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# Eco Control of Agro Pests using Imaging, Modelling & Natural Predators

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## Abstract

Caterpillars in their various forms: size, shape, and colour cause significant harm to crops and humans. This paper offers a solution for the detection and control of caterpillars through the use of a sustainable pest control system that does not require the application of chemical pesticides, which damage human health and destroy the naturally beneficial insects within the environment. The proposed system is capable of controlling 80% of the population of caterpillars in less than 65 days by deploying a controlled number of larval parasitoid wasps (*Cotesia Flavipes*, *Cameron*) into the crop environment. This is made possible by using a continuous time model of the interaction between the caterpillar and the *Cotesia Flavipes* (*Cameron*) wasps using a set of simultaneous, non-linear, ordinary differential equations incorporating natural death rates based on the Weibull probability distribution function. A negative binomial distribution is used to model the efficiency and the probability that the wasp will find and parasitize a host larva. The caterpillar is presented in all its life-cycle stages of: egg, larva, pupa and adult and the *Cotesia Flavipes* (*Cameron*) wasp is present as an adult larval parasitoid. Biological control modelling is used to estimate the quantity of the *Cotesia Flavipes* (*Cameron*) wasps that should be introduced into the caterpillar infested environment to suppress its population density to an economically acceptable level within a prescribed number of days.

**Keywords:** caterpillar pest control, system modelling, sustainable biological control, *cotesia flavipes* (*cameron*) wasps

## 1. Introduction

Caterpillars are the larvae of insects which belong to the second largest of all insect orders Lepidoptera. There are thousands of species of caterpillars inhabiting different countries worldwide. They are a serious pest and voracious feeders that can destroy entire food crops within a short time interval. They appear in different shapes, colours, and sizes. Some species are bare skinned, others have sparse or dense fine hair (setae); some have dull colours, others are brightly multi-coloured; some have even and regular bodies, others carry one to many protuberances, bristles, spines, and/or structures resembling horn projections. Many are equipped with the ability to repel predators due to their poisonous glands (non – edible); as a result they defend themselves by ejecting acid.

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They are camouflaged or cryptically colored and almost look similar to the plants on which they feed and might have sections that resemble plant parts as illustrated in Figs. 1 and 2. Frazier [1] and Hyche [2] classified caterpillars into stingers and non- stingers according to the nature of the harm they do to crops and humans. Stinging caterpillars are equipped with urticaceous setae or spines, which are hollow and contain toxins secreted from poison-gland cells; these are defensive structures for protection against predators. The stinger caterpillars are so dangerous that contact with either the live or dead spines of some of the species may cause skin irritation and burning sensations; dermatitis and pustules; inflammation and numbness at or around the area of contact; fever and nausea; and intense pains - depending on the degree of contact, the specie of caterpillar and the type of toxin the caterpillar possesses. Non–stinger caterpillars have a frightening look but some may be harmless as shown in Fig. 2.

Caterpillars can cause life threating diseases, Malaque [3] reported the life threatening ailments caused by accidental contact with caterpillars - in some cases burning pains, oedema and erythema. Arocha-Piñango [4] reported Fibrinolysis, blood coagulation disorders or miscarriage from contact with caterpillars. Kelen [5] demonstrated Hemorrhagic syndrome induced by contact with the *genus Lonomia (Saturniidae, Hemileucinae)*. Brady [6] and Burdmann [7] reported severe acute renal failure induced by the venom of *Lonomia* caterpillars. Several studies have revealed that most caterpillars have developed resistance to chemical pesticides, which has resulted in a resurgence of their population and pest outbreaks Chikwenhere [8], Wakamura [9]. Our focus is specifically on the deployment of natural enemies (parasitoid wasp) into areas where heavy pesticide use is common such as vegetable and cereal crops.

