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A Simple and Rapid Algorithm for Predicting Froghopper (*Aeneolamia* spp.) Population Increase in Sugarcane Fields based on Temperature and Relative Humidity

Un algoritmo simple y rápido para predecir el aumento de la población de mosca pinta en los campos de caña de azúcar, en términos de temperatura y humedad relativa.condiciones de Laboratorio

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Abstract

In Integrated Pest Management practices, knowledge from multiple disciplines is incorporated to facilitate the understanding of a problem and the development a practical, feasible, and ecologically sustainable solution. A froghopper (*Aeneolamia* spp.) plague can trigger major economic losses in sugarcane plantations in countries such as El Salvador and others in Latin America. Losses are often due to a lack of understanding of the life cycle of a pest and the underestimation of its annual reproductive potential. An algorithm was developed to model the most relevant aspects of froghopper reproduction and its interactions with the environment, to facilitate the prediction of potential increases in adult populations and its propagation in fields. Data on several biological variables were collected as numerical measures and used to perform calculations based on a mathematical model designed particularly to simulate the reproduction of the pest, its economic threshold, and potential losses due to major natural events, with the aim of developing a tool that could support decision-making. The predictions of the tool were consistent with the findings of other studies in the field. The software and its installation instructions can be downloaded for free from *https://drive.google.com/file/d/1oUWTTbilWMhoFuTH4wCKtuzjFwDd89/view*

Key words: Pest management, applied software, population prediction, entomology

Resumen

En las prácticas de Manejo Integrado de Plagas, el conocimiento de múltiples disciplinas coopera para ayudar a entender el problema y, por lo tanto, para deducir una solución práctica, viable y ecológicamente sostenible. La plaga de la mosca pinta (*Aeneolamia* spp.) es capaz de producir importantes pérdidas económicas en los cultivos de caña de azúcar en países como El Salvador y el resto de América Latina. Las causas a menudo se deben a la falta de conocimiento sobre el ciclo de vida de la plaga y la subestimación de su potencial reproductivo de un año a otro. Por este motivo, se desarrolló un algoritmo para modelar los aspectos más relevantes sobre la reproducción de mosca pinta y su interacción con el entorno, a fin de predecir el posible aumento de la población adulta y su propagación en un área de campo. Los datos de varias variables biológicas se almacenaron como medidas numéricas y sirvieron para realizar cálculos en base a un modelo matemático especialmente diseñado para simular la reproducción de la plaga, su umbral económico y posibles pérdidas debido a importantes causas naturales, para constituir una herramienta de software que puede respaldar la toma de decisiones cuyos resultados concuerdan con las medidas encontradas en la literatura. El software y sus instrucciones de instalación se pueden descargar libremente desde *https://drive.google.com/file/d/1oUWTTbilWMhoFuTH4wCKtuzjFwDd89/view*

***Palabras clave**: Manejo de plagas, software aplicado, predicción poblacional, entomología.*

Introduction

Froghopper (*Aeneolamia spp.*) is an insect in the family *Cercopidae*. It is a homopterous insect that affects the production of sugarcane and other grasses in tropical and subtropical countries. Its life cycle involves several stages including egg, nymph, and adult (Peck, Pérez, & Medina, 2002; Valbuena, 2006; Cruz-Zapata *et al*., 2016).

The oviposition of the insect is performed in the vicinity of the host-plant roots, up to depths of 2 cm; while other species may perform oviposition on plant sections at lower depths (Peck *et al*., 2002; Cruz-Zapata *et al*., 2016). *Aeneolamia spp.* commonly produces diapausal eggs, a characteristic that facilitates their persistence under

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adverse conditions until conditions improve so that they can resume development and hatch (Peck *et al*., 2002). The capacity of *Aeneolamia spp*. to produce diapausal eggs makes the plague particularly challenging to control. When environmental conditions are suitable, the eggs hatch within 12 to 18 days of oviposition (Thompson & León, 2005); however, it has been reported that they can maintain the diapausal state for several months to hatch under suitable conditions. Female individuals often lay between 20 and 50 eggs per posture (Peck *et al*., 2002) and between 50 and 100 eggs per posture under optimum conditions (Thompson & León, 2005). Diapause of the egg stage is important because more than 98% of the eggs are laid in the upper 2-cm soil layer during the dry season (Fewkes, 1963), and only hatch when environmental conditions are more favorable. Up to 85% of the eggs wait for the rainy season of the following year to hatch, 48 hours after the first heavy rainfall and adults emerge after 27 to 34 days (King, 1975). Morales (1993) observed three distinct types of diapause under field and laboratory conditions, including a “short” diapause, with hatching a month after oviposition, a “moderate” diapause, with hatching three months after oviposition, and a “long” diapause, with hatching after six months. In the same study, Morales (1993) observed that different generations of *Aeneolamia varia* overlapped resulting in periods where plagues displayed population peaks, an observation that was also made by Valbuena (2006).

