SIMULATION MODEL APPLIED TO BIOLOGICAL PEST CONTROL BY ENTOMOPHAGOUS SPECIES IN COMMERCIAL TOMATO GREENHOUSES

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Abstract

Our aim was to find a dynamic model describing the effect of the simultaneous application of the egg-parasitoid Trichogramma achaea and the predator Nesidiocoris tenuis to control the phytophagous pest South American Tomato Moth (Tuta absoluta). We found that a Lotka-Volterra type system could be well fitted to the data, estimating the phytophagous growth rate, the parasitoid and predator mortality rates, the predation and parasitism rates and the parasitoid emergence rate. The two-agent biological control mechanism can be applied to find optimal rates and timing of the release of parasitoid and predator agents in commercial greenhouse crops.

Keywords

biological pest control, phytophagous-parasitoid-predator system, Tuta absoluta, Trichogramma achaea, Nesidiocoris tenuis

Introduction

Biological control of pest insects in greenhouse crops has an unquestionable advantage in economic, environmental and public health terms (Shipp et al., 2007). While chemical protection has a single and immediate effect, in biological control, the time scale of the protection based on the interaction of insect populations is longer, and the eventually remaining entomophagous populations can reduce the damage caused by future infections (Van Driesche et al., 2008; Varga et al., 2010).

Pest control in greenhouse crops in Europe has shown an important development within the last 30 years through the replacement of chemical control by biological control, mainly due to pest resistance to insecticides (Van Lenteren, 2007; Blom, 2010). In greenhouse tomatoes, biological control programs used several natural enemies (predators and parasitoids), mainly two predator species for biological control of whitefly Bemisia tabaci (Gennadius) (Hem.: Aleyrodidae): Nesidiocoris tenuis (Reuter) (Vila et al., 2012) or Macrolophus pygmaeus Wagner (Hem.: Miridae) (Chailleux et al., 2013) in countries where the use of the first species is not authorized (Cabello et al., 2012a). This situation changed with the introduction of the South American tomato moth, Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) (Desneux et al., 2010). For its biological control, different natural enemies (predators, parasitoid and entomopathogens) have been studied. Since then, by now the use of the egg-parasitoid Trichogramma achaeae Nagaraja and Nagarkatti (Hym.: Trichogrammatidae) has been developed, which is applied in several countries of Europe and the Mediterranean area at the commercial level (Cabello, 2010; Cabello et al., 2012a). However it has been shown, on the one hand, the predators N. tenuis and M. pygmaeus eggs Wagner also kill eggs of the pest species (T. absoluta) (Urbaneja et al., 2009), on the other hand, it was also found that intraguild competition took place, both predator species also kill eggs previously parasitized by T. achaeae (Cabello et al., 2012b; Chailleux et al., 2013). This competition makes it more difficult to manage both entomophagous in biological control programs in greenhouse tomatoes in Europe.

The economic utilization of the developed, fitted and validated population-dynamical model will consist in planning the time and abundance of the introduction of entomophagous insects that should be released for the biologically and economically most efficient plant protection, given a certain level of pest infection (Varga et al., 2010).

The objective of this work has been the elaboration of a practical method to be applied in greenhouse production. This method will have two main components: (1) Population dynamics of the pest species and (2) timing and determining the number of individuals of predator and parasitoid species that should be released for an efficient control of the pest species. Of course, this objective is being realized in collaboration with industrial producers of biological agents, when both the selection of the agent and the way of its utilization would be necessary for its applications by farmers and agronomists.

Material and methods

Experimental design: Trials were carried out from July and November 2009 at two different commercial greenhouses A and B (2,000 and 3,100 m^2) with soil with gravel-sand mulch located in Alhama (Almeria, Spain; 36.962321N, 2.555434S). The crop was tomato (Ikram ® variety, Syngenta, Madrid, Spain). The infestation by the pest species, T. absoluta, was natural. Furthermore, two natural enemies were used: T. achaeae and N. tenuis (Trichocontrol ® and Nesidiocontrol ®, Agrobio SL, La Mojonera, Almeria, Spain). Release doses and timing for both natural enemies were determined according to the requirements in biological control programs for greenhouses in Southeast Spain (Cabello et al., 2012a; Vila et al., 2012).

