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A Hybrid Model For Simulating Interactions Between Crop And Insecticide-Stressed Pest Dynamics: An Application To Cotton Crop And The Pest *helicoverpa armigera*

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ABSTRACT

In the view of acknowledging the power of matrix population models, we developed a hybrid model that simulates crop-pest interactions with insecticide application. The hybrid model is a coupled time continuous model and time discrete matrix model. The time continuous model in the form of Ordinary Differential Equations simulates cotton growth and insecticide kinetics. The time discrete model is the extended Leslie model which was used here to simulate the population dynamics of *helocoverpa armigera* and combines its age and stage structures. The coupled model is solved as a sequence of initial value problem for cotton crop dynamics. This hybrid model allows for the simulation of complex structured pest population dynamics and can be used to evaluate treatment schemes with target on pest life stage or age class for a more efficient and sustainable crop protection.

Keywords: Crop dynamics, Pest population dynamics, Pest control, Insecticide application.

1. Introduction

Insect pests are a major constraint on production and their management imposes significant costs and environmental problems (Fitt, 2000). Even with the implementation of intense efforts to control insects, pest management persists as a significant challenge for this century (Ferron and Deguine, 2005) and control is usually achieved with insecticides. The use of pesticides has been increasing in many parts of the world, and their excessive application is a really threat to the environment. Due to the enormous variety of different types of pesticides, crops, hydrological and soil conditions and the application time of pesticides, the use of computer simulation models is indispensable (Groen, 1997). Several simulation models were developed describing crop-pest interactions and insecticide application. These models are usually formed of Ordinary Differential Equations (ODE) and consider the pest population density as a single state variable for the pest population dynamics. Adams *et al.*, (2005) described most of these models with application to the population dynamics of aphids in broccoli. The model described in this paper is a hybrid model coupling a time continuous model for cotton growth and insecticide kinetics in the form of ODE, with a time discrete matrix model for the population dynamics of *Helicoverpa armigera (HA)*. The development of a hybrid model is motivated by the application of matrix population models which offer several advantages (Salguero-Gómez and De Kroon, (2010)): Matrix models (i) are relatively easy to formulate, (ii) compile complex data in a structured and analytically tractable manner, (iii) provide numerous parameter with direct biological meaning, (iv) allow the investigator to address broad or specific, experimental and/or theoretical, ecological and evolutionary questions, and (v) produce uniform outputs, enabling direct comparisons between the results of different studies.

Moreover, Matrix population models provide a link between the individual and the population, built around a simple description of the life cycle (Caswell, 2001). The matrix model involved in this paper is the extended Leslie model. The extended Leslie model describes the dynamics of populations classified by age and other criteria like size or stage (Söndgerath, 2011). This model will be employed to simulate the temporal dynamics of *HA* combining its four life stages: egg, pupae, larva and adult, on a cotton plot in a daily time step. The extended Leslie model had been used to simulate the population dynamics of *Scolothrips longicornis* Pristner (Söndgerath and Richter, 1990) and cabbage root fly (*Delia radicum* L.) (Söndgerath and Müller-Pietralla, 1996) and yielded remarkable results. The simulation model developed in this study can help to simulate crop and pest population dynamics in interaction and evaluate the efficiency of insecticides-pest management strategies.

2. Model development

The development of the hybrid model required the following components: crop dynamics, pest population dynamics and insecticide application. A cotton growth model based on ODE is developed first; then, the extended Leslie model is described for the population dynamics of *H.A.* and coupled to the cotton growth model. Finally the model for insecticide application is developed and is coupled to the pest population model.

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2.1. Cotton growth model

Numerous cotton growth models had been developed and each for a particular purpose as in the following examples:

Wall *et al.,* (1994) developed the cotton simulation model COTCO2 for cotton response to atmospheric CO_2 concentration;
Zhang *et al.,* (2008) Developed SUCROS-Cotton with a particular attention to the phenological development of the plant and the plasticity of fruit growth in response to temperature, radiation, day length, variety traits, and management;
Liang *et al.,* (2012, a and b) developed a geographically distributed cotton growth model from the original GOSSYM and optimized it for coupling with the regional Climate-Weather Research Forecasting model (CWRF). GOSSYM predicts crop growth (with detailed plant chemistry, morphogenesis, and phenology) and soil responses to environmental stresses, primarily from heat, water, carbon, and nutrients;
Yang *et al.,* (2008) reported that COTTON2K V4.0 is a process based model that can simulate soil and plant processes as influenced by meteorological conditions and field management practices.