Following emergence from eggs, the nymphs undergo five different stages where they parasitize and feed on root systems initially to when they emerge on the soil surface later in the last two larval stages, producing foamy secretions that facilitate tolerance against adverse environmental conditions and offer protection against predators until the sclerotization of their exoskeleton is complete and adult life begins (López-Collado, Pérez-Aguilar, & Villanueva-Jiménez, 2012; Cruz-Zapata *et al*., 2016; Peck *et al*., 2002). The nymph cycle is complete within 25 to 35 days, going through the five instars. In their adult stages, *Aeneolamia spp*. display yellow and red stripes on a black background, exhibiting limited flying capacity, although the can jump during feeding. They suck sap directly from the plant and introduce enzymes and divers compounds that damage and kill plant tissue (Thompson & León, 2005; López-Collardo *et al*., 2012). In addition, adults have a five–eight day lifespan (Peck *et al*., 2002).

Aeneolamia spp. have a sucking mouth and feed by sucking sap directly from plant, through which they are also able to introduce diverse toxic compounds and enzymes into the foliar tissues that cause yellow and white spots and the leaves gradually dry out. When the populations of insects increase, the damages observed on foliar systems are considerable, which in turn impairs the photosynthetic capacity of the foliar systems greatly, resulting in a substantial decrease in the contents of sugars in plants such as sugarcane at the time of harvesting (Thompson & León, 2005; López-Collardo *et al*., 2012; Cruz-Zapata *et al*., 2016). Severe infestations in sugarcane plantations could decrease production in terms of both raw tonnage and sucrose yield. Mendoza (2001) and Mendoca (2001) reported sucrose losses of 34% in Ecuador and losses of 60% in Brazil, respectively. According to Fewkes (1969), pest levels lower than 0.5 adults per plant do not cause significant damage within a maximum of two weeks; however, with an increase population level or time, yield could decline by 20%, which is equivalent to 0.8 tons of sugarcane per hectare. A key factor to consider is that humidity and temperature levels influence the severity of the effects of the pest on sugarcane plant. In addition, temperature and humidity influence sugarcane growth and development. Guagliumi (1972) reported that severe infestation of young sugarcane plantations could lead to losses equivalent to a 40% decrease in sugarcane tonnage per hectare, which is a major negative setback for farmers since their profits reduce considerably.

Cultural control refers to all the strategies aimed at providing plants with optimum conditions for development and enhancing resistance to infestation by pests, in addition to the creation of conditions unfavorable conditions for the proliferation of insects (Sotelo & Cardona, 2002). For field sampling activities, Gómez (2007) proposed the placing of two sticky yellow traps per hectare, which has to be complemented with the inspection and counting of nymphs and adults per unit land area. Similarly, the author recommended the use of 25 traps per hectare to reduce *Aeneolamia spp*. populations. Field preparation activities could decrease the incidence of the pests since they expose the eggs to harsh environmental conditions, in addition to natural predators and enemies. Soil tillage has been demonstrated to reduce pest populations significantly compared to the case in uncultivated soils (Guitiérrez & Gómez, 2009). Considering its high economic costs, soil tillage should be considered under severe cases (Rueda-Ramírez, Torrado-León & Becerra, 2013). Constant monitoring of crops is required to facilitate the timely detection of the pests. In addition, the conditions and microclimates within crop systems should be monitored since they could favor the growth and development of the pests (Gómez, 2007). Finally, Gómez (2007) recommended the management of host weeds, particularly grasses, since they provide excellent host on which *Aeneolamia spp*. complete their life cycles.