To find lasting solutions to the problem of caterpillars, we hypothesize that the timely detection of caterpillar pests reduces its effects on crops and human health. Coming into contact with some species of the caterpillar can be dangerous with victims having to seek medical attention. For farmers to avoid encountering the caterpillar, a detection system capable of detection and eradication of the different species of caterpillar at minimum cost is proposed. All the different species and varieties of caterpillars have the same developmental life cycles stages, though the seasons of development may differ; for the purposes of this work we shall consider the detection and eradication of the larva stage of the moth *Spodoptera Exempta* (army worm), a non-stinger caterpillar. The egg stage is important because the very plant that harbours the eggs is usually the first victim of the hatching caterpillar, as it serves as its food plant. The larva stage is the eating and the rapid growth stage of the moth. At this stage the larva eats voraciously for 24 hours to nourish it body and store up the food that will be used later in its transition to the pupa and to the adult stage.

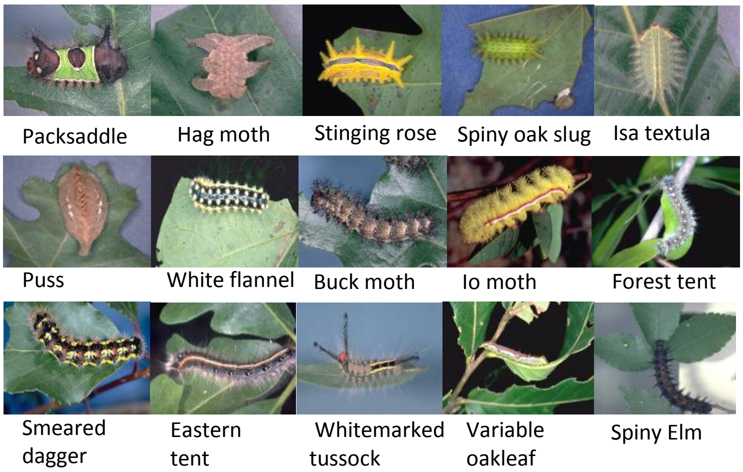



Fig. 1 Stinger caterpillar database


Fig. 2 Non- stinger caterpillar database

Timely detection implies identifying the caterpillar from the eggs to the pupae stage. This will be achieved by the application of the sustainable pest control system. This system can achieve the detection and control of the three pre-adult stages automatically, at low cost, without coming into contact with the caterpillar and without subsequently requiring the application of chemical pesticides. Solving the caterpillar problem will increase the quantity and quality of food production, which would be a great achievement to maintain food security and good health.

For this simulation, a cereal crop farm, and the "*Spodoptera Exempta (Se)*(caterpillar)" pest is considered using a high speed video camera (*Gopro Hero 3*) mounted on a Pest surveillance system as shown in Fig. 3. *Spodoptera Exempta* is chosen as a case study, since it requires early discovery of all three pre-adult stages of its life cycle (Eggs, larva and pupa) monitoring and treatment to prevent spreading, uncontrollable infestation and out breaks as shown in Fig. 4. A video camera is required because of its ability to capture moving images of the insect at up to 12 fps with continuous autofocus for razor sharp tracking of moving objects.

For this simulation, the surveillance system captures the caterpillar images and transmits these via a wireless network to the detection system (Automatic plant pest detection and recognition algorithm) (APDRS) for detection and analysis of the images captured. The detection subsystem processes the images as demonstrated by the pest detection and recognition system of Faithpraise [10] and Kypraios [11] .

