Article

Alert system against the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Insecta: Lepidoptera: Noctuidae)

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Abstract

Integrated pest management can be understood as an information system that supports decision-making regarding the phytosanitary management of crops. This system is built around the understanding of the population dynamics of the pest organism in its interaction with the host and the environment. In Mexico, in 2003, the phytosanitary alert system of the state of Guanajuato (SIAFEG) was established as an instrument to evaluate the impact of the main pests and diseases of some crops of economic importance in the state. In 2010, studies were begun to build the fall armyworm model, joining the SIAFEG in 2011. The elements that were combined to integrate the warning system for *S. frugiperda* were: the information of the network of agrometeorological stations of INIFAP-COFUPRO in Guanajuato, a model of dynamic simulation of the growth and development of the insect and data on the population dynamics of the insect. The model estimates the population dynamics of the fall armyworm. Comparing the estimates of the model with the adult trapping data, a significant relationship was found, which indicates that the model can be used reliably. Applied to long-term studies (2 or more years), the model can be very useful to understand the causes of the variation in population levels and damage to crops from one year to the next.

Keywords: *Spodoptera frugiperda*, population dynamics, simulation models.

Reception date: January 2019
Acceptance date: March 2019

Introduction

Given that the concept of integrated pest management (IPM) can be interpreted in different ways, it is important to clarify that this work assumes a broad definition of the term, in which IPM is understood as a strategy that seeks to maintain populations of organisms plague below the economic threshold of damage of a crop, planning and implementing actions or measures that do not put people, the environment or other species at risk. In this broad sense, the IPM is conceptualized as an information system that supports decision-making regarding the phytosanitary management of crops.

This information system is built around the understanding of the population dynamics of the pest organism in its interaction with the host and the environment, represented the latter mainly by weather conditions. As in any system to support decision-making, the use of mathematical models allows complementing the data coming from the sampling or trapping of the pest organism.

This type of approach has been successfully applied in support of phytosanitary management of crops since the end of the last century, highlighting the developments achieved at the University of California Davis in the phytosanitary management of vegetables and fruit trees and those obtained in the management of late blight of the potato (Krause *et al*., 1975). These examples have served as a reference for the application of the IPM approach as a support system for decision-making practically all over the world.

In Mexico, in 2003, the first system of this type was established in the state of Guanajuato; through the collaboration of the federal and state authorities in matters of plant health with the State Committee of Plant Health of the State of Guanajuato (CESAVEG) and the National Institute of Forestry Agricultural and Livestock Research (INIFAP) (Quijano and Rocha, 2011). This system called the Phytosanitary Alert System of the State of Guanajuato (SIAFEG) is currently operated by CESAVEG, in support of the planning, programming and operation of phytosanitary campaigns in the state of Guanajuato.

Originally, only three phytosanitary problems were included in the SIAFEG, which were the rootworm of the corn (*Diabrotica virgifera zeae* K. and S.), the rust of the bean (*Uromyces phaseoli* Reben) and the grasshopper of the milpa (*Sphenarium purpurascens* Charpentier). Subsequently, other phytosanitary problems were added according to the state priorities. In 2010, studies began to build the model of the fall armyworm, joining at SIAFEG in 2011.

The noctuids (Lepidoptera: Noctuidae) possibly constitute the largest family of macrolepidoptera with 20 000 species. Of these, some are pests of great economic importance worldwide. This family for several decades has been the subject of numerous studies related to its biology, distribution, phenology, control methods, natural enemies, etc. The fall armyworm *S. frugiperda* is a plague of economic importance and wide distribution in the American continent.

Considering that the phenology of insects varies according to the amount of heat in their environment, it is possible to predict their development rate with some precision by using heat units also expressed as day degrees, anticipating the time of appearance in the field of some of the stages of development of the insect, especially those susceptible to be controlled chemically.

The objective of this work was to design an alert system, based on meteorological information, trapping data and simulations of the population dynamics of the insect that allows to explain the interannual variations in the incidence of the fall armyworm in Guanajuato.

