Prediction of infestation by true bugs in hazelnut orchards: feasibility and preliminary approaches in the case of *Halyomorpha halys*

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Hazelnut plantations are worldwide endangered by a plethora of newly introduced pest species, such as the brown marmorated stink bug *Halyomorpha halys*

The use of Decision Support Systems (DSS) and forecasting tools in Integrated Pest Management of hazelnut orchards brings many advantages:

- **Safeguard** of environmental and human health
- **Reduction** of production costs
- **Increase** of the biodiversity

We may think that monitoring is enough to estimate pest populations on cultivated fields, but monitoring only gives a picture from the past to today.

We need to know more about tomorrow.
Aim of the work

*Halyomorpha halys* is a key pest for hazelnut for many Countries. Optimizing control strategies is a must.

DSS may be a good solution. To date there are models that:

- are mostly formulated once the species is defined
- after their first validation are sometimes adapted to other species

These limitations have recently been overcome by introducing a new general theory that describe

- Insects’ life cycles
- The development through life stages associated to environmental and biological factors
- Spatial diffusion

Let us apply this theory to *H. halys*!
The general model

Analysing the assumptions behind most of the models existing in literature, we can set the following general compartmental scheme:

This scheme is apparently “nonsense” until we define the species and its life cycle.
Model overview

In general:

- To each life stage is associated a scalar state representing the number of individuals in the population that at time $t$ are in the stage $i$.
- Population is divided by sex. Females are, in turn, divided in two sub-stages that may be considered as non-mated/mated or young/old.
- The transition between life stages is ruled by specific development, fertility and mortality rates which may depend, in general, on environmental factors and/or by some of the states of the population.

This naturally leads to a system of Ordinary Differential Equations:

- Life stages are biologically defined and discrete.
- To each stage corresponds a specific ODE.
Model’s equations

To each “identifiable” stage corresponds a specific ODE:

**Egg stage:**

\[
\frac{d}{dt} x_e(t) = G_{A_1}(t)\beta_1(t)x_{A_1}(t) + G_{A_2}(t)\beta_2(t)x_{A_2} - G_e(t)x_e(t) - M_e(t)x_e(t)
\]

**Preimmmaginal (larva or nympaha) stages:**

\[
\frac{d}{dt} x_{L_i}(t) = G_{L_{i-1}}(t)x_{L_{i-1}}(t) - G_{L_i}(t)x_{L_i}(t) - M_{L_i}(t)x_{L_i}(t), \quad i = 1, \ldots, n,
\]

**Adult males:**

\[
\frac{d}{dt} x_{A_m}(t) = (1 - S_R(t)) G_{L_n}(t)x_{L_n}(t) - M_{A_m}(t)x_{A_m}(t)
\]
Model’s equations

Adult females stage 1:

\[
\frac{d}{dt} x_{A_{f_1}}(t) = S_R(t)G_{L_n}(t)x_{L_n}(t) - G_{1\rightarrow 2}(t)x_{A_{f_1}}(t) - M_{A_{f_1}}(t)x_{A_{f_1}}(t) + G_{1\leftarrow 2}(t)x_{A_{f_2}}(t)
\]

Adult females stage 2:

\[
\frac{d}{dt} x_{A_{f_2}}(t) = G_{1\rightarrow 2}(t)x_{A_{f_1}}(t) - M_{A_{f_2}}(t)x_{A_{f_2}}(t) - G_{1\leftarrow 2}(t)x_{A_{f_2}}(t)
\]

Hence, to apply the model we have to:

- Define how many “identifiable” stages the species has
- Define the transition rates on the basis of the life cycle

What if we do not need a part of the model?
Just set the corresponding “rate function” to zero
Spatialization of the model

The “punctual” model can be replicated if we:

- divide an area of interest in subparcels
- consider the interaction between neighbouring parcels

...obtaining a spatial version on the general ODE model!
Application: the case of *Halyomorpha halys*

Let us apply the model to *H. halys*, evaluating what the literature offers.

