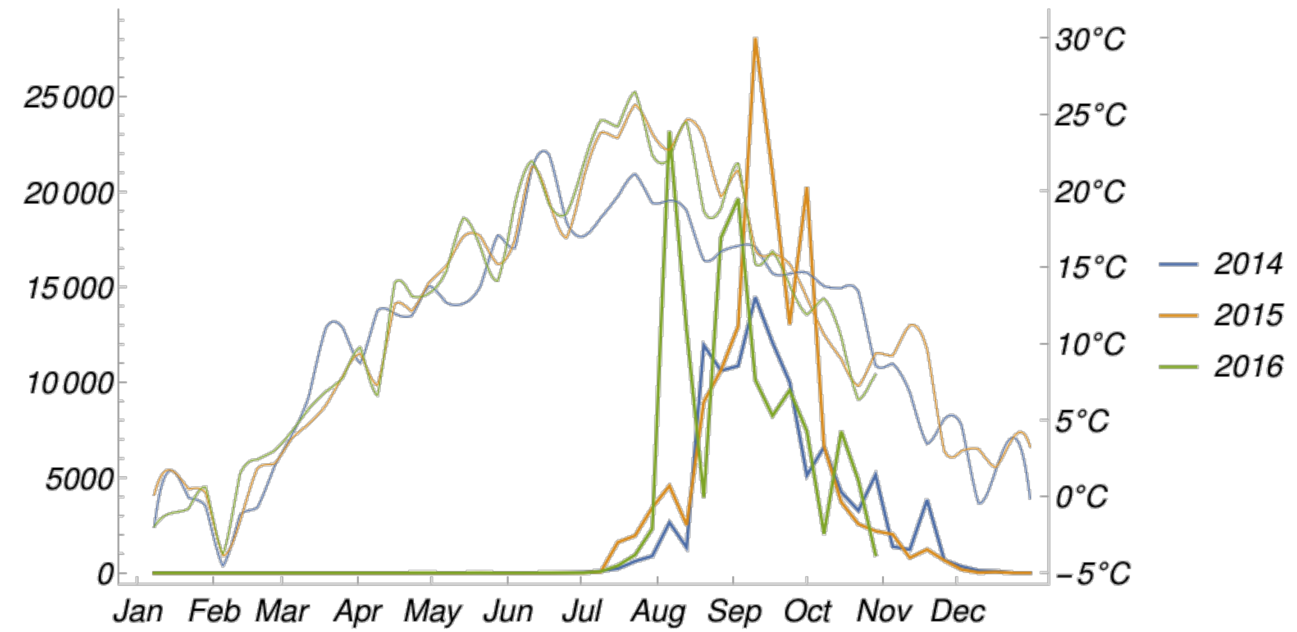
Traps around Pergine (near orchards)



- No consistent differences among years (but very high peaks in 2016)
- No consistent trend in averages between August and November

CATCHES 2014-16

High-elevation sites (near orchards)