The cotton growth model we developed is a simple descriptive model, not simulating physiological behaviors but offering many advantages such as:

- Contains only few parameters. The increased number of parameters in the models with a time-varying coefficient makes them more difficult to fit (Adams *et al.,* 2005).
- Applicable to a large class of plant growth.
- Parameter estimation problem does not pose any difficulties regarding both numerical aspects and experimental design.

The cotton plant develops in three main organs: leaf, stem and boll. Since leaves are essential for the whole growth, the starting point is a mass balance equation for leaves biomass. Leaves develop with respect to a temporal pattern governed by a time dependent control function $f_s\ (t)$ (2) termed senescence function which starts with its maximum value and decreases in a sigmoid manner. The developments of the other organs are proportional to assimilate, therefore to leaves biomass.

Equation for leaves development

$$\frac{dL}{dt} = f_s r_{max} L - \mu L \qquad (1)$$

Where r_{max} is the maximal growth rate and L is the biomass density of cotton leaves with the initial density $L\ (t=0) = L_0 > 0$. The senescence function considered has the following form:

$$f_s = (1-a)\frac{e^{(-b(t-t_{min}))}}{1+ae^{(-b(t-t_{min}))}} \qquad (2)$$

a and ρ are positive fitting parameters. More senescence functions are discussed in Richter and Söndgerath (1990). The growth of all other organs is closely related to photosynthetic activity within leaves, which is in turn a function of leaves biomass. Equations for stem and boll are then derived as follow.

Equation for stem development

The differential equation for stem development was developed with the idea of logistic growth with the consideration that the rate of stem development is proportional to leaves density.

$$\frac{dS}{dt} = r_S L\left(1 - \frac{S}{K_S}\right) \qquad (3)$$

With the initial condition $S\ (t=0)=S_0 \geq 0$. S is the stem biomass density, r_s is the stem growth rate and K_s is the field carrying capacity for stem biomass. The term in brackets (3) is the retardation factor limiting to K_s; the maximum attainable biomass on the field for stem.

Equation for bolls development

The differential equation for boll development was developed with the idea of logistic growth with the consideration that the rate of boll development is proportional to leaves density. Boll development started when a critical time t_s was reached, after the beginning of the development of leaves and stem, with a smooth transition. This pattern is governed by the time dependent switching function $f_b(t)$ (5).

$$\frac{dB}{dt} = f_b r_b L\left(1 - \frac{B}{K_b}\right) \qquad (4)$$

With the initial condition $B\ (t=0)=B_0 \geq 0$. B is the boll biomass density, r_b was the boll growth rate and K_b was the field carrying capacity for boll biomass.

$$f_b = 1 - e^{\left(-\frac{t-t_{min}}{t_s}\right)^{\alpha}} \qquad (5)$$

t_s and α are positive parameters.

2.2. Pest population model

The pest *Helicoverpa armigera* has a life cycle development of four stages: egg, larva, pupa and adult; therefore, presents an age and stage structure. The extended Leslie model combining both structures writes as follow:

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Let there be $s=1,\dots,n$ stages with $i=1,\dots,m_s$ age classes.

The following notations are used:

$x_{si}(t)$ = expected number of individuals in age class i of stage s at time t $(t=1,2,\dots)$;
P_{si} = probability of surviving from age class i of stage s to age class $(i+1)$ of the same stage;
F_i = expected number of offspring per individual in age class i of stage n;
$U_{si}(t)$ = probability of transition from age class i of stage s to age class 1 of stage $(s+1)$ at time t.