Materials and methods

Structure of the alert system

The elements that were combined to integrate the warning system for *S. frugiperda* were: the information of the network of agrometeorological stations of INIFAP-COFUPRO in Guanajuato, a dynamic simulation model of the growth and development of the insect and data on the population dynamics of the insect. For the parameterization of the life cycle of the insect, the information generated by Ramírez *et al*. (1987) and that relates the phenological response of *S. frugiperda* to temperature. The population fluctuation data were obtained through traps with pheromones of sexual attraction established by the State Committee of Plant Health of the State of Guanajuato (CESAVEG) in 2010 in different localities of the state of Guanajuato.

This adult trapping of *S. frugiperda* has been carried out systematically by CESAVEG since 2008, in order to support the monitoring and control of this pest. These data were used to validate the simulation model. In order to verify the performance of the model under different meteorological conditions, trapping data reported by the INIFAP in Zacatecas in 2013 was also used.

The agrometeorological network of INIFAP-COFUPRO, is operated by the Guanajuato Produce AC Foundation and currently has 55 stations distributed in the main agricultural areas of the state. This network offers registers every 15 min of 7 meteorological variables, among which the temperature, precipitation, relative humidity and predominant direction of the wind are the most used to feed the warning system. To complement the trapping data and estimate the population dynamics of *S. frugiperda*, a dynamic model of growth and development of the insect was built, which is fed with meteorological information.

Characterization of the life cycle of *Spodoptera frugiperda*

The biological cycle of this insect includes egg stages, 6 or more larval instars, prepupa, pupa and adult (Casmuz *et al*., 2010). Figure 1 shows the temperature response curves for the days of development (a) and the mortality percentages (b) in the different stages of *S. frugiperda*, according to the data published by Ramírez *et al*. (1987), standing out an evident greater sensitivity to the temperature of the pupa stage.

Table 1 shows the values of the minimum threshold temperature and the requirement of heat units for each stage of this insect. In both cases, the information was obtained from the study by Ramírez *et al*. (1987).

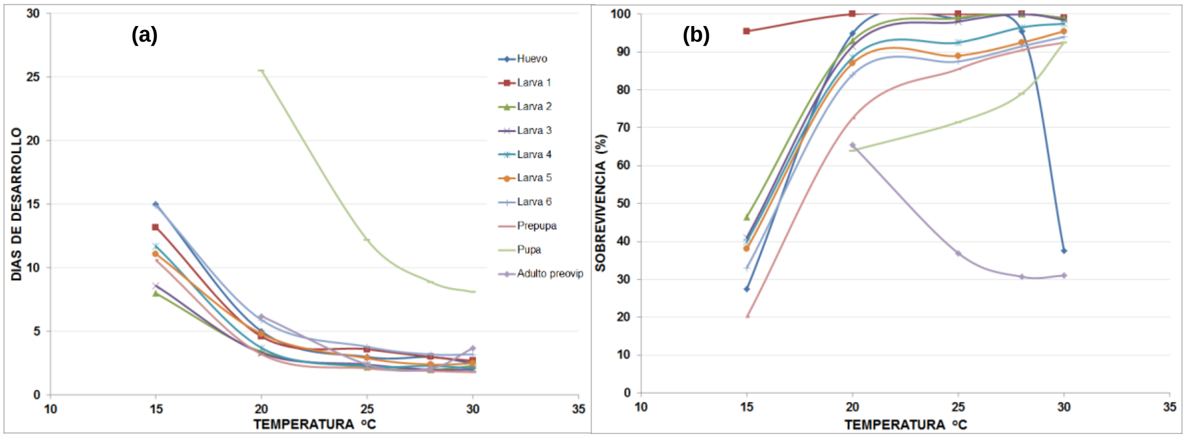

Figure 1. Temperature response curves for the days of development (a) and survival percentages; and (b) of *S. frugiperda* as a function of temperature.

Table 1. Threshold temperature and heat units for each stage of *Spodoptera frugiperda*.