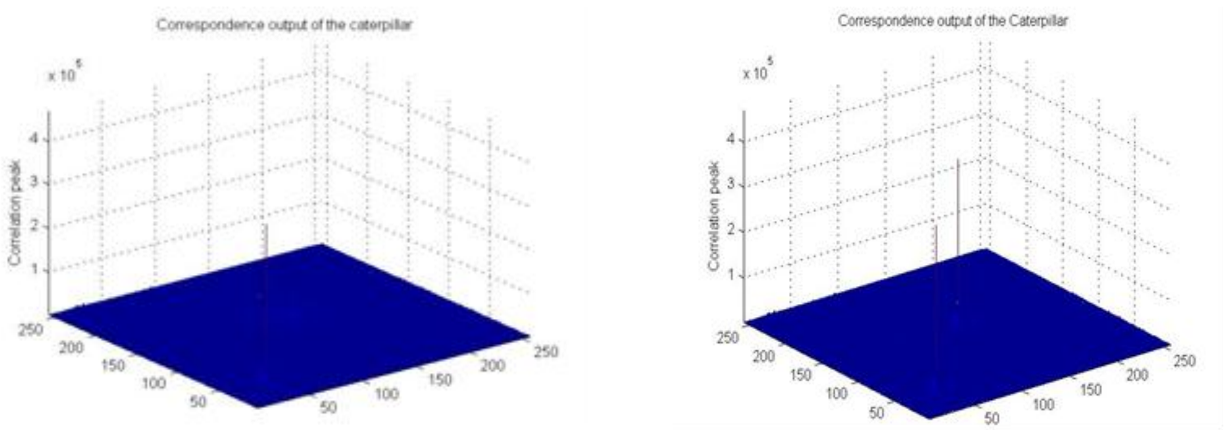
The system transmits the output, as displayed in Fig. 5, to the pest recognition unit to be processed in order to know the exact species of the pest dominating the cereal farm. The recognition algorithm matches the detected pest to the e-database and displays the result as a 3D plot confirming the number of pests present in each crop image by the number of output spikes, as shown in Fig. 6.

From the APDRS system, the sampled field images are forwarded to the biological control model (ECM) designed by Faithpraise [12] to estimate the approximate population density of caterpillars in the field, to enable the deployment of the correct population density of wasps to accurately combat and control the population growth rate of the pest within an estimated period of time. For more information on the pest surveillance system, see Faithpraise [13]


Fig. 3 Pest surveillance system

Fig. 4 Pest Outbreak [7]


Fig. 5 Detected pest images of the different caterpillar species




(a) (b)

Fig. 6 Output of caterpillar image from the correspondence filter

## 2. Eco Control Model (ECM)

The goals of the ECM are to:

(1) Maintain the density of the pest population at an equilibrium threshold below the economic damage level.
(2) Reduce the pest population to a low level but not to completely destroy them as can occur with pesticides.
(3) Publicize the effectiveness of biological control systems and their sustainable control capabilities.
(4) To preserve the existence of the naturally beneficial insects and encourage the increase in their numbers
(5) To encourage the restoration of natural habitats and discourage completely the application of all classes of pesticides
(6) To estimate the right quantities of the naturally beneficial insects to deploy in any pest infested habitat

## 3. Laval Parasitoid wasps

The parasitoid wasps use the host as illustrated by Godfray [14] and Yuan [15] who report that the larval parasitoids deposit and develop their offspring in the body of an insect pest (host). Edson [16] illustrates the injection of venom by parasitoids wasps, which paralysed and modified the host's tissues making the host more nutritious for the developing wasp larva. In most cases the wasp enters the insect's body and reproduces within the insect as illustrated by Grosman [17] on the interaction of braconid parasitoids (*Glyptapanteles sp.*) with the moth caterpillar (*Thyrinteina leucocerae*). The wasps reproduce by laying eggs within the bodies of the caterpillars. The wasps develop and feed on life–supporting tissues in the inside of the caterpillar, it eventually forces it way out from the host to pupate, the wasps metamorphose into adult larval parasitoids and the life cycle repeats. A Pascal (negative binomial distribution) is used to model the efficiency and probability that the wasp will find and parasitize a host larva, this probability distribution is described in [18]

## 4. Materials and Methodology

As an illustration of the concept, we propose a model of the interaction between a population of *Spodoptera Exempta* moths ($N_h$) and its life cycle stages: the egg ($N_e$), larvae ($N_l$) and pupae ($N_p$) with the larval parasitoid ($N_{lw}$) *Cotesia Flavipes* (*Cameron*) as shown in Fig. 7. The *Spodoptera Exempta* moth is considered because of its economic importance and its affinity to vegetables and cereal crops, which often suffer loses of hundreds tonnes of crops due to this pest, Chikwenhere [7].