The model equations are deduced as follows:
The individuals in age class i of stage s at time $t+1$ are those surviving from age class i at time t and not developing to individuals of stage $s+1$.

$$x_{s,i+1}(t+1)=(1-U_{si}(t))P_{si}x_{si}(t) \quad for\ i=1,\dots,m_s-2\ \ and\ \ s=1,\dots,n \tag{6}$$

Again, it is assumed that all individuals surviving the last age class of any stage are collected in this age class,

$$x_{s,m_s}(t+1)=(1-U_{s,m_s-1}(t))P_{s,m_s-1}x_{s,m_s-1}(t)+(1-U_{s,m_s}(t))P_{s,m_s}x_{s,m_s}(t) \quad for\ s=1,\dots,n \tag{7}$$

The first age class of a stage $s=1,\dots,n$ is composed of those individuals of stage $s-1$ developing to individuals of the next stage s at time t.

$$x_{s1}(t+1)=\sum_{i=1}^{m_{s-1}}U_{s-1,i}(t)x_{s-1,i}(t) \quad for\quad s=2,\dots,n \tag{8}$$

For the first age class of the first stage the fertility coefficients have to be taken into account.

$$x_{11}(t+1)=\sum_{i=1}^{m_n}U_{ni}(t)F_i x_{ni}(t) \tag{9}$$

Employing matrix notation with $x(t)=\left[x_{11}(t),\dots,x_{n,m_n}(t)\right]'$ and an appropriate projection matrix M_t, these equations become:

$$x(t+1)=M_t x(t) \tag{10}$$

A thorough description of this model can be found in the book of Richter and Söndgerath (1990).

Crop consumption

With the consideration that the larvae of *H.A.* feed on cotton bolls, we assumed that cotton bolls are consumed by the pest employing a consumption rate of the Michaelis-Menten type because of its saturation behavior. The pest density at time t ($H(t)$) considered for crop-pest interactions is the total sum of larvae from all the larval age classes at time t. Equation (4) then becomes (11). The second term of equation (11) describes the consumption of cotton bolls by the pest.

$$\frac{dB}{dt}=f_b r_b L\left(1-\frac{B}{K_b}\right)-\frac{\gamma BH}{B+K_B} \tag{11}$$

Where K_B is the saturation constant and γ is the maximal consumption rate.

2.3. Insecticide application

Dirac delta function (12) is employed to assign the input insecticide dose D_i at time t_i ($i=1,2,\dots,n$) as punctual events which is approximated by a Gaussian type density distribution with small values of σ:

$$\delta(t-t_i)=\lim_{\sigma\to 0}\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(t-t_i)^2}{2\sigma^2}}\right) \tag{12}$$

Total insecticide input is thus represented by the superposition of single inputs (13).

$$D_s(t)=\sum_{i=1}^{n}D_i\delta(t-t_i) \tag{13}$$

Equation (14) below describes the evolution in time of the total concentration of the applied insecticide with the consideration that insecticide concentration decays linearly with a rate constant k given by the relation $k=ln\,2/DT_{50}$ where DT_{50} is the half life time of the insecticide.

$$\frac{dP}{dt}=D_s(t)-kP \tag{14}$$

With the initial condition $P(t=0)=P_0\geq 0$.

Effect of insecticide on the pest

The effect of insecticides on pest is expressed by a Weibull survival function (15).

$$R(P)=e^{-\left(\frac{P}{t_{hr}}\right)^{\varphi}} \tag{15}$$

Where t_{hr} is related to the ED_{50} value by $ED_{50}=t_{hr}\,Log(2)^{1/\varphi}$ and φ is a form parameter determining the slope of the survival function.

In our model, insecticide was used against the larval stage of the pest. The interaction insecticide-pest was realized such that the action of insecticide occured in the survival probabilities of the larval stage in the pest

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population model. Thus P_{si} for the larval stage became $P_{si}R(P)$.

2.4. Numerical solution

The hybrid model is solved as a sequence of initial values problem for cotton dynamics. The time discrete pest population dynamics model was computed at regular time steps (days). Since the time continuous crop dynamics and insecticide kinetics models were ODEs solved via the Matlab numerical solver ode45, the computation time step may not be regular. The initial values at time t_0 for both crop and pest densities were given as input variables, and the problem was first solved in the interval Tspan = [t_0, t_1] (i.e. day 0 to day 1). Next, the crop density and the pest density at time t_1 were called by the program as initial values and the problem was solved in the interval Tspan = [t_1, t_2], and the previous and the later results were linked together by concatenation. The process then continued in this way until the end of the simulation period. The pesticide was introduced by interpolating to find the value of the underlying function (function for insecticide application described in paragraph 2.3) at each time step.