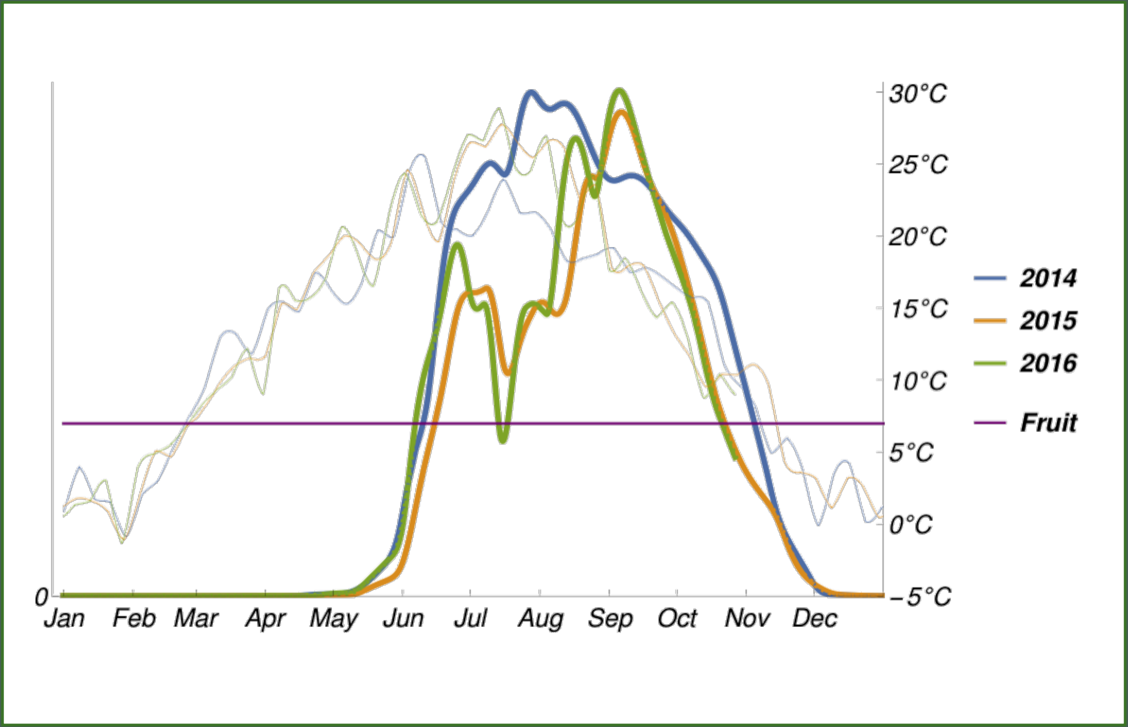


- Somewhat lower peak in 2014 than other years
- Period with high densities shorter than at lower altitudes.

WHOLE-YEAR SIMULATION WITH CARRYING CAPACITY

temperatures San Michele

fixed carrying capacity (effect on fecundity and larval mortality)

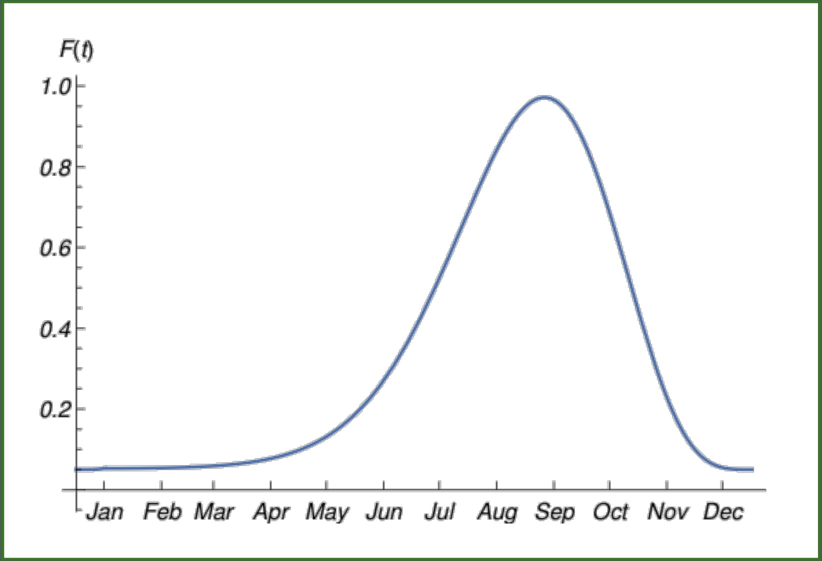


- **No population burst in November.**
- **Possible explanations**?
  - Migration btw. sites (mark-recapture experiments support the possibility)
  - Attractiveness of traps related to fruit availaibility.
- Also missing **winter morph**

ADDITIONAL MODEL INGREDIENTS

Fruit function

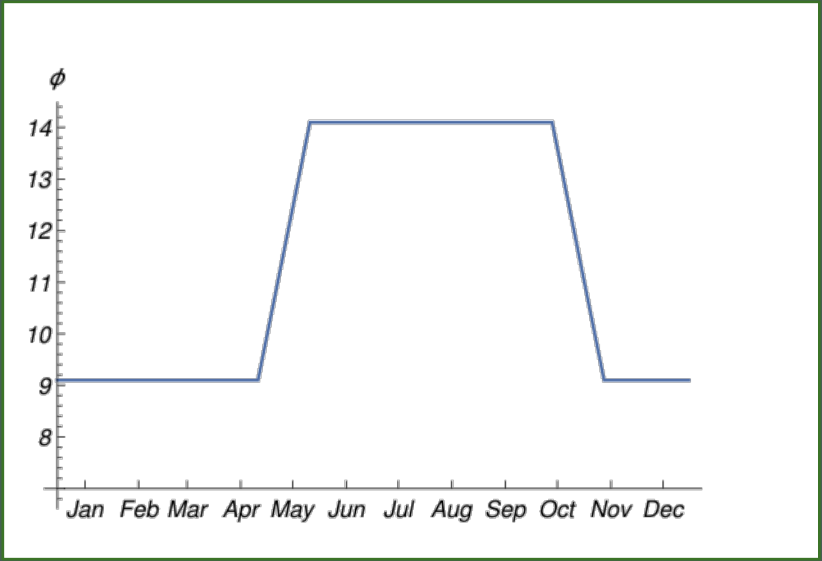
(inspired to Poyet *et al*, 2015)