Cereal crops are: maize, wheat, oats, barley, rye and rice, in addition to legumes, forage grasses, and various vegetable crops. Of the cereal crops maize is chosen because it is economically important with broad recognition across nations. Maize is very susceptible to the attacks by the Se caterpillar.

The *Cotesia Flavipes* (*Cameron*) is a braconidae gregarious larval endoparasitoid wasp, which can lay 40 eggs in the host larva, Kfir [19] and can deposit up to 40 eggs in 3-4 host larvae in a day. It has the ability to parasitize 20 host larvae in its life span, as demonstrated by Potting [20]

Table1. Parasitoid wasp's life span. The table records the number of eggs produced by the larval parasitoid wasp, the incubation periods, the length of time it takes for the wasps to emerge and the wasp's life span in the presence and absence of food. [19], [21], [22] and [23]

| Life span of the Larval parasitoid wasps (*Cotesia Flavipes (Cameron)*) | |
|---|---|
| No of eggs | 35-40 |
| egg incubation period | 2 -3 days |
| Larva - wasp larva emerges from larva | 12-16 days |
| Pupa | 4-8 days |
| Adults emerge | 9-11 days |
| Wasp lifetime in the presence of food | 6-10 days |
| Wasp lifetime in the absence of food | 2-3.2 days |

Table 2. *Spodoptera Exempta* development from egg to adult, [24], [25],[26]and [27]

| Life span of the *Spodotera exempta* (Cameron) | |
|---|---|
| No of eggs per day | 100-300 |
| egg incubation period | 2 -5 days |
| Larva | 14-19 days |
| Pupa | 7-8 days |
| Adults life span | 10-14days |

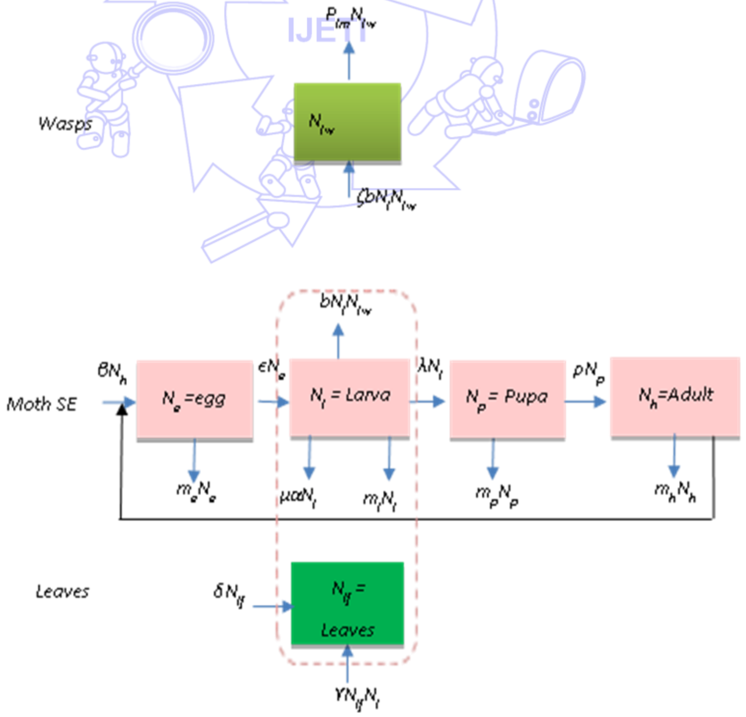



Fig. 7 Population dynamics schematic for wasp-pest-crop interaction model describing the detailed activities of how the wasps exercise control over pest population in its habitat