3. Application

3.1. Cotton growth model

Parameters for the cotton growth model were estimated by fitting the model to the data of cotton development recorded in the software DSSAT v.4.5 (data courtesy of Guerrit Hoogenboom). Estimates were recorded in Table 1 and Figure 1 which showed the fitted curves. The employed method was the nonlinear least square fitting technique. The performance of the estimates was judged via the model residual analysis and the Nashs Sutcliffe factor of model efficiency:

$$M_f = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (16)$$

With O observed and P predicted values.

Table1: Estimated parameters for the cotton growth model.

Parameter	Estimated value	Unit
μ	0.000881	1/day
r_{max}	0.428	1/day
r_s	0.051	1/day
a	188	-
r_b	1.06	1/day
K_s	3660	Kg/ha
K_b	6190	Kg/ha
α	4	-
t_s	92.2	days
b	0.428	-

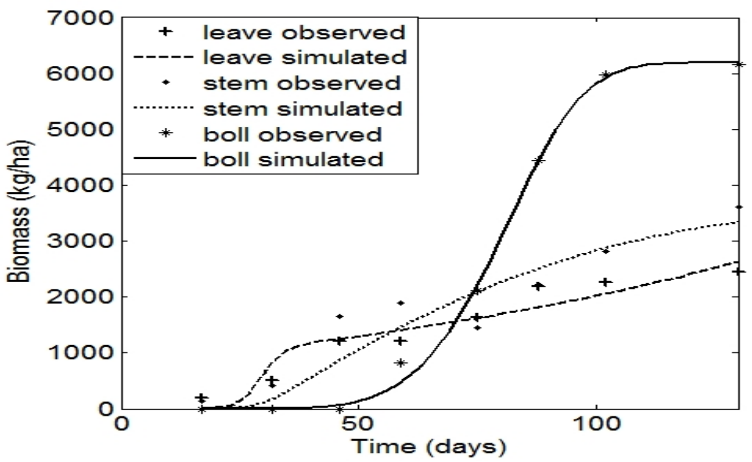

Figure 1: Cotton growth simulation model fit with data (data courtesy of Guerrit Hoogenboom, (Hoogenboom *et al.,* 2012)).

The obtained Nash-Sutcliffe model efficiency factor was M_f = 0.99, suggesting a very good fit of the model with the data. The scatter plot of the residuals (Figure 2) was disordered and did not show any trend suggesting that the errors were independent and had a constant variance. This indicated that the model did not exhibit systematic deviations.

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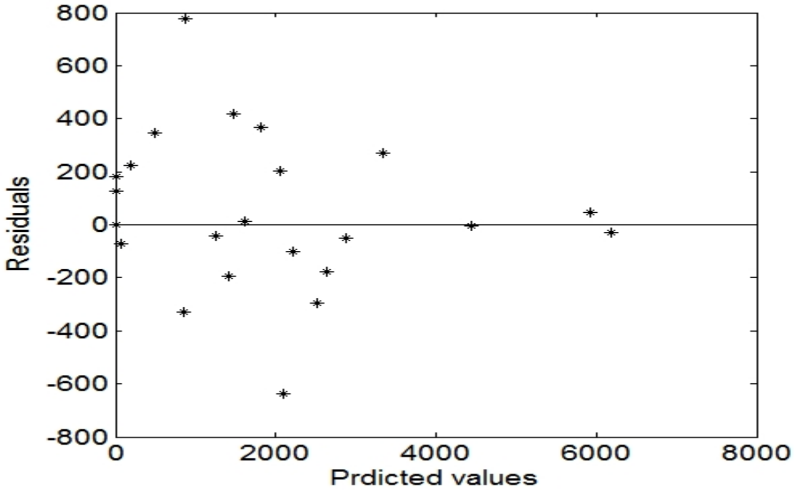

Figure 2: Scatter plot of residuals.

3.2. Pest population model

Mironidis and Savopoulou (2008) conducted laboratory studies to assess the effect of temperature on the survival development, fecundity, and longevity of *H.A.* (Hübner) at 11 constant temperatures ranging from 12.5 to 40° C and alternating temperatures. We used their alternating temperatures data ranging from 35° C to 27.5° C to simulate the dynamics of *H.A.* in its four life stages. We used data of Mironidis and Savopoulou (2008) because we found it more furnished than others we could get from the literature. In their study adult females' longevity was found to be 14.11 ± 1.73 days with an average oviposition rate of 26.18 ± 2.15 eggs per day. We considered the following assumptions:

-constant survival probabilities exist within life stages
-no individual can transit to the next life stage without completing its life stage
-transition probability to the next life stage is equal to the survival probability of the current life stage
-adults survive all their age classes.