Biological state	Threshold temperature	Heat units
Huevecillo	11.2	46.7
Larva	9.9	278.7
I	9.9	53.9
II	8	42.6
III	9.5	38.2
IV	10.4	38.6
V	10.5	44.8
VI	10.4	58.9
Prepupa	10.8	32.8
Pupa	15.4	116
Preoviposition	15.7	24.4
Egg-preoviposition	10.9	559.1

The oviposition rate (a) and the oviposition period; and (b) were estimated as a function of temperature, from the functions shown in Figure 2. For the construction of these functions were taken based on the values reported by Murua and Virla (2004).

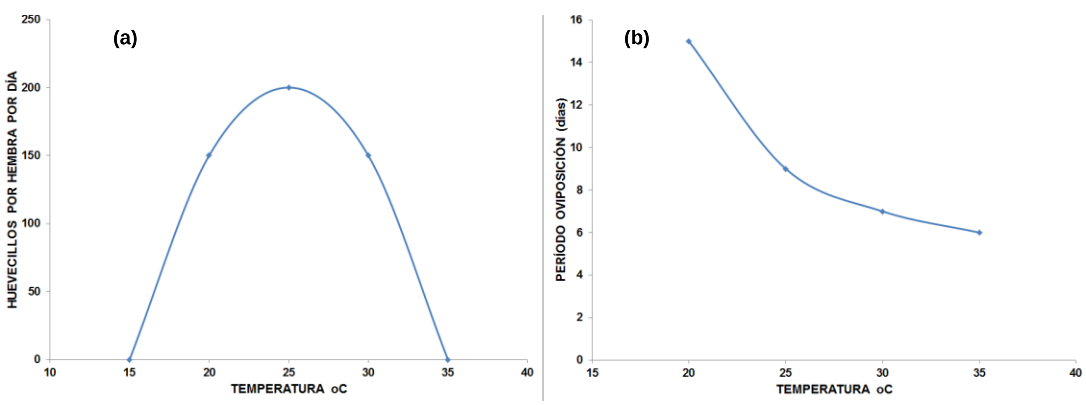

Figure 2. a) oviposition rate; and b) oviposition period of *S. frugiperda* as a function of temperature.

Phenological model of *S. frugiperda*

The computational algorithm of the model was developed on the Vensim platform, version 5.9, which has a graphical interface that allows writing the program code from the flow diagram of the program. The constants (development rates, mortality, oviposition) of the model were established from the data of Ramírez *et al*. (1987) and the experimental data obtained through adult trapping. The processes included in this model are:

- Mating and reproduction, where the average prolificacy of the females and the fraction of fertile females in the population were taken into account.
- Oviposition, a process that was modeled according to the temperature and host availability.
- Hatching and development of nymphs, processes dependent on temperature.
- Maturation and longevity of adults, which depends on the temperature.

Figure 3 shows the flow diagram of the model in which the described processes are included. The main structure of the model consists of 11 rectangles or levels, which represent the number of individuals in each stage of development and 22 keys or flows, which regulate the number of individuals entering and leaving the levels. The meteorological variables, such as temperature and precipitation, are fed externally to the model on an hourly or daily basis according to availability, while solar radiation and potential evapotranspiration, which are used to determine host availability, are estimated through the model.