Carrying capacity proportional to fruit function.
Trap attractiveness decreasing with fruit abundance

Winter adaptation

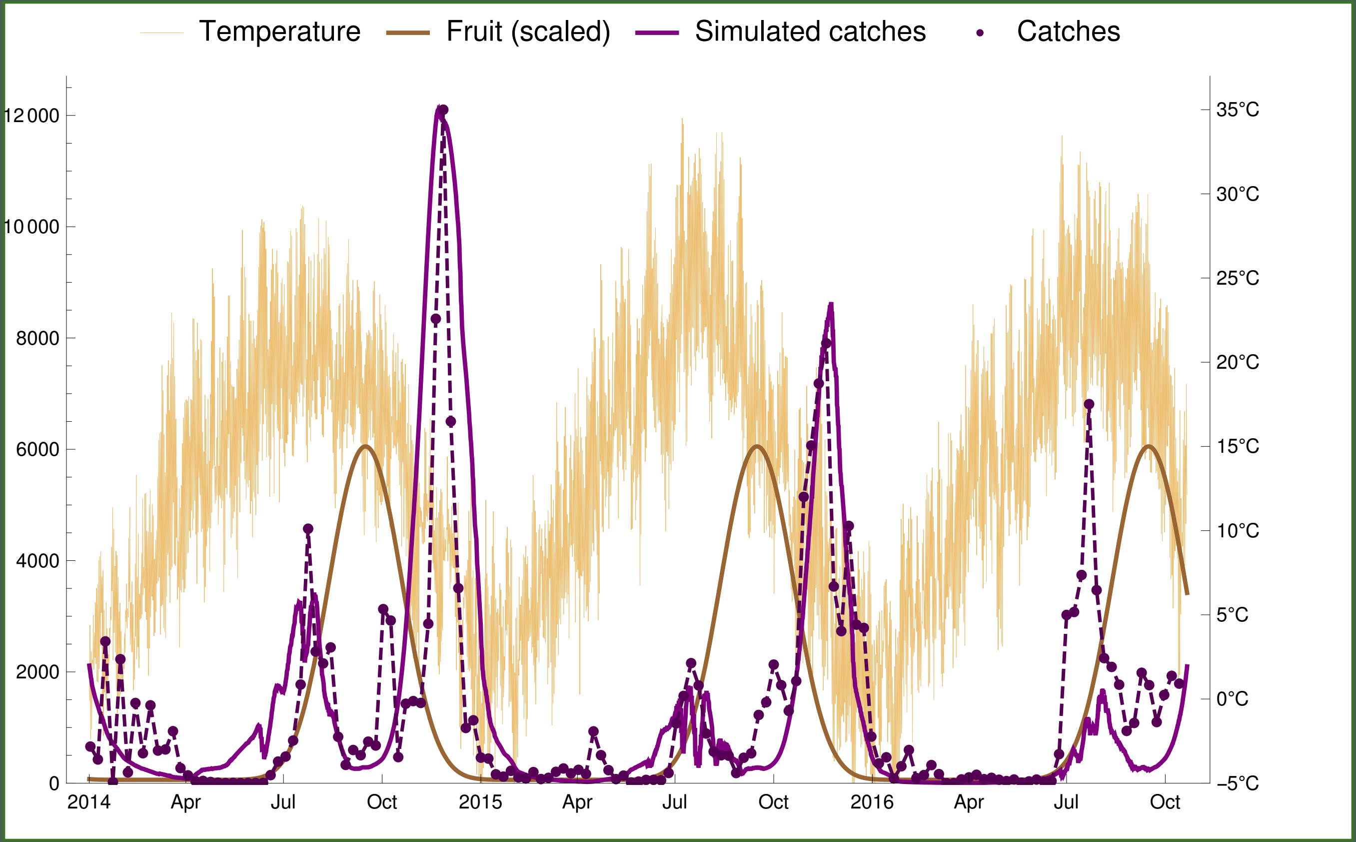
(inspired to Shearer *et al*, 2016)