Weekly samples were taken for the three species: pest, predator and parasitoid. 50 plants, randomly selected in each greenhouse, predator number were counted in situ on 10 top leaves per plant. The pest and parasitoid numbers were sampled separately. Twenty-five young leaves recently expanded in the upper part of the plant, were taken in each greenhouse also randomly selected. The leaves were collected, labeled, and transported in an icebox to the laboratory and then examined under a stereoscopic microscope to determine whether eggs had hatched or had been killed by predators. Eggs not in these categories were individually isolated and incubated at 25±1 ºC and 60-80% R.H. to assess T. achaeae parasitism. The found data (number of pest eggs, parasitoid adults and predator nymphs+adults) for each greenhouse and week were represented by their mean values per square meter and they were used in the mathematical model. Temperature and relative humidity values for each greenhouse were monitored by means of thermo-hygrometers (EBI 20-TH1, Ebro Electronic GmbH & Co. KG, Ingolstadt, Germany) placed inside a meteorological box.

Mathematical model: Fig. 1 shows the considered network interactions according to the nomenclature employed by Mill (2006) used in the model. Its mathematical expression is shown below:

$$\begin{array}{ll} \text{Phytophagous species:} & x_1' = x_1\left(m_1 - \alpha \cdot x_2 - \gamma_1 \cdot x_3\right) \\ \text{Parasitoid species:} & x_2' = x_2\left(-m_2 + \beta \cdot \alpha \cdot x_1 - \gamma_2 \cdot x_3\right) \\ \text{Predator species:} & x_3' = x_3\left(-m_3 + \gamma_1 \cdot x_1 + \gamma_2 \cdot x_2\right) \end{array} \qquad 1$$

Where x_1, x_2 and x_3 are the densities (number / m^2) of phytophagous, parasitoid and predator species, respectively; m1 the phytophagous growth rate; m_2 and m_3 the parasitoid and predator mortality rates, respectively; α the parasitism rate; β the parasitoid emergence rate; γ_1 and γ_2 the predation rates on phytophagous and parasitoid, respectively.

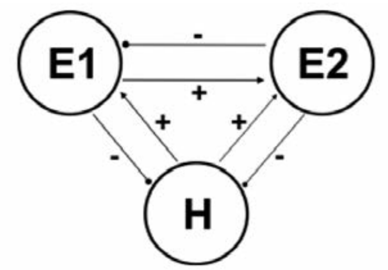

Figure 1. Network of interactions considered in the model herbivore – parasitoid – predator (H = Tuta absoluta; E_1= Trichogramma and E_2 = Nesidiocoris tenuis), the linking arrows and clubs show benefits (+) and losses (-).

Condition for local asymptotic stability equilibrium

For the stable coexistence of the population system, the following method will be applied. Let $f \in C^1(\mathbf{R}^3,\mathbf{R}^3)$ and $x^* \in \mathbf{R}^*$ such that $f(x^*)=0$. Consider the following system in $\mathbf{R}^3$

$$x' = f(x) \qquad 2$$

Calculate the Jacobian

$$A := f'(x^*)$$

and let

$$p(\lambda) = \lambda^3 + b_1\lambda^2 + b_2\lambda + b_3$$

be its normed characteristic polynomial. Then by the Routh-Hurwitz criterion (see e.g. Chen et al., 2004) a matrix $A \in \mathbf{R}^{3x3}$ is stable or Hurwitz (all its eigenvalues have negative real part) if and only if

$$b_1, b_2, b_3 > 0 \quad and \quad b_1 \cdot b_2 > b_3 \qquad 3$$

Under this condition x^* is an asymptotically stable equilibrium of system (2).

Optimal control of the population system

For system (1), we set up a general optimal control problem that will be solved for the dynamic model fitted to the data. Based on (1), consider the control system

$$x' = F(x_1,x_2,x_3,u_2,u_3) := \begin{bmatrix} x_1\left(m_1 - \alpha \cdot x_2 - \gamma_1 \cdot x_3\right) \\ x_2\left(-m_2 + \beta \cdot \alpha \cdot x_1 - \gamma_2 \cdot x_3\right) + u_2 \\ x_3\left(-m_3 + \gamma_1 \cdot x_1 + \gamma_2 \cdot x_2\right) + u_3 \end{bmatrix},$$

where functions u_2 and u_3 describe the time-dependent rate of release of parasitoid and predator agents, respectively, realizing the biological control of the pest. Fix a time interval $[t_1, t_2]$, and for each $\varepsilon > 0$ we define the class of essentially bounded ε-controls

$$U_\varepsilon[t_1,t_2] := \left\{ u = (u_2,u_3) \in L^2_\infty[t_1,t_2] \mid 0 \le u_i(t) \le \varepsilon \ \ \textit{for almost every} \ \ t \in [t_1,t_2] \right\}$$