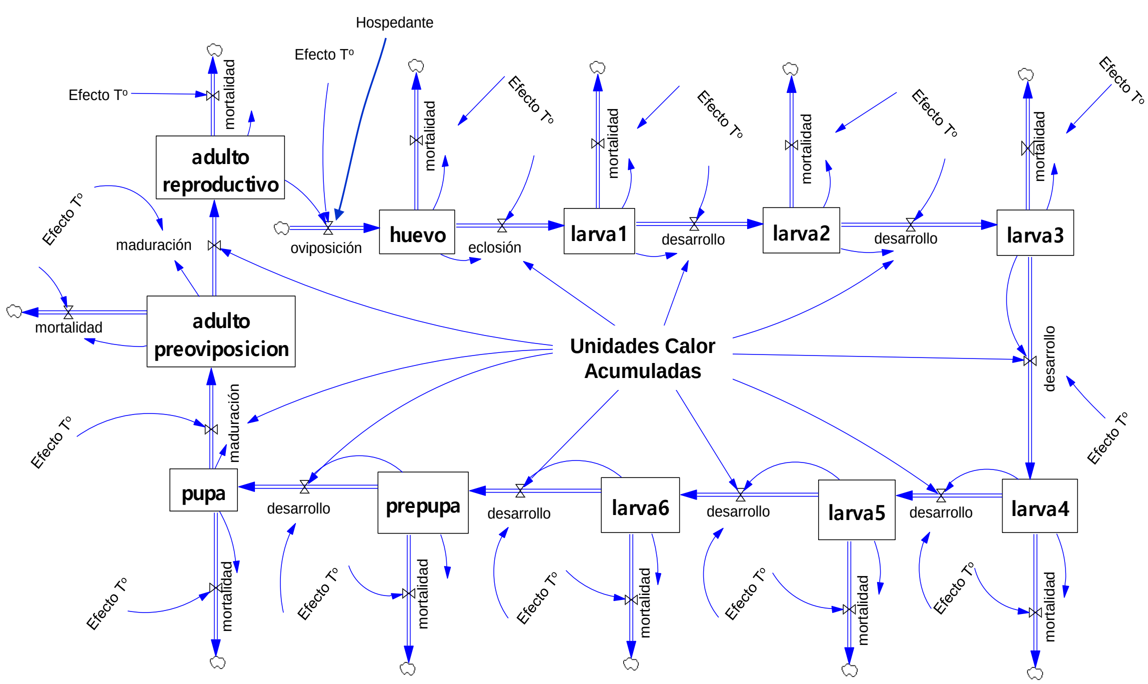

Figure 3. Flow diagram of the life cycle module of *S. frugiperda*.

The model can be configured to simulate a few months, a year or a period of several years. In each simulation, it is necessary to specify the stage of the life cycle of the insect in which it starts, specifying the corresponding accumulated heat units (UC). Each time a generation is completed, the model restarts the calculation of the heat units for the start of a new generation.

The model processes the daily temperature data to calculate the units heat per day (UC). At the beginning of the simulation only individuals in the pupal and pre-oviposition adult state are present. The average temperature and the presence of hosts determine the moment of beginning of oviposition and therefore of the beginning of the first generation. From this moment on the model starts the calculation of the number of individuals and their development rate based on the accumulated UC. The successive emergence of generations requires that in the oviposition process there is host availability, which is estimated from a moisture balance that involves precipitation and potential evapotranspiration. At the end of each new generation, the oviposition rate and the start of the next generation are calculated again.

Interannual variations in the population dynamics of *S. frugiperda*

The damages caused by *S. frugiperda* in crops such as corn and sorghum usually vary from year to year, making planning and timely application of preventive measures difficult. Within the IPM approach, several authors have tried to develop algorithms or models to predict the population fluctuation of this organism (Martínez-Jaime *et al*., 2011) generated a self-regressive stationary model from a series of time data of adult catches, the which when not considering any meteorological variable is basically applicable to the site in which the data were generated. On the other hand, Valdez-Torres *et al*. (2012) developed a phenological model of the rate of development as a function of temperature for which they adjusted polynomials of the second degree.

In particular, the rate of development of crops, pests and diseases, depending on the environmental temperature, allows us to calculate their maximum and minimum threshold temperatures and their optimal development temperatures (Zalom *et al*., 1983). With this information, it is possible to construct mathematical models of phenological development for crops, pests and diseases according to their thermal requirements (Damos and SavopoulouSoultani, 2012), which allow predicting unfavorable events for the crop, through the monitoring of meteorological variables such as temperature, radiation and relative humidity (Agrawal and Metha, 2007).