Natural enemies such as *Salpingogaster nigri* have been applied as alternative biological control methods (Guitiérrez & Gómez, 2009) since two or three generations of *Aeneolamia* spp. insects may overlap during a life cycle, a biological control method would be appropriate. Although *Salpingogaster nigri* exhibit high reproduction rates in the field, Granobles *et al.* (2012) observed that large-scale production of the parasitic fly under laboratory conditions was a major challenge. Regarding the use of entomopathogenic fungi as biological pesticides, the application of *Metarhizium anisopliae* is a good alternative for the control of *Aeneolamia* spp. nymphs and adults. The adhesion of the entomopathogenic fungus to the exoskeletons of the insects lead heir degradation by the action of various enzymes and chemical compounds, facilitating penetration into the insects, where the fungi multiply and colonize the internal organs and utilize them as sources of nutrition during growth and development. Following the death of the insects, and if the environmental conditions including humidity and temperature are favorable, the fungi emerge from the insects and release conidia, which infect other individuals (Somoza-Vargas *et al.*, 2018). Matabanchoy, Bustillo, Castro, Mesa, & Moreno (2012) tested the efficiency of *M. anisopliae* as a biological control method and obtaining promising results. The fungus can be propagated relatively easily under laboratory conditions, where it is placed in aqueous solution and sprayed on the plants to be treated. Favorable environmental conditions such as high temperature and high relative humidity are required for its proper development and efficiency in the control of *Aeneolamia* spp. (Sotelo, 1984). Other natural enemies that could be used in the biological control of *Aeneolamia* spp. are nematodes in the *Heterorhabditis* and *Steinernema* genera (Sendoya, *et al*., 2012). Moreno, Bustillo, López, Castro, & Ramírez (2012) reported that the use of *Heterorhabditis bacteriophora* could result in mortality rates of up to 48% for *Aeneolamia* spp. nymphs in sugar cane. Chemical control of *Aeneolamia* spp. is recommended when their populations exceed the economic threshold to minimize production costs and economic losses, and after considering the potential effectiveness of cultural and biological control methods (Gómez, 2007; Guitiérrez & Gómez, 2009). The persistent application of chemical pesticides can lead to resistance against the active ingredients in subsequent pest generations, which, in turn, would prompt a farmer to increase doses or mix different agrochemicals, which could also have adverse impacts on beneficial insect species (Sotelo & Cardona, 2002). Imidacloprid, endosulfan, and pyrethroids have been applied extensively due to their rapid and effective insecticidal effects.

Population dynamics can be defined as the changes exhibited by biological communities in addition to the various mechanisms that influence and regulate such changes and mechanisms (Vargas & Rodríguez, 2008), in addition to how such factors interact. Population dynamics are influenced by three types of distribution, including uniform (individuals are dispersed with similar distances among them, so that intraspecific relationships may not seem ideal), random (in the case of species that do not seek coexistence in groups), and aggregated (individuals seek to exist in different large groups that are separated and most agricultural pests display such distribution since it maximizes multiplication and survival rates of groups) (Vargas & Rodríguez, 2008). Among the external factors that influence population dynamics, temperature is one of the most influential factors influencing key aspects of insect development, including larvae, average life span of adults and female oviposition capacity. To determine how influenced the insect development can be by the environment conditions, Degrees Days and Growing Degree Days (GDD) are the most common measures used to evaluate how environmental conditions influence insect development. The measures, which are based on temperature, facilitate the prediction pest activity based on environmental conditions, and could facilitate early planning for effective control measures (Adams, 2014; Vargas & Rodríguez, 2008). Other environmental variables that influence the population dynamics of *Aeneolamia* spp. are relative humidity and photoperiod.

Due to the need for increased food production to sustain growing populations, modern agricultural activities have led to irreversible damage in ecosystems. The application of insecticides for crop protection is widespread among farmers because of its low cost and high level of effectiveness in the short-term. In the case of the control of froghopper in sugarcane plantations in El Salvador, unanticipated challenges have emerged due to the intensive application of insecticides such as pyrethroids, endosulfan, and Counter®, which have polluted shallow waters, deteriorated ecosystems, and decreased the populations of natural controlling agents, in addition to enhancing the resistance of pests to pesticides overall and ushering in other complications associated with a poor understanding of key biological and ecological aspects of the pest, including its reproductive capacity and its natural enemies (Gómez, 2007; Cruz-Zapata *et al*., 2016). In integrated pest management control, the single action of spraying agrochemicals should not be considered adequate to prevent losses. Indeed, chemical control should be the last strategy after attempting cultural and biological control methods (Gómez, 2007).

To facilitate the addressing of the challenge of *Aeneolamia spp*. in sugarcane production, the present paper describe the development and testing of a simple software tool that has been demonstrated to predict increases in froghopper populations that could infest a sugarcane plantation under field conditions accurately based on the two most critical environment variables including temperature and relative humidity. The development of the tool required an extensive literature review on the biology of *Aeneolamia spp.*, particularly their life cycle and diapause capacity (Morales, 1993). The information was combined with agronomic knowledge on sugarcane cultivation, in addition to biological insights and observations following the treatment of *Aeneolamia spp*. with numerous natural enemies (Sendoya *et al.,* 2012; Moreno *et al.,* 2012; Matabanchoy *et al*., 2012). The studies above were carried out to present simulation of froghopper reproduction and decline due to environmental and biological factors that influence their infestation capacity. A project of this nature could facilitate the understanding of the challenge and decision-making processes for its effective management, while integrating knowledge from diverse disciplines such as biology, agronomy, and bioinformatics. The algorithm was executed in a front-end desktop application compatible with the most common operative systems available to computer users, using a programming language.