Adult mortality curve shifted 5 °C to the left in winter.
Minimum mortality at 9 °C instead of 14 °C

SIMULATIONS OF REVISITED MODEL

San Michele temperatures and standard fruit function

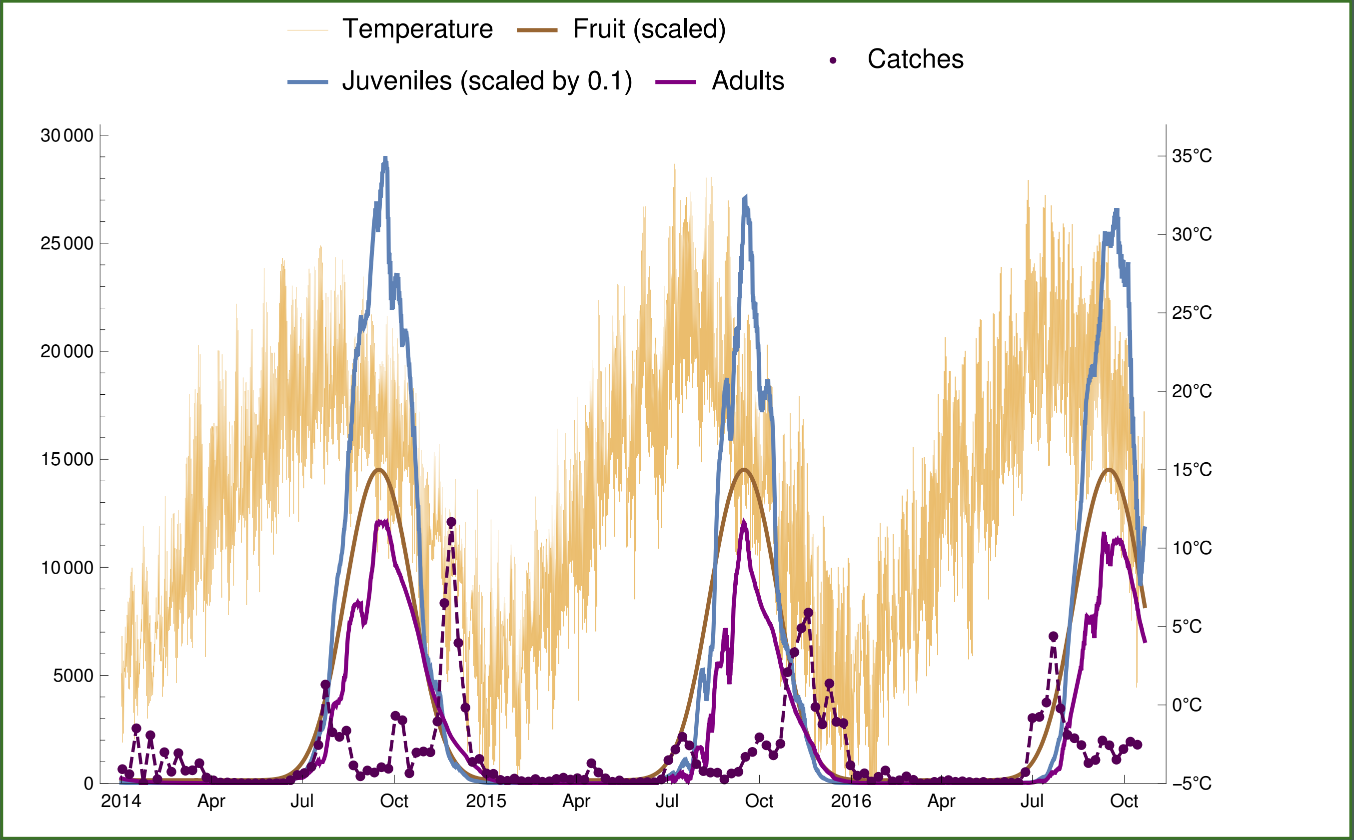


Solid lines:
simulated catches
Dotted lines:
actual catches

In the model catches are low in the middle of the season, but pop. density is high.