By not explicitly including time this approach remains at the descriptive level and its applicability is also limited to the experimental sites. The approach applied in the present study consists of the presentation of a series of differential equations, in which time is an explicit component and variables that are decisive in the behavior of the system, such as meteorological ones, are included. The system is solved by numerical methods which facilitates the inclusion of as many variables as necessary and gives the model the ability to represent the behavior of the system under different environments (Peart and Curry, 1988; Thornley and France, 2007).

The model developed in this study was used to try to understand interannual variations in the population dynamics of *S. frugiperda*, taking as reference the state of Guanajuato in the period 2012 to 2014. After conducting some preliminary simulations, it was determined that this insect regularly it remains as a pupa during the winter season, which coincides with the statement by

Martínez-Jaime *et al*. (2011) that this insect probably spends the winter as a pupa on the ground, emerging in the month of February when there is already sweet corn available for feeding. Therefore, the scenarios presented in this study are based on the assumption that there are populations of the insect in the pupal stage and that adults also arrive in the preoviposition phase (EPPO, 1997).

Results and discussion

Figure 4 shows the comparison between the simulated data (line) and observed data (points), for the adult reproductive stage in the localities of Abasolo (a) and Apaseo el Alto; and (b) in the state of Guanajuato in 2010.

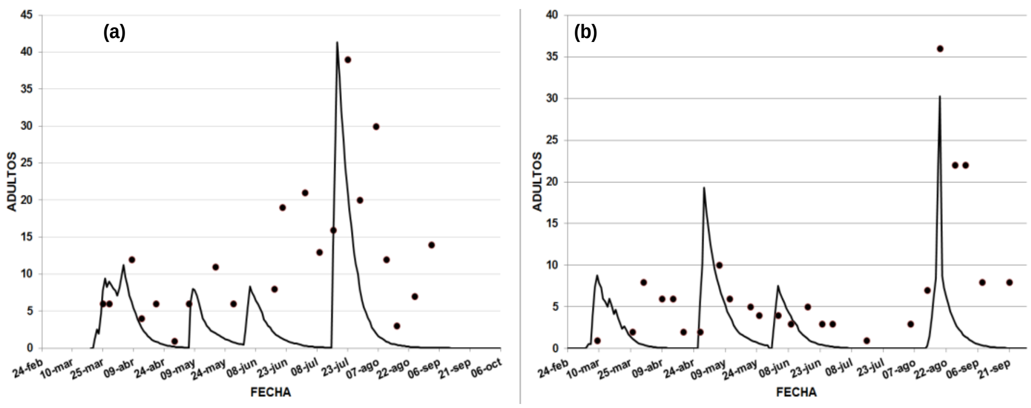

Figure 4. Simulated and observed population dynamics of Adults of *S. frugiperda* in the localities of a) Abasolo; and b) Apaseo el Alto, Guanajuato in 2010.

In the case of the town of Abasolo, the beginning of the activity of the insect was presented at the end of March, in addition there are several peaks that indicate the diversity of conditions that determine the presence of the adult mainly at the end of July and the beginning of August. In the case of the town of Apaseo el Alto, the start of the activity was presented in mid-March and the largest presence was mid-August and early September. In both cases, it can be observed that the model generates behavior similar to that of adult traps carried out by CESAVEG. Based on this validation of the model, a bulletin was designed on the population dynamics of this insect, which is published weekly on the SIAFEG page since 2011.

The estimate that serves as the basis for this bulletin includes the date of captures of adults from which oviposition is calculated and the development of the larval instars of *S. frugiperda*. This information is used as a basis for the recommendation of preventive applications in the integrated management of this organization. Figure 5 shows an example of this bulletin for the town of San Lorenzo in Acambaro, Guanajuato (www.siafeg.org.mx).

In order to expand the validation data of this model, in 2013 its performance was evaluated under the conditions of other states. Figure 6a shows the comparison between the results of the simulation with the model and the adult trapping data recorded by the INIFAP in the state of Zacatecas in the town of Calera by Victor Rosales in 2013. These data were taken from the site of phytosanitary alert of Zacatecas (www.zacatecas.inifap.gob.mx/plaga/).