The following simultaneous, ordinary differential equations are derived from Fig.7, provide a dynamic model of the evolving pest, *Spodotera exempta cameron*, *Cotesia Flavipes* (*Cameron*) and leaf population per square metre

$$\frac{dN_e}{dt} = \beta N_h - \varepsilon N_e - m_e N_e \tag{1}$$

$$\frac{dN_l}{dt} = \varepsilon N_e - \lambda N_l - bN_l N_{lw} - m_l N_l - \mu\alpha N_l \tag{2}$$

$$\frac{dN_{lw}}{dt} = \zeta b N_l N_{lw} - p_{lm} N_{lw} \tag{3}$$

$$\frac{dN_p}{dt} = \lambda N_l - \rho N_p - m_p N_p \tag{4}$$

$$\frac{dN_h}{dt} = \{\rho N_p - m_h N_h\}\left[N_h\left(\frac{K_h - N_h}{K_h}\right)\right] \tag{5}$$

$$\frac{dN_{lf}}{dt} = \delta N_{lf} - \gamma N_{lf} N_l \tag{6}$$

where

$N_h, N_e, N_l, N_p$ = Population density of *Spodotera exempta:* adult, egg, larvae and pupae.

$N_{lw}$ = Population density of parasitoid wasps.

$K_h$ = *Spodotera exempta* carrying capacity of the environment.

$m_h, m_e, m_l, m_p$ =*Spodotera exempta*: adult,egg, larvae and pupae mortality rate, respectively.

$p_{lm}$ = larval parasitoid wasp mortality rate.

$\zeta$ = efficiency of turning prey into parasitoid wasps offspring.

$b$ = probability that a parasitoid finds and parasitizes a larva prey

$\beta$ = Number of eggs per day from each *Spodotera exempta*

$\varepsilon$ = Fraction of eggs hatching into larvae

$\lambda$ = Fraction of larvae changing to pupae

$\rho$ = Fraction of pupae turning into moths

$\alpha$ = Leaf impact factor

$\delta$ = Leaf growth rate

$\gamma$ = Fraction of leaves eaten by a caterpillar per unit time

${}_iN_{lf}$ = Initial population of leaves

$N_{lf}$ = Population of leaves

$\mu = \frac{{}_iN_{lf} - N_{lf}}{{}_iN_{lf}}$ Leaf-larvae coupling coefficient

Eqn. 6 models the leaf population and leaf growth rate, which is determined using the Hoffmann's [28] relative growth rate equations, maize growth rate and development Tóth [29], Nelissen [30] and Hardacre [31].

The proposed model consists of six simultaneous non-linear, ordinary differential equations (1) to (6), which are solved using a 4th order Runge –Kutta method as described by Fehlberg [32]; Dormand [33]; Mangano [34]; and Schreiber [35] , and using the life span of all the insects and their mortality rates as displayed in Tables 1 & 2.

The *Se* moth and its life cycle forms (egg, larvae and pupae) and the *Cotesia Flavipes* (*Cameron*) wasps have a unique death rate as shown in Table 1 and Table 2, which is already established from the literature and several research papers. The parasitoid wasps mortality rate was determined by the use of a distributive function as described by Chatfield [36] and Ostle [37] in their work on the Weibull distribution. Hence, the mortality rates of the *Se* moth and its offspring and the larval parasitoid wasps can be modelled using eqn. (7) to (10).

Application of the Weibull probability distribution function was seen in the determination of the mortality rates of mosquitoes and the predators *Odonata* and *Toxorhynchites* , Faithpraise [38]. In a similar manner, we have determined the mortality rates of the *Cotesia Flavipes* (*Cameron*) wasp and the *Spodoptera Exempta* using the Weibull probability distribution functions, the results are summarized in Table 3.