What we know:

- The species has a total of 9 stages: egg, 5 nymphal stages, males, non-mated females, mated females ($\beta_2(t) = 0$)
- The sex ratio is 1:1 (males:females) $S_R = 0.5$
- **Thermal response** to development, fertility and mortality has been studied by Nielsen et al. (2008) and Govindan and Hutchinson (2020)
- There is not (known) cyclicity in reproduction $G_{1\rightarrow 2}(t) = 0$
- In cultivated fields there is high probability for males and females to mate, $G_{1\rightarrow 2}(t) = 1 - M(t)$
- Adult mortality is composed of a survival rate $G_A(t)$ and a “generic” mortality rate $M'_A(t)$
Application: the case of *Halyomorpha halys*

Temperature-dependent development rate is usually represented by the following functions:

- **Logan rate function** (Logan et al. 1976)

  \[ G(T) = \psi \left[ \exp(\rho T) - \exp\left(\rho T_M - \frac{T_M - T}{\Delta T}\right) \right] \]

- **Briére rate function** (Briére et al. 1999)

  \[ G(T) = a(T - T_L)(T_M - T)^{\frac{1}{m}} \]

- **Sharpe and De Michele rate function** (Sharpe and De Michele, 1976)

  \[ G(T) = \frac{T \exp(A - \frac{B}{T})}{1 + \exp(C - \frac{D}{T}) + \exp(E - \frac{F}{T})} \]

We can test these functions with the dataset published by Nielsen et al. (2008) and Govindan and Hutchinson (2020). Who’s the best one?
The best representative development rate equation was the Brière. The dataset allowed to estimate the parameters for all the life stages:

Let’s see temperature-dependent mortality and fertility rates..
Application: the case of *Halyomorpha halys*

Temperature-dependent fertility can be represented by the Gaussian-like function (Ryan et al. 2016):

\[
\beta_1[T] = \left[ \frac{\gamma + 1}{\pi \lambda^{2\gamma+2}} \left( \lambda^2 - \left( [T - \tau]^2 + \delta^2 \right) \right)^\gamma \right]
\]

Two expressions can be evaluated for temperature-dependent mortality:

- The mortality rate of Kim and Lee (2003):

\[
M[T] = 1 - \left[ k \exp \left( 1 + \frac{T_{\text{MAX}} - T}{\rho_T} \exp \left( \frac{T_{\text{MAX}} - T}{\rho_T} \right) \right) \right]
\]

- The “bathtub” function of Wang et al. (2002):

\[
M[T] = aT^4 + bT^3 + cT^2 + dT + e
\]

Again, we can test these functions with the dataset published by Nielsen et al. (2008) and Govindan and Hutchinson (2020). Who’s the best one?
Application: the case of *Halyomorpha halys*

The best representative mortality rate equation was the bathtub function of Wang et al. (2002), while the Gaussian-like fertility well represented the dataset of Nielsen et al. (2008)

![Best fit fertility and mortality rate functions](image)

The application of the punctual model seems feasible. What about its spatialized version?
Application: the case of *Halyomorpha halys*

What we know about *H. halys* movement strategy:

- In flight mills distances up to 5 km were recorded (Aita et al. 2021, Lee and Leskey 2015, Wiman et al. 2015)
- In flight mills an average speed of 5 km/h is recorded (Wiman et al., 2015)
- No flights were recorded in wind speed conditions above 0.75 m/s (Lee and Leskey 2015)

However, we have no quantitative information to estimate:

- migration rates
- traps attractivity
- food/sexual attractivity
- movement due to other factors

We are on the right way, but further investigations are needed (besides field data!!)
Take home message

The preliminary results on the “punctual” model are promising:

- literature fully supports the model parameterization
- we have a high detail in modelling development and mortality of all life stages

...in other words: we are ready for a field validation!

However more information is needed to:

- insert other environmental parameters (i.e., relative humidity, photoperiod) into the model
- improve the description of reproduction
- estimate migration rates and apply the spatialized model

Let’s go back to work!
Thank you

More about me:

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A general ODE-based model to describe the physiological age structure of ectotherms: Description and application to *Drosophila suzukii*

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Modelling ectotherms’ populations considering physiological age structure and spatial motion: A novel approach

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or.. ask me! :)}