As in the case of Guanajuato, it can be seen that there is agreement between the trapping data and the estimated data with the model, with the start of activity at the beginning of April, with a population peak at the end of June. Through the regression analysis, an adjustment test was performed between the estimated and observed data, finding a significant relationship between both series with a coefficient of determination of 0.74 for the line 1:1 (Figure 6b).


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En cada fila se estima el ciclo de desarrollo de gusano cogollero a partir de la fecha de captura de adulto. Para identificar los estadios que posiblemente estén presentes en tu parcela es importante que ubiques dentro de estas filas la fecha actual.

Los datos meteorologicos empleados para el analisis se obtuvieron de la siguiente estacion meteorologica debido a que es la mas cercana a su área de cultivo.

Estacion meteorologica **San Lorenzo**

Gusano Cogollero

Fecha de Captura	Huevecillo	Larva 1	Larva 2	Larva 3	Larva 4	Larva 5	Larva 6	Pupa	Adulto
3 Septiembre	7 Septiembre - 12 Septiembre	17 Septiembre - 20 Septiembre	22 Septiembre - 25 Septiembre	28 Septiembre - 1 Octubre	5 Octubre - 8 Octubre	8 Octubre - 13 Octubre	18 Octubre - 23 Octubre	12 Noviembre - 23 Noviembre	1 Diciembre - 7 Diciembre
27 Agosto	31 Agosto - 5 Septiembre	9 Septiembre - 12 Septiembre	14 Septiembre - 17 Septiembre	19 Septiembre - 22 Septiembre	25 Septiembre - 28 Septiembre	1 Octubre - 6 Octubre	8 Octubre - 13 Octubre	29 Octubre - 9 Noviembre	18 Noviembre - 24 Noviembre
20 Agosto	25 Agosto - 30 Agosto	3 Septiembre - 6 Septiembre	8 Septiembre - 11 Septiembre	13 Septiembre - 16 Septiembre	18 Septiembre - 21 Septiembre	22 Septiembre - 27 Septiembre	2 Octubre - 7 Octubre	20 Octubre - 31 Octubre	6 Noviembre - 12 Noviembre
13 Agosto	17 Agosto - 22 Agosto	26 Agosto - 29 Agosto	31 Agosto - 3 Septiembre	5 Septiembre - 8 Septiembre	10 Septiembre - 13 Septiembre	14 Septiembre - 19 Septiembre	22 Septiembre - 27 Septiembre	8 Octubre - 19 Octubre	25 Octubre - 31 Octubre
6 Agosto	10 Agosto - 15 Agosto	19 Agosto - 22 Agosto	24 Agosto - 27 Agosto	29 Agosto - 1 Septiembre	3 Septiembre - 6 Septiembre	6 Septiembre - 11 Septiembre	15 Septiembre - 20 Septiembre	1 Octubre - 12 Octubre	15 Octubre - 21 Octubre

Figure 5. Weekly bulletin of the fall armyworm (*Spodoptera frugiperda*). SIAFEG. 2014.