The life expectancy of the parasitoid wasps and pest can be represented by the Weibull distribution below:

$$X \sim W(\psi, \theta) \tag{7}$$

so that

$$m = \frac{\psi}{\theta}\left(\frac{x}{\theta}\right)^{\psi-1} \tag{8}$$

where

$m$ = mortality

$\psi$ = gradient of the least squares line of the Weibull probability plot. θ is the 63.2$^{th}$ quantile of a Weibull distribution. The intercept $= -\psi \ln(\theta)$, if we decide to calculate the least square line equation based on the plotted points $x_{(1)}$ .... $x_{(n)}$, then $b_1$ and $b_0$ will be estimates for $\psi$ and $-\psi \ln(\theta)$, such that $\psi \approx b_1$ and $\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$ where $b_0$ is the intercept point and $b_1$ is the slope Chatfield [31]and Ostle [32].

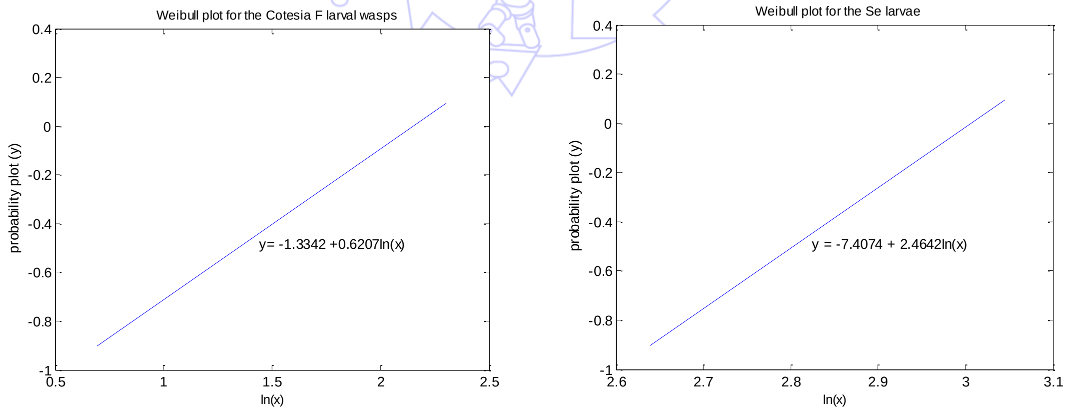



Fig. 8 Weibull plot of the Se moth larvae and *Cotesia Flavipes* (*Cameron*) wasp to determine the mortalities as illustrated in the data in Table 3.

To determine $\psi$ and $\theta$, a graphical technique, shown in Fig. 8, was used; this considers the age factor (x) and the probability distribution function (y). The variable (x) is estimated using the minimum and maximum life span of the insects, $p_i$. The distributed data points are calculated from equation 9, while $y_i$. the probability function is determined from equation 10, where n is the total number of data points, Faithpraise [39].

$$p_i = \frac{i}{n+1} \tag{9}$$

$$y_i = \ln\left[\ln\left(\frac{1}{1-p_i}\right)\right] \tag{10}$$

Table3. Life expectancy of larval wasps, Tanwar [21], Murthy [20]and the caterpillar, Mangano [23]and Mahmoud [26]. Mortality rates of the wasps and pest were obtained from the life span by applying the Weibull probability distribution function

| Mortalities | life span in days (x) | ln (x1) | ln (x2) | $\psi = b_1$ | $(b_0/b_1)$ | $\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$ | Mortality obtained |
|---|---|---|---|---|---|---|---|
| $p_{lm}$ | 2-10 | 0.6931 | 2.3026 | 0.6207 | -2.1495 | 8.5806 | 0.0683 |
| $m_h$ | 10 – 13 | 2.3026 | 2.4765 | 5.9820 | -2.5490 | 12.7947 | 0.5061 |
| $m_e$ | 2 – 5 | 0.6931 | 1.2528 | 1.7849 | -1.1996 | 3.3187 | 0.60 |
| $m_l$ | 7-14 | 2.6391 | 3.0445 | 2.4642 | -3.0060 | 20.2065 | 0.134 |
| $m_p$ | 7 - 10 | 1.9459 | 2.3026 | 2.8007 | -2.2686 | 9.6663 | 0.308 |

The mortality rates of the *Cotesia Flavipes (Cameron)* wasps ( $p_{lw}$ ) and the Se moth life cycle stages ( $m_h, m_e, m_l, m_p$ ) are estimated using equations (7) to (10) and the results are summarised in Table 3.