Methodology

1) Design of the algorithm

The first step in the design of the simulating algorithm was understanding the life cycle of the pest and obtaining scientific data for developing a data model stored in arrays categorized for based on periods such as months and quarters in a year. The environmental and pest variables that were considered for the algorithm included monthly average temperature in the site where the sugarcane is planted (expressed in Celsius), monthly average relative humidity, the threshold temperature at which plant and pest biological activity is halted, the theoretical rate of population increase observed after every generation, the proportion of the insect population that is female, the number of eggs laid per female, the proportion of eggs that would be damaged at a given relative humidity range, and diapause levels in froghopper species can have three potential outcomes: (1) instant hatching, (2) short diapause where eggs hatch two months after oviposition and (3) long diapause with hatching after six months. Other key variables were obtained from literature and are appropriate methods for evaluating populations based on temperature, for example, the number of nymphs and adults present per square meter per each GDD, above the threshold temperature. All the input variables integrated into the algorithm are listed in the second frame of Figure 1. Two sets of values per variable are embedded within the

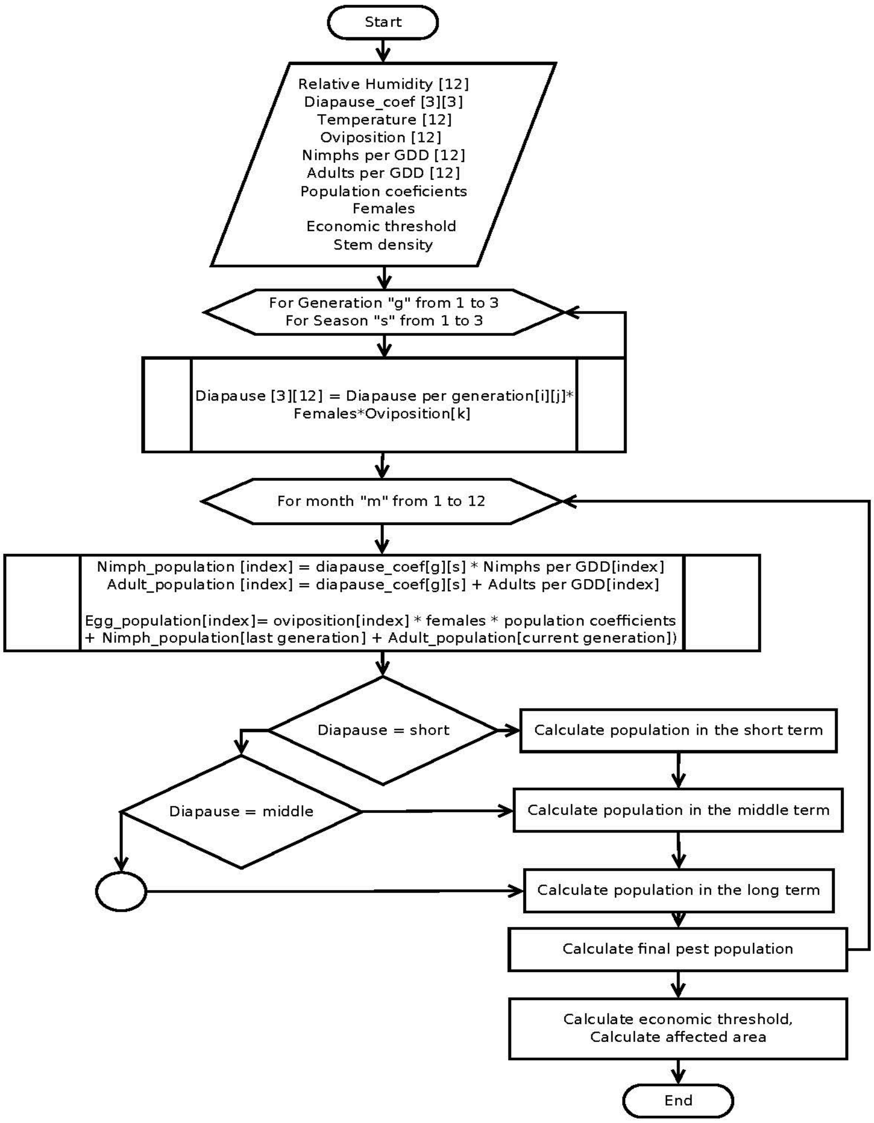


Figure 1: Simplified flowchart of the algorithm, with emphasis on the input data required for the numeric simulation. The clause [3] refers to each iteration for the three known diapauses, and [12] is the number of monthly iterations and data used for calculations; the arrays modeling diapause are bi-dimensional because three ratios of diapause are present for different periods throughout the year.

source code and can be loaded by a user to simulate low or high population conditions. In every instance, a user could modify the values using data based on assumptions or applied research. The flowchart in Figure 1 represents a tool required for software development, which in the present case was used to define the data requirements of the code routines that estimated the pest populations.