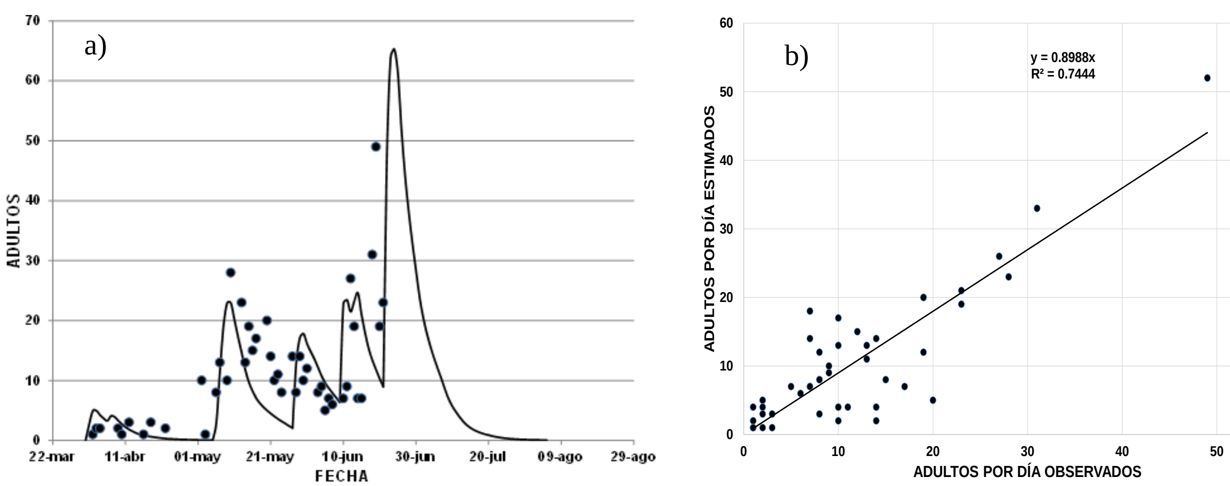

Figure 6. a) Simulated and observed population dynamics of adults of *S. frugiperda* in the town of Calera de VR, Zacatecas in 2013; b) test of adjustment of the data to a line 1:1.

These results indicate that the model can be used with reliability to support the management of this organism in different environments. As an example of a long-term estimate to try to understand the interannual variation in the behavior of this organism in Figure 7, the results of the simulation with the model for the stages of pupa, adult, egg and larva 4 in the locality are observed of Celaya, Guanajuato in the period from 2012 to 2014.