In order to steer the system from an initial state $x(0)=x^0$ to a final state with pest level $x_1^F \in]0,K]$, keeping the latter below K and minimizing the total release of agents, we have to solve the following optimal control problem, with c_2, c_3=0 or 1:

$$\begin{gathered} \Psi(u) := \int_{t_1}^{t_2} \left(c_2 u_2(t) + c_3 u_3(t)\right) dt \to \min, \\ u \in U_\varepsilon[t_1,t_2] \\ x' = F(x_1,x_2,x_3,u_2,u_3) \\ g(x_1(t),x_2(t),x_3(t)) \le 0 \quad (t \in [t_1,t_2]) \\ x(0) = x^0 \quad x_1(t_2) = x_1^F \end{gathered} \qquad 4$$

where $g(x_1,x_2,x_3) := x_1 - K$. For the solution, the toolbox developed for MatLab in Banga et al. (2005) and Hirmajer et al. (2009) is applied.

Results and discussion

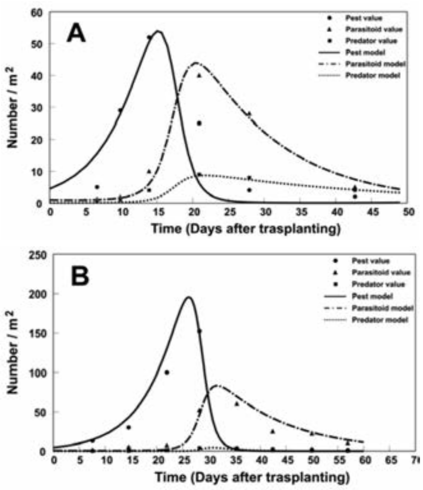

Figure 2. Densities obtained from the fitted model: Prey species = *Tuta absoluta* (egg stage), Parasitoid species = *Trichogramma achaeae*, Predator species = *Nesidiocoris tenuis*, in commercial tomato greenhouses A and B.

The model was well fitted to the data of three species, the obtained fitting parameters and the corresponding statistical parameters are shown in Table 1, the corresponding curves are plotted in Figure 2. The results show the importance of the egg-parasitoid species in the biological control of pest species in the first weeks of the crop cycle, and then its action as a biological control agent is lower. This is caused, first, by increasing predator populations and consequently, by the effect of intraguild competition. These results corroborate those cited in papers Cabello et al. (2012 a,b).

Table 1. Fitting of model (1) to the data of tomato greenhouses A and B.

Greenhouse	Fitting parameters							Statistical parameters			
	m_1	m_2	m_3	α	β	γ_1	γ_2	Variable	d.f.	r^2	P
A	0.14	0.06	0.26	0.01	0.23	0.00098	0.0009	Pest	5	0.7515	0.0254
								Parasitoid		0.9747	0.0002
								Predator		0.8399	0.0102
B	0.2	0.096	0.063	0.016	0.58	0.0067	0.00013	Pest	7	0.9697	0.0001
								Parasitoid		0.9065	0.0003
								Predator		0.8600	0.0009

Stable coexistence of the population system

For the fitting parameters corresponding to the greenhouse A the equilibrium x^*=(26.087,14,0) is asymptotically stable for system (1): the Jacobian at x^* is

$$A=\begin{pmatrix} -4.16334\times10^{-16} & -0.26087 & -0.0255652 \\ 0.0322 & 1.59595\times10^{-16} & -0.0126 \\ 0 & 0 & -0.221835 \end{pmatrix}$$

verifying conditions (3) implying asymptotic stability. In fact, the eigenvalues of A are

$$\lambda_1=-0.221835$$
$$\lambda_2=-1.2837\times10^{-16}+0.0916515\,i$$
$$\lambda_3=-1.2837\times10^{-16}-0.0916515\,i$$

Since two eigenvalues have a very small negative real part, the convergence to the equilibrium is slow.

Solution of the optimal control problem

Due to the slow convergence of the population system to the equilibrium, we intervene in the dynamics with controls corresponding to the release of parasitoid or predator agents, in order to keep the prey (pest) at levels that do not harm the crop too much, minimizing the total release of agents. In the first phase only parasitoid, in the second one only predator individuals are released. That is why we intervene in problem (4), in a first phase with the parasitoid and in a second one with the predator with the following parameter values:

Phase 1: $[t_1, t_2]:=[0,20];c_2:=1;c_3:=0;\ \varepsilon:=2;\ K:=20$ and $x_1^F:=7$.