2) Growing Degree Days equation

The *GDD* was considered a key factor influencing pest reproduction, and indices for high and low populations or nymphs and adults were formulated to simulate the presence of individuals in sugarcane plantations based on temperature and area per unit square meter. The data were based on Wiedijk (1982) and Olán-Hernández, Sánchez-Soto, Bautista-Martínez, Zaldívar-Cruz, & Cortez-Madrigal (2016). Therefore, the potential presence of the insects was calculated by multiplying the indices obtained from literature by the GDD, as presented in equations 1 and 2. All the GDD calculations were performed with a base temperature of 15°C; however, in the front-end interface of the software, the variable could be modified freely by a user based on their requirements. In addition, the egg diapause rates were based on the results reported by Morales (1993), and the amounts of fertile eggs oviposited by the female individuals were based on Chaves *et al.* (2014). Equation number 3 was formulated to model the phenomena of diapause. The constant of adult population variation per generation "K_p" is a rate for measuring the increase in adult froghoppers after each generation based on data from Valbuena (2006), while offering a user the possibility to alter the value.

$$A_{GDD} = I_{Ad} GDD \tag{1}$$

$$N_{GDD} = I_{N} GDD \tag{2}$$

Where,

A_{GDD} :Adult population at field conditions based on given *GDD*.

N_{GDD} :Nymph population at field conditions based on given *GDD*.

GDD :Growing Degree Days, using Celsius scale to measure temperature units.

I_{Ad} :Rate of increase in adult population per *GDD*.

I_{N} :Rate of increase in nymph population per *GDD*.

$$D_m = \frac{K_m P_{fem} E_{fem}}{K_p} \tag{3}$$

Where,

D_m :Diapause rate for a given month, which is the amount of eggs that may hatch immediately at a particular moment based on some population parameters.

K_m :The theoretical proportion of eggs that hatch per month.

P_{fem} :Proportion of the adult population that are reproductive females.

E_{fem} :The amount of viable eggs laid per female.

K_p :Constant of adult population variation per generation

3)Diapause consideration and equations

The three types of diapause identified for the pest, implied that there was a need to model three equations to predict population in the short, medium, and long term, for one (equation 4), three (equation 5), and six (equation 6) months, respectively. This would allow the determination of the extent of overlap across the different generations. However, since external factors such as relative humidity and natural enemies could influence the increase in populations of froghopper species, the factors were modeled into each equation as the percentage of the population that would survive at any given conditions. The percentage of the population surviving under different levels of relative humidity could be entered manually by the user in the front-end interface of the software; however, sample data and routine tests were based on information presented by Suiji, Alice, Fontes, Pires, & O'neil (2002) and Wiedijk (1982). Reduction in pest populations due to biological control were incorporated into the equations for the fungus *Metarhizium anisopliae* and the nematode *Heterorhabditis bacteriophor*, and both integrated into a single factor for biological control that represented the proportion of the froghopper population capable of surviving such an exposure.

$$P_{1m} = (N_{GDD} + A'_{GDD} D_s K_p) F_{RH} F_{bio} \tag{4}$$

$$P_{3m} = (N_{GDD} + A'_{GDD} D_s K_p + A''_{GDD} D_m K_p) F_{RH} F_{bio} \tag{5}$$

$$P_{6m} = (N_{GDD} + A'_{GDD} D_s K_p + A''_{GDD} D_m K_p + A'''_{GDD} D_l K_p) F_{RH} F_{bio} \tag{6}$$

Where,

P_{1m} :Predicted population within one month.

P_{3m} :Predicted population within three months.

P_{6m} :Predicted population within six months.

N_{GDD} :Nymph population in based on given *GDD*.

A'_{GDD} :Adult population of the past month in based on given *GDD*.

A''_{GDD} :Adult population of the past three months based on given *GDD*.

A'''_{GDD} :Adult population of the past six months based on given *GDD*.

D_s :Short diapause of eggs that would hatch soon after being laid.

D_m :Middle diapause of eggs that would hatch approximately two months after being laid.

D_l :Long diapause of eggs that would hatch in approximately five months after being laid.

F_{RH} :Fraction of the population that would survive due to relative humidity (*RH*).

F_{bio} :Fraction of the population that would survive due to biological control.

K_p :Constant of adult population variation per generation.