SIMULATIONS OF REVISITED MODEL. 2

San Michele temperatures and standard fruit function



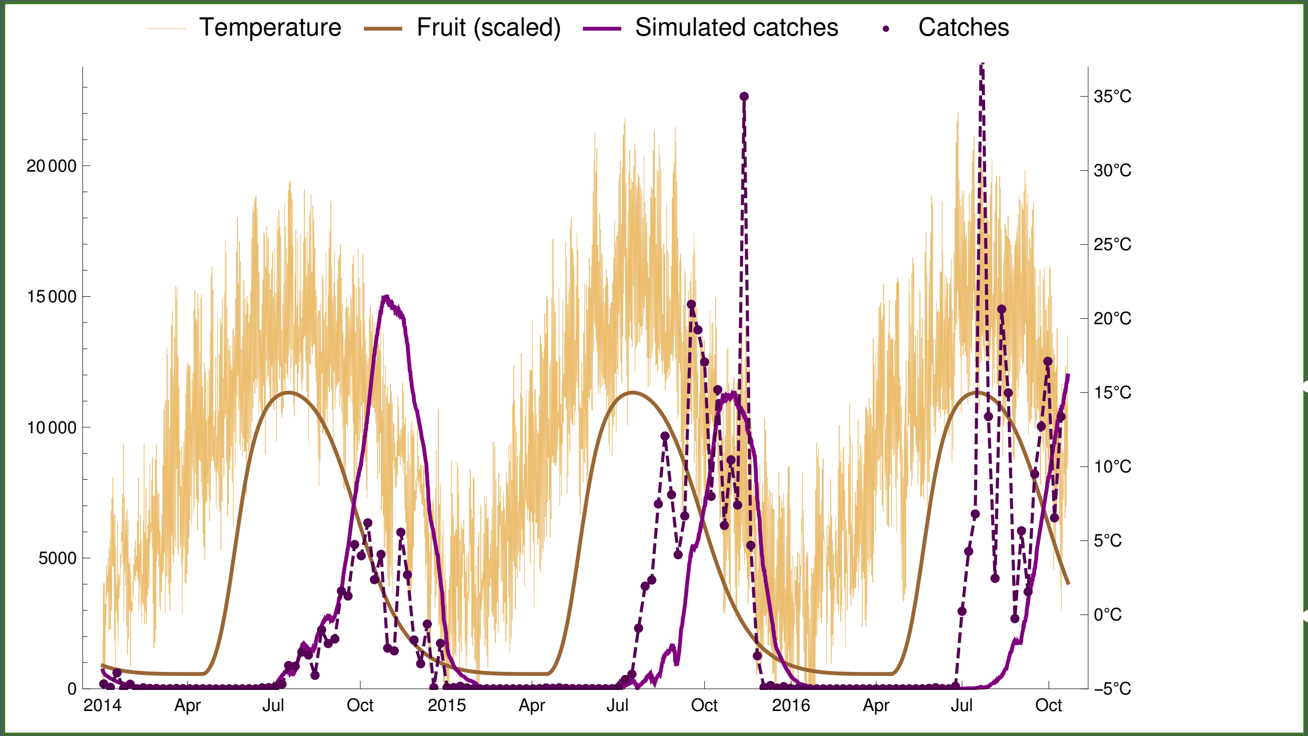
Solid lines:
simulpop. density (adults & juv.)
Dotted lines:
actual catches

In some cases, external validation of result could be obtained by fruit infestation assessments.

SIMULATIONS OF REVISITED MODEL. 3

Pergine temperatures; modified fruit function

(accounting for cherry and berry orchards)



Thick solid lines: simulated catches

Dotted lines: actual catches

- Change in temperatures and fruit function cause a different qualitative pattern of simulations
- Increase in catches 2014-16 require external driver

CONCLUSIONS

- Models based on laboratory data emphasize a strong effect of temperature on population dynamics.
  The comparison among years of catches at different altitudes supports the relevance of this on field data.
- Different annual patterns among sites are explained by the model through different “fruit functions”, mimicking fruit availaibility.
- Lower attractiveness of traps at times of fruiting plays an essential role in model fitting. Support only anecdotal so far.
- Multi-year increase of population density not really explained: endogenous pattern, or external factors?