The model was run in its matrix form for a period of 130 days (Figure 3) with the following initial population: 0 eggs, 1000 larvae, 0 pupae and 0 adults.

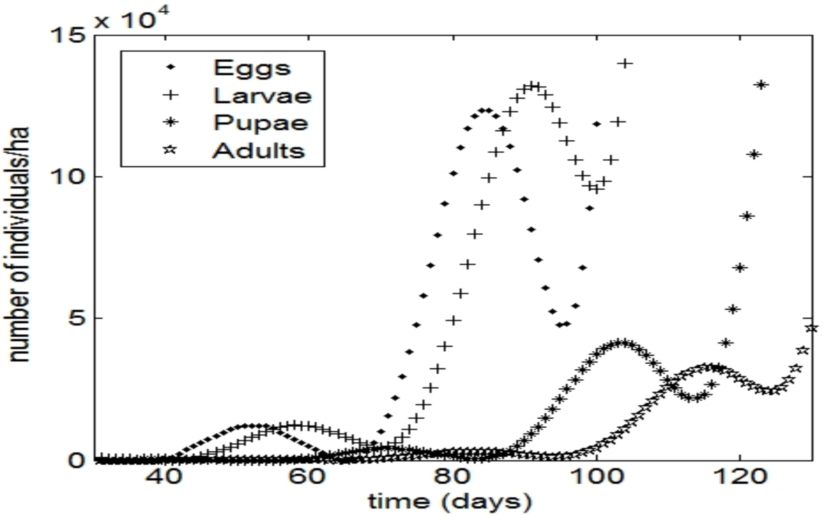

Figure 3: Dynamics of a growing population of *helicoverpa harmigera* in the absence of control measure (e.g. insecticide application). Pest invasions start on day 30 after crop planting.

The oscillation of the curves (Figure 3) described the evolution of the pest population in generations. The overlapping generations in the population of *H.A.* (Gupta *et al.,* 2003) was clearly observed in Figure 3 because the

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pest did not vanish in at least one life stage within the simulation period. The larvae density increased when the egg density decreased, indicating eggs hatching. In the same sense, the pupae density increased slowly with the decrease of larvae. These were larvae going into the pupa stage. The emergence of adults was synchronized with the decrease in pupae population. These observations suggest a very good behavior of the model. Advantages are associated with the model's ability to incorporate actual biological conditions, which is beyond the scope of this paper.

3.3. Crop-pest interaction

Data of Twine (1978) on the consumption of fresh matter by each larval instar of *H.A.*, were used to estimate parameters γ and K_B. We fitted the data to the second term of equation (11) and obtained γ = 991.9 mg/day and K_B= 2516 mg with the Nash-Sutcliffe efficiency factor of 0.99 (Figure 4).

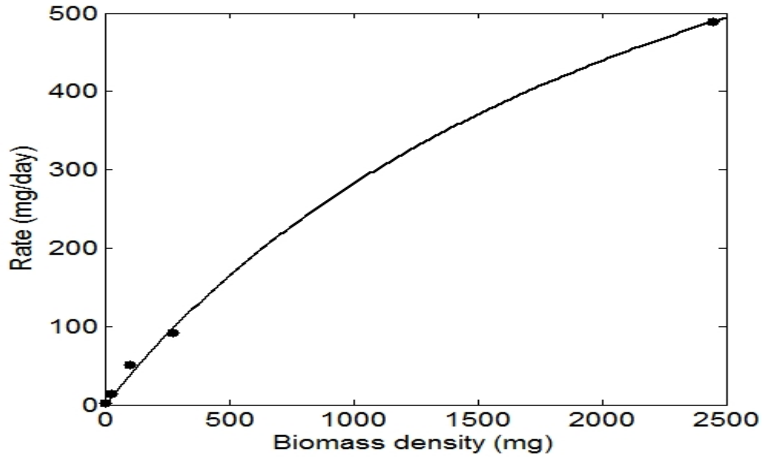

Figure 4: Estimation of the maximal consumption rate γ and the saturation constant K_B (Data from Twine, 1978).