Considering a future estimate of froghopper population within a year is essential for taking appropriate preventive action, equation 7 was developed for making predictions based on eggs laid and their respective diapause levels that are consistent with diapause indices as demonstrated in equation 3. Future populations within six, three, and one month were estimated, considering all the potential generational overlaps within each period. For the long term diapause, only one generation was considered; however, for the middle-term diapause, it was assumed that one generation could persist for two months while another could persist for a month, so that in equation 7, it was necessary to integrate two diapause indices and two generational constants in equation 7. For the population with a short-term diapause, two generations of one month, one generation spanning two months, and one generation spanning six months were considered, since it was assumed that the most critical part of the population could be observed one year in the future, which is why all the diapause indices and the four generational constants were multiplied. Equation 8 is a factorized form of the previous formula. Once the future froghopper population was obtained suing the algorithm and stored as the $P_{12\,m}$ array, it was calculated the intercrossed addition to population between future months, as presented in equation 9.

$$P_{12m} = \left(P_{6m} D_l K_p + P_{3m} D_s D_m K_p^2 + P_{1m} D_s^2 D_m D_l K_p^4\right) K_p F_{RH} \qquad (7)$$

$$P_{12m} = \left(P_{6m} D_l + \left(P_{3m} + P_{1m} D_s D_l K_p^2\right) D_s D_m K_p\right) K_p F_{RH} \qquad (8)$$

$$P_{i12m} = P_{12m} + \left(P_{11m} D_s + P_{9m} D_m + P_{6m} D_l\right) K_p F_{RH} \qquad (9)$$

Where,

P_{12m} :Predicted population within 12 months..

P_{11m} :Predicted population within 11 months based on short diapause individuals.

:

P_{9m} :Predicted population within 9 months based on middle diapause individual.

P_{6m} :Predicted population within 6 months based on long diapause individuals.

P_{i12m} :Predicted population within 12 months, including new generations that would be produced in the following year.

N_{1m} :The value of calculated P_{12m} corresponding to one month in the past.

N_{3m} :The value of calculated P_{12m} corresponding to three months in the past.

N_{6m} :The value of calculated P_{12m} corresponding to six months in the past.

4) Biocontrol estimates

The impact over of the fungus *Metarhizium anisopliae* on the froghopper population was based on data published by Matabanchoy, Bustillo, Castro, Mesa & Moreno (2012). The results of the study were tabulated and a regression equation (10) obtained to determine the effects of the treatment based on the amount of conidia applied in a field. A similar procedure was applied with the data of Salguero et al (2012) with regard to treatments with the nematode *Heterorhabditis bacteriophor*; however, in the case of the nematode, two different trends for froghopper control were examined under low dosage (equation 11) and under high dosage (12).

$$S_m = 26.61 + 18.88 \ln(con) \qquad (10)$$

$$S_{(l-n)} = 4.9e^{0.15i} \qquad (11)$$

$$S_{(h-n)} = 39.01 \ln(i) + 10.4 \qquad (12)$$

Where,

S_m :Proportion of the population surviving following *Metarhizium* application..

$S_{(t-n)}$:Proportion of population surviving when the nematode *H. Bacteriophora* is applied at relatively low doses..

$S_{(h-n)}$:Proportion of population surviving when the nematode *H. Bacteriophora* is applied at relatively high doses..

con :Conidia per hectare, in the order of magnitude of 10^{12}.

i :Infective juveniles (individuals) per hectare, in the order of magnitude of 10^{10}..

Since the algorithm was intended to be rapid and simple, it was based only on the major environmental variables and froghopper population dynamics parameters, assuming that other circumstances had limited influence on population prediction. Some assumptions were required to simplify the data processing and the amount and complexity of input variables to be entered by the user. Some of the considerations included instead of considering the direct effects of harvest, the algorithm was based on indices that described the rate of nymphs and adults per *GDD* in each month. Another consideration was that environmental variables such as average temperature and RH remained constant throughout the months from the hypothetical year prior to the running of the simulation run and the following predicted year. Other parameters associated with insect biology were also considered constant, such as the monthly oviposition rate, the proportion of females within the population, the responses of individuals to incidental heavy rains, among others.