Our aim is to find a lasting solution to the damaging effect of the caterpillar, which are very harmful to the crop and to also to understand how effective the *Cotesia Flavipes* (*Cameron*) larval parasitoid wasp can be, when deployed for pest control. In this illustrative simulation we consider a square metre area of maize growing habitat with 4 plants per square metre each with 13 – 17 leaves per plant, Bean [40]. We assume an initial equilibrium population density of 7 adult female Spodoptera Exempta (Se), which lay an average of 150 eggs per day. The model is run with only an assumption about the number of invading Se moths, with no initial number of eggs, larva or pupa. The outcome is very interesting but it is more interesting to investigate an established infestation. The initial estimates of infestation population density can be provided using a pest surveillance system as illustrated in Fig. 3, or possibly the data may be collected by manual counting and inspection of leaves depending on the size of the field. After some eggs transform into larva, a significant effect is noticed on the growth of the leaves, as indicated in Fig 9. To prevent the total destruction of the maize crop we introduce larval parasitoid wasps, *Cotesia Flavipes* (*Cameron*), into the growing habitat. For this illustration we set the initial *Cotesia Flavipes* (*Cameron*) wasps population to 5 per square metre, the simulation results are presented in Fig. 9 to Fig. 15.

## 5. Results and Observations

### *5.1. A constant maize leaf growth*

Fig. 9 illustrates a scenario where there is an absence of caterpillars in the crop habitat (maize field). Hence all the insect variables ($N_h$= $N_e$ =$N_l$ =$N_p$ = 0) are set to zero, indicating the absence of moths visiting the habitat. The results plotted in Fig. 9 shows the normal uninterrupted growth rate of the crop over an interval of 100 days, the leaves increased from 68 to 281.

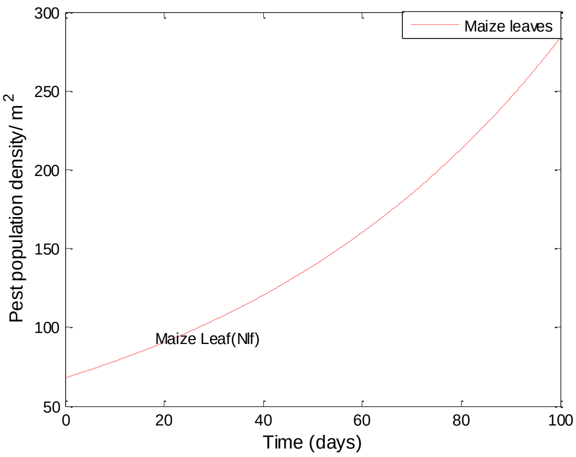



Fig. 9 Leaf growth in the absence of pests

### 5.2. *Spodoptera Exempta* (*Se*) *visitation*

In Fig. 10 a scenario is presented where seven Se ( $_iN_{h\,=\,7}$) are alighting on the maize leaves and laying eggs, The initial pest populations are: $N_e = N_l = N_p = 0$; there are no wasps deployed, so the infestation has just begun. After a period of 17 days, there was a significant drop in the leaf population which was 81 and dropped to 33 in 60 days; subsequently the leaves continued to drop to 21 within a period of 100 days; this is the result of the larvae eating the leaves. After an interval of 20 days the population of the Se moths saturates at 50, which is the environmental carrying capacity; this limits the population density of the eggs, which also saturates and peaks at 842 in 25 days. The transformation of eggs into larva peaks at 481 larvae in 24 days causing a significant drop in the leaf population, which adversely affects the population of the larvae as the population dropped to 281 in 60 days with a subsequent drop to 250 in the 100 day period, this is due to the shortage of food.