Phase 2: $[t_1, t_2]:=[20,40];x_1^0:=x_1^F;c_2:=0;\ c_3:=2;\ \varepsilon:=2;\ K:=7$ and $x_1^F:=3$.

In Figure 3 we can see the coordinates of the optimal trajectory and controls for both phases.ε

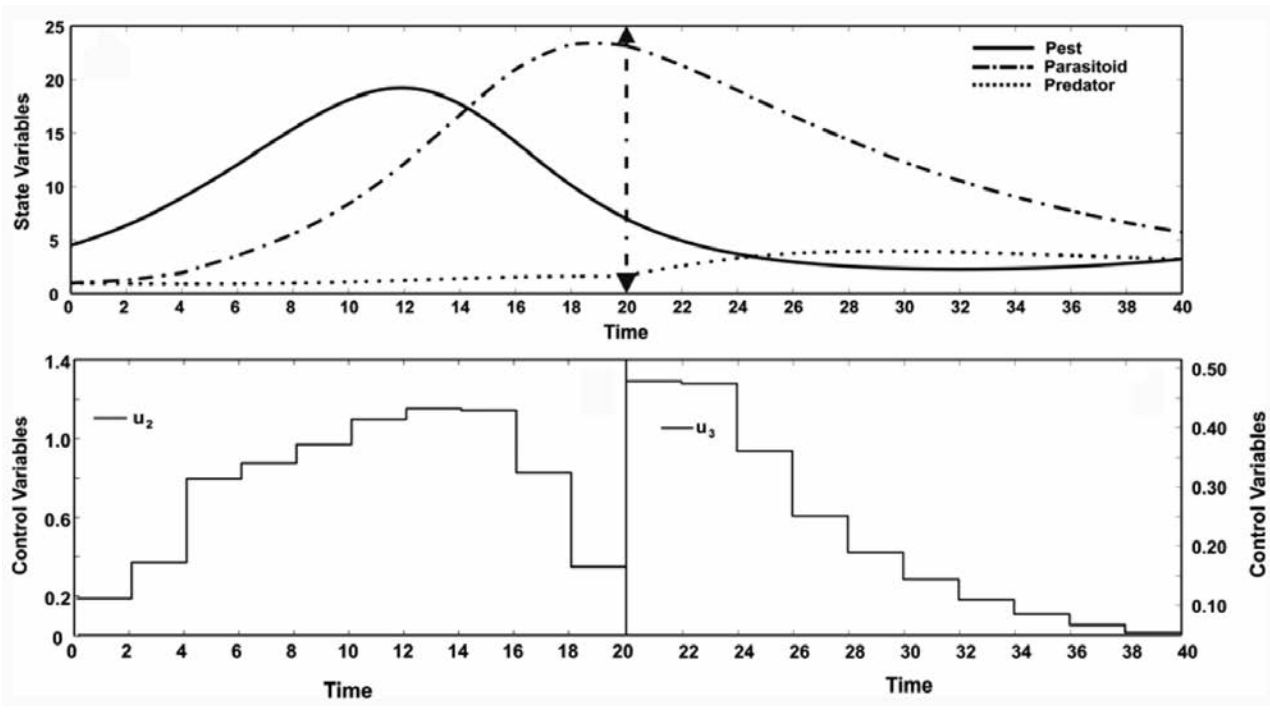

Figure 3. Optimal trajectory and controls of problem (4), for Phases 1 and 2. Pest species: *Tuta absoluta* (egg stage), parasitoid species: *Trichogramma achaeae*, predator species: *Nesidiocoris* tenuis in commercial tomato greenhouse.

The introduced optimal control model is a contribution to the methodological development of biological control of Tuta absoluta in greenhouse crops. On the one hand, in the early stages of the crop, by the release of the parasitoid agent, the pest density remains below a certain value, small enough not to cause serious economic damage to the crop. On the other hand, at the end of the first control period, the pest level must be sufficient for the colonization and subsequent establishment of the predator population. In the second part of the crop cycle, when predator population is higher, the action of the parasitoid is less necessary. This mathematical approach also makes it possible to minimize the cost of the application of agents, highlighting the importance of the proposed optimal control model in the integrated pest management (IPM) and/or biological control programs.

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