Results and Discussion

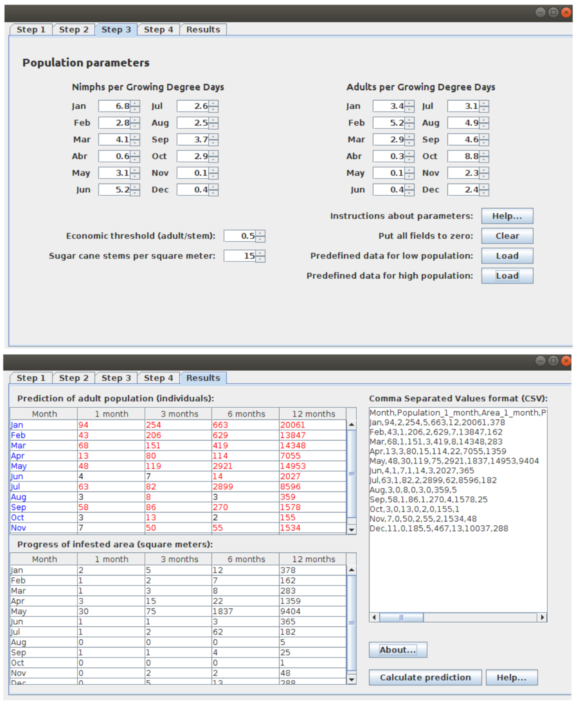
Using the temperature and the humidity levels presented in a report on the environmental profiles of the coastal zone of El Salvador (Table 1), a prediction sequence was run in the software, using a high population density based on relatively high indices of nymph and adult existence per GDD (Figure 2, upper part) without any control to produce a numeric simulation (Figure 2, lower part), which illustrated the trends in the reproduction of the pest without any corrective strategies.

Table 1. Monthly average temperatures and relative humidity in the coastal zone of El Salvador.

Month	Average Temperature °C	Average Relative humidity %
January	30.6	68
February	31.4	75
March	32.5	78
April	32.3	80
May	30.9	83
Jun	28.9	86
July	30.2	68
August	29.8	88
September	28.7	84
October	28.8	86
November	28.8	72
December	29.5	69

Source: National Service of Territorial Studies of El Salvador (SNET), http://www.snet.gob.sv/meteorologia/Perfiles.pdf

The results (Figure 3A) are consistent with those of Olán-Hernández *et al*., (2016), which identified population peaks of *Aeneolamia contigua* (Walker) adults in the months preceding months with higher records of RH and precipitation, in addition to being consistent with the effects of the three types of diapause defined by Morales (1993) and the influence of temperature on mortality as described by Suiji *et al*. (2002). In a second run, a biological control



Population parameters

Nimphs per Growing Degree Days

Jan	6.8	Jul	2.6
Feb	2.8	Aug	2.5
Mar	4.1	Sep	3.7
Abr	0.6	Oct	2.9
May	3.1	Nov	0.1
Jun	5.2	Dec	0.4

Adults per Growing Degree Days

Jan	3.4	Jul	3.1
Feb	5.2	Aug	4.9
Mar	2.9	Sep	4.6
Abr	0.3	Oct	8.8
May	0.1	Nov	2.3
Jun	0.4	Dec	2.4

Economic threshold (adult/stem): 0.5
Sugar cane stems per square meter: 15

Prediction of adult population (individuals):

Month	1 month	3 months	6 months	12 months
Jan	94	254	663	20061
Feb	43	206	629	13847
Mar	68	151	419	14348
Apr	13	80	114	7055
May	48	119	2921	14953
Jun	4	7	14	2027
Jul	63	82	2899	8596
Aug	3	8	3	359
Sep	58	86	270	1578
Oct	3	13	2	155
Nov	7	50	55	1534

Progress of infested area (square meters):

Month	1 month	3 months	6 months	12 months
Jan	2	5	12	378
Feb	1	2	7	162
Mar	1	3	8	283
Apr	3	15	22	1359
May	30	75	1837	9404
Jun	1	1	3	365
Jul	1	2	62	182
Aug	0	0	0	5
Sep	1	1	4	25
Oct	0	0	0	1
Nov	0	2	2	48
Dec	0	5	13	288

Comma Separated Values format (CSV):

```
Month,Population_1_month,Area_1_month,P
Jan,94,2,254,5,663,12,20061,378
Feb,43,1,206,2,629,7,13847,162
Mar,68,1,151,3,419,8,14348,283
Apr,13,3,80,15,114,22,7055,1359
May,48,30,119,75,2921,1837,14953,9404
Jun,4,1,7,1,14,3,2027,365
Jul,63,1,82,2,2899,62,8596,182
Aug,3,0,8,0,3,0,359,5
Sep,58,1,86,1,270,4,1578,25
Oct,3,0,13,0,2,0,155,1
Nov,7,0,50,2,55,2,1534,48
Dec,11,0,185,5,467,13,10037,288
```

Figure 2. Upper part: Froghopper population calculation software, this image illustrates the user interface where population rates of nymphs and adults per GDD can be input. Lower section. Froghopper calc software, this image exhibits the user interface where output of the simulation is presented.