Since we are interested in the consumption of cotton bolls by the larval stage of the pest, the pest density $H(t)$ in equation (11) for crop-pest interactions is the total sum of larvae from all the larval age classes at time t. Both models were coupled to each other and computed as a sequence of initial value problem. The result is shown in Figure 5.

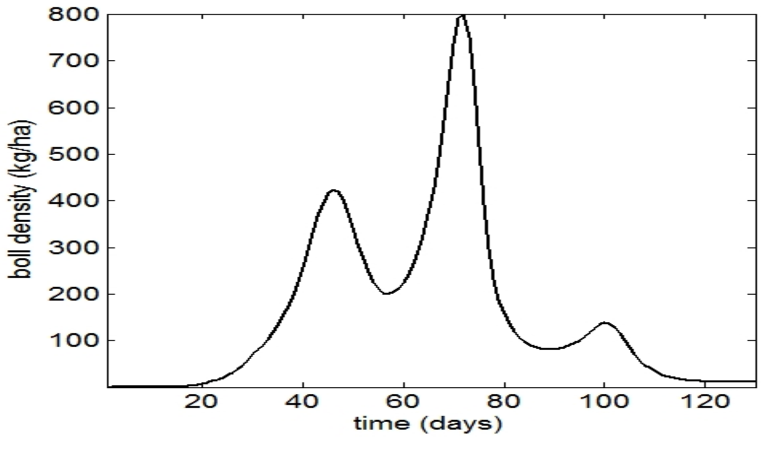

Figure 5: Cotton boll dynamics response to pest population dynamics.

In the beginning, the crop grew normally until the pest emergence (Figure 5). Because the pest density was not yet enough to cause substantial damage, the crop continued to develop until the pest reached the density susceptible to cause significant damage, indicated by the first decrease in the curve. Because the cotton plant had the ability to recover its losses (Poveda et al., 2012, Men et al., 2005, and Thomson et al., 2003) to some extent, it would grow again when the population of larvae decreased (second increase in Figure 5). The oscillation in the curve is explained by the fluctuation of the population density of larvae as indicated in Figure 3.

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These are indications that the model behaves as expected.

3.4. Insecticide application

Spinosad insecticide was used for our simulation. We estimated parameters of equation (15) by fitting the curve to the data of Ramasubramanian and Rgupathy (2004) who conducted studies on the response of the larvae of *H.A.* to different doses of Spinosad. We obtained the fitted curve (Figure 6) and the estimates t_{hr}=40.73 and φ= 0.32. The DT_{50} <1 for Spinosad is given by López and Fernández-Bolaños (2011).

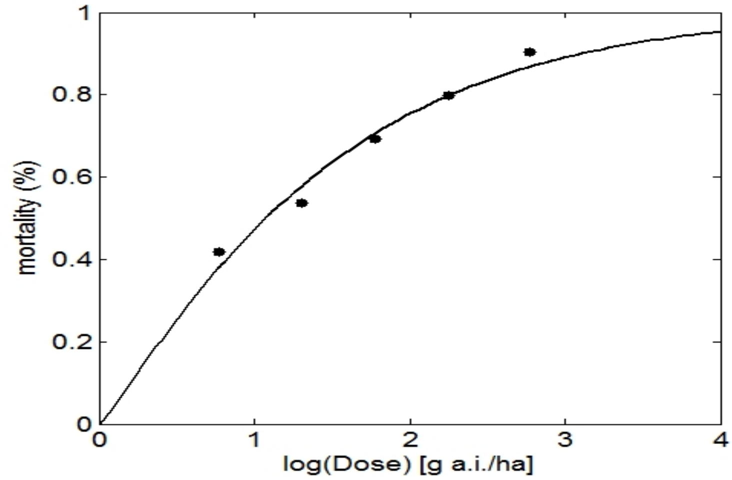

Figure 6: Fitted dose-response curve for the effect of Spinosad on the larve of *H.A.*

The recommended dose for Spinosad 60g a.i./ha for treatments against the cotton boll worm *H.A.* (Ramasubramanian and Regupathy, 2004) was used for this simulation, following a calendar based application scheme (Table 2). We considered two application schemes: the first with the recommended dose recorded in Table 2 and the second with a drastic reduction of the recommended dose recorded in Table 3:

Table 2: Application scheme1 with Spinosad insecticide

Dose (g a.i./ha)	60	60	60	60	60	60
Time (days after cotton planting)	45	59	73	87	101	115

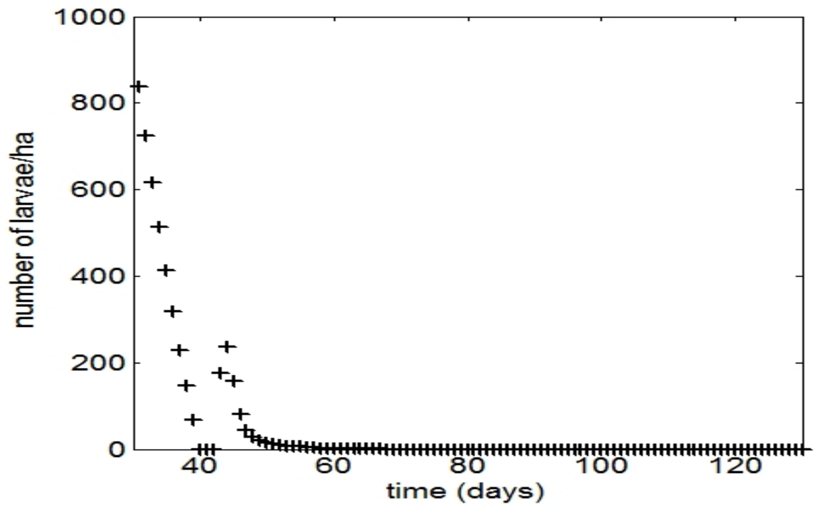

Figure 7: Pest response to Spinosad. Insecticide application was done according to the application scheme in Table 2.

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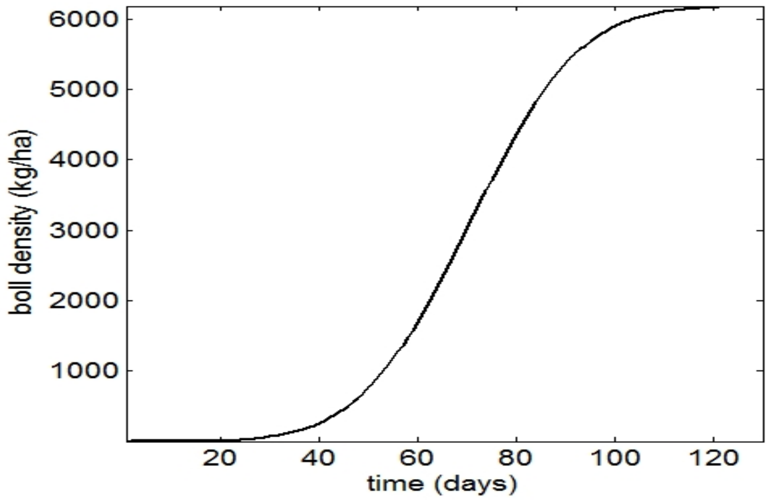

Figure 8: Crop response to pest after application of Spinosad. Insecticide application was done according to the application scheme in Table 2.

With the application scheme in Table 2, Spinosad could effectively control the pest population by maintaining the population density at a very low level (Figure 7). Cotton boll dynamics responded accordingly (Figure 8). The effect of the insecticide on the pest population dynamics and the effect of the pest on the cotton boll dynamics were thus observed.

Table 3: application scheme2 with Spinosad insecticide

Dose (g a.i./ha)	0.006	0.006	0.006	0.006	0.006	0.006
Time (days after cotton planting)	45	59	73	87	101	115