CURRENT WORK AND OBJECTIVES

- Obtain objective indices of fruit abundance;
- Parameter fitting and statistical comparison of models;
- Use infestation indices as external model validation;
- Consider using other environmental variables;
- Use more realistic models for winter adaptation;
- Include control measures (parasitoids, spraying,...);
- Spatio-temporal dynamics.

Thanks for the attention

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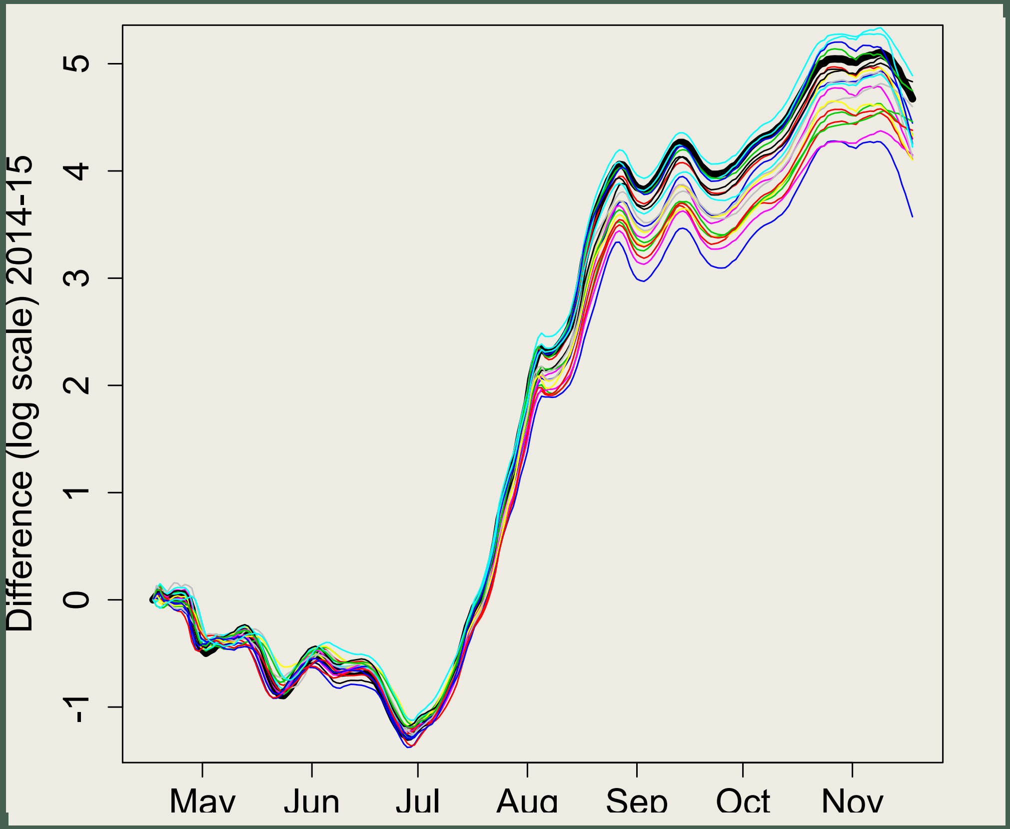
EFFECT OF UNCERTAINTIES IN DEMOGRAPHIC FUNCTIONS



Different demographic functions randomly chosen within 95%-C.I. provide similar predictions.

Connection between PSP model and time-dependent delay equation

Start from $\frac{\partial L}{\partial t} + \frac{\partial}{\partial x}(g_L(E(t))L(t,x)) = -\mu_L(E(t))L(t,x)$.

Find $T(t_0)$ such that $\int_{t_0}^{T} g_L(E(\sigma))\,d\sigma = 1$. $(t_0 = \tau(T))$ Then

$L(T,1) = L(t_0,0)\exp\{-\int_{t_0}^{T} \mu_L(E(\sigma))\,d\sigma\}$.

Using b.c. $g_A(E(t))A(t,0) = g_L(E(t))L(t,1)$, one has

$$g_A(E(t))A(t,0) = \frac{g_L(E(t))}{g_L(E(\tau(t))} e^{-\int_{\tau(t)}^{t} \mu_L(E(\sigma))\,d\sigma} \int_0^\infty b(E(\tau(t)),x)A(\tau(t),x)$$

If $b(E,x) \equiv b(E)$, $\mu_A(E,x) \equiv \mu_A(E)$, one gets a DDE for $\bar{A}(t)$.