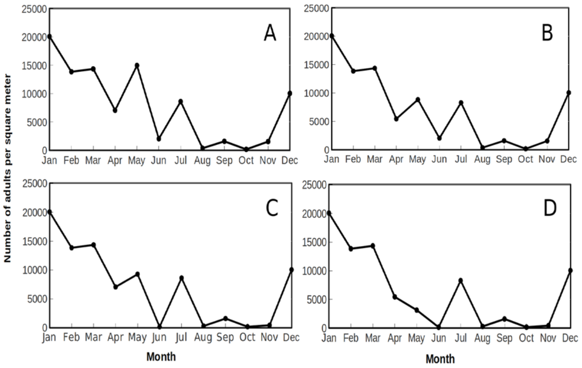


Figure 3. A) Line graph illustrating the population dynamics predicted by the software for one year in the future without any control strategy applied for the pest. B) Line graph illustrating the population dynamics predicted by the software for a year in the future taking into account the application of 5×10^{13} conidia.ha^{-1} of *M. anisopliae* in April. A decrease in the population can be observed in the following month. C) Line graph illustrating the population dynamics predicted by the software for one year in the future taking into account the application of 15×10^{10} IJ.ha^{-1} of *H. bacteriophora* D) Line graph illustrating the population dynamics of *Aeneolamia* spp. in sugarcane following the application of a first biological control of 5×10^{13} conidia.ha^{-1} of *M. anisopliae* strategy in April followed by the application of a biological control strategy using 15×10^{10} IJ.ha^{-1} of *H. bacteriophora* in May.

of 5 × 10^{13} conidia/ha of *M. anisopliae* was applied in April, and a reducing effect of the population in the month following the application was observed (Figure 3B), directly affecting the nymphs with a short diapause and reducing the rate of population increase in May.

These results are consistent with those presented by Matabanchoy *et al*. (2012), who reported mortality ranging from 62.5 to 71.4% with a similar concentration of *M. anisopliae* conidia following application to control *Aeneolamia varia* in sugarcane. However, in the software prediction, although only two applications of the treatment were considered, it is safe to say that an increase in the number of applications increase the effectiveness of the biological control method. A third run with a biological control of 15 × 10^{10} IJ.ha^{-1} of *H. bacteriophora* (Moreno *et al.*, 2012), with May as the time of the application, was predicted. Although the results predicted an almost complete decrease of the adults in June based on the estimate of a single control event, generational overlap allowed the pest to be present normally again from the month of July and in the following months (Figure 3C). In a last simulation, the two previously defined biological control strategies were applied simultaneously (Figure 3D). The combined effects of the fungus and the nematodes caused the disappearance of the population peak in and a minimum value for the adult population reached was observed in June. The results of the study reinforced the need to adopt integrated pest management systems to maximize the effectiveness of each strategy. Notably, the software predicted the expected results of control strategies against the pest accurately, which could facilitate the minimization of the negative economic impacts associated with the pest. Similarly, it is critical to note that it is possible to reduce the incidence of the pest in the month of June, when dam levels of up to 86% are reported, which offer ideal conditions for the recovery of the insect populations. The spatial distribution of adults (Figure 4) was consistent with an aggregation pattern based on the oviposition sites, as observed by Figueredo, Andrade, Niño, Quintero, & Azad (2011). They observed that the infestation began from aggregation centers, and spread across entire plantations.

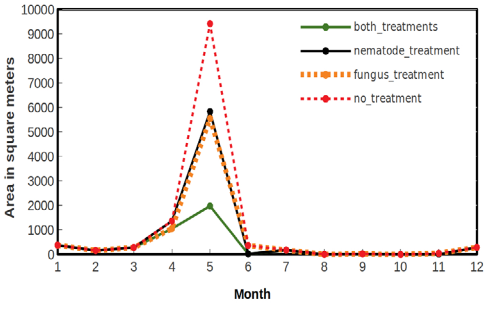


Figure 4. Graphic representation of the increase of the area of infestation one year in the future.

The sofwtare accurately predicted such a trend, with 30 m^2 infested in May without the application of any control strategies. In a year, the plague would have reproduced adequately to infest 9404 m^2. However, such values may change in the field due to the ever-changing conditions that could influence pest growth and development.

Conclusion

The software was developed based on an elaborate mathematical model that predicted the trends of a pest in a crop of interest. Using global and regional data, it is possible to identify the appropriate periods for implementing corrective actions using biological control strategies reduce the need for the application of agrochemicals. Adopting biological control strategies could minimize the potential negative environmental and health impacts of such agrochemicals. RH and temperature are the most influential environmental factors influencing the development of *Aeneolamia spp*., and they can be used to simulate potential increases in pest populations, with results similar to those reported by other studies based on open-field experiments. Tools such as the one presented in the present paper facilitate the formulation of action plans to mitigate the effects of pests on crops using alternatives that are more environmentally friendly.

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