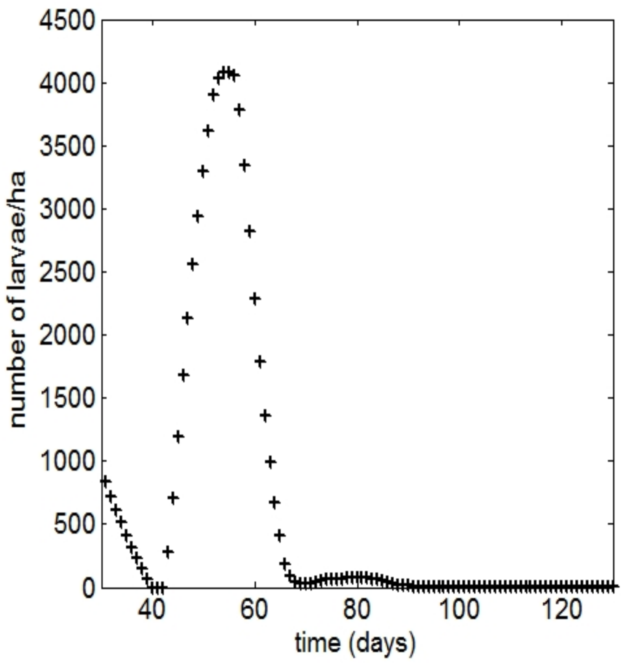

Figure 9: Pest response to Spinosad. Insecticide application was done according to the application scheme in Table 3.

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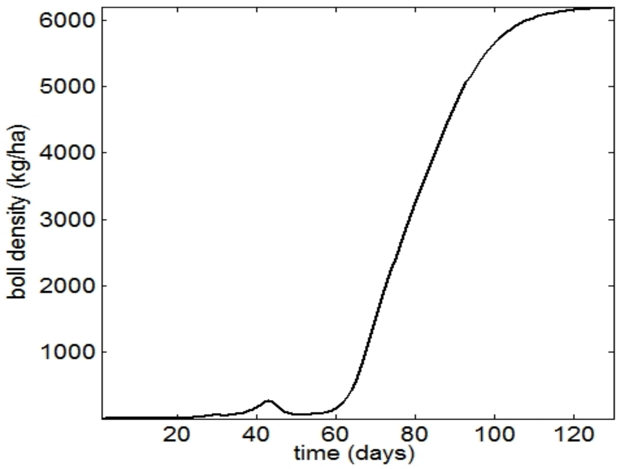

Figure 10: Crop response to pest after application of Spinosad. Insecticide application was done according to Table 3.

With the application scheme in Table 3, Spinosad could effectively control the pest population by maintaining the population density at a very low level (Figure 9). Cotton boll dynamics responded accordingly (Figure 10). The effect of the insecticide on the pest population dynamics and the effect of the pest on the cotton boll dynamics were thus observed.

4. Discussion and conclusions

The model developed in this paper simulates cotton crop and *H.A.* population dynamics in interaction, and the effect of insecticide on the population dynamics of *H.A.*. The cotton growth model we developed was relatively simple and could well simulate the dynamics of cotton bolls density. This model was applicable on a plot and the parameters which may change after some crop years, due to some changes in the environmental conditions such as soil type or weather. Therefore, the lifetime of this model needed to be determined.

The pest population model simulated the age and stage structured population dynamics of *H.A.* under the assumptions made in paragraph 3.2. These assumptions were not realistic but were adopted here just for simulations because we found no realistic data for the application of this model to the population dynamics of *H.A.*. As applied for the population dynamics of *Scolothrips longicornis* Pristner (Söndgerath and Richter, 1990) and cabbage root fly (*Delia radicum* L.) (Söndgerath and Müller-Pietralla, 1996), successful application of the extended Leslie model requires not only to know the life cycle of the population, but also the survival and transition probabilities calling for biological parameters such as: development times, emergence times and life times which are quite random. Studies aiming at furnishing such data for the cotton boll worm are encouraged. The temporal pattern of the life cycle can be determined by the probability distribution functions of these random variables, which depend on the time course of environmental covariates.

In the crop-pest interaction, further development is needed. The pest population dynamics should be a function of resource availability, which is not the case in our model. Insecticide applied at the recommended dose (Table 2) could maintain the pest population density at a very low level (Figure 7) and allowed the crop to grow effectively (Figure 8). A reduction of the recommended dose by 1/10000 (Table 3) also could maintain the pest population density at a very low level (Figure 9) to allow a final substantial yield (Figure 10). This remark suggested that the effect of pesticide on the pest may be inhibited into the model. This was not dramatic and can be taken into account when calibrating the model.

The hybrid model developed in this paper allowed for the simulation of complex structured pest population dynamics in interaction with crop dynamics. With the integration of insecticide kinetics in the model, it can be used to evaluate treatment schemes with target on pest life stage or age class for a more efficient and sustainable crop protection. The model was not complete as such, much still have to be done in the improvement, calibration and validation.

Acknowledgments

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