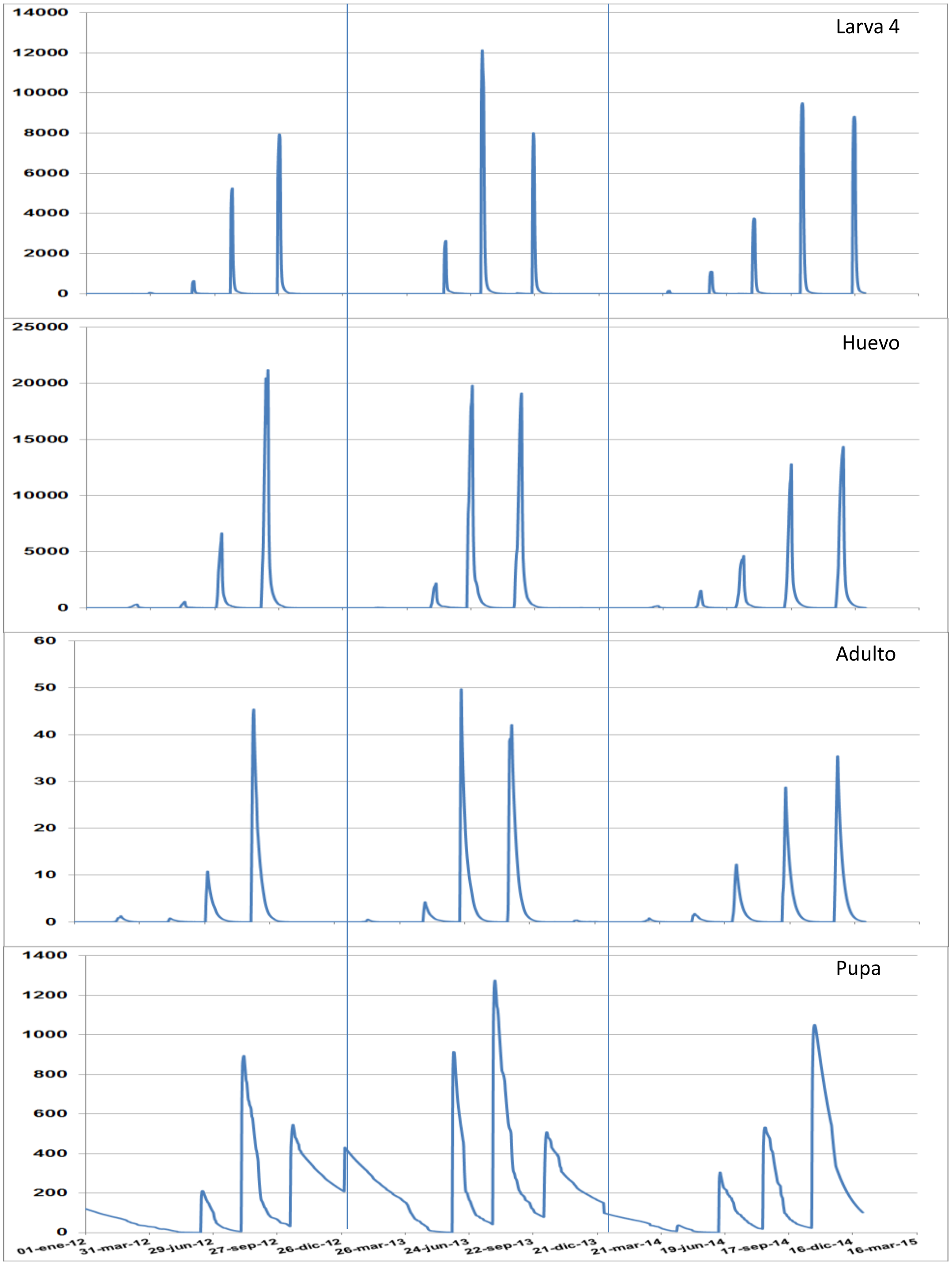

Figure 7. Population dynamics (number of individuals) simulated of *S. frugiperda* in the period 2012-2014 in Celaya, Guanajuato.

The simulation model was run with 150 initial pupae from which the population dynamics that represents the behavior of the different stages of the fall armyworm during the three years of its analysis was generated. Given the favorable temperature conditions at the end of 2012, the individuals in the pupa stage maintained a high population level in the winter, which favored that in 2013 the insect population increased since May. This coincides with the reports of severe damage caused by this pest in corn and sorghum crops in those months.

Coinciding with (Andrews, 1988; Willink *et al*., 1993; Artigas, 1994; Virla *et al*., 1999; Clavijo and Pérez-Greiner, 2000; Pogue, 2002), which mention the losses caused by *S. frugiperda* are due to its power of adaptation to different conditions which has allowed its geographical distribution to be broad and lasting.

At the end of 2013, temperature conditions determined that the population of pupae decreased considerably with respect to the previous winter. This condition determined that in 2014 again high levels of population will move towards the months of September and October. If there are no extreme cold conditions in the remaining months of this year, a high pupal population could be expected, which would determine high early populations of this insect in 2015. In tropical and subtropical regions damage is regularly greater than 60% (Andrews, 1988; Willink *et al*., 1993).

Conclusions

From the previous results it can be concluded that the ecological models are an analytical tool useful to understand the interannual variations in the behavior of the plague organisms, since this type of models allow to include the variables that influence mainly the development of the plague organisms.

The capacities of this type of models can be enhanced by proposing hypotheses about those components of the life cycle of the insect that are difficult to measure or verify. In the case of *S. frugiperda*, this study supports the hypothesis that the initial population of the insect in each cycle will probably be composed of an amount (x) of pupae that slowly complete their development in the soil, in addition to an amount (y) of adults in the preoviposition phase who come from other regions. This composite population will start its breeding cycle as soon as the appropriate conditions of temperature and host availability exist. The population levels of these stages at the end of each cycle will determine the growth potential of the fall armyworm populations in the subsequent cycle.

In all cases, the predictive capacity of the studies based on the simulation models will be increased by extending the observation-simulation period so that the conditions that determine high populations and probably severe damages in the early stages of the crops are analyzed not only in the current cycle, but through several cycles. On the other hand, the estimates obtained through the simulation are an excellent reference to decide which stages to verify by means of the physical monitoring and at what moment to do it to alert opportunely about significant increases in the population of the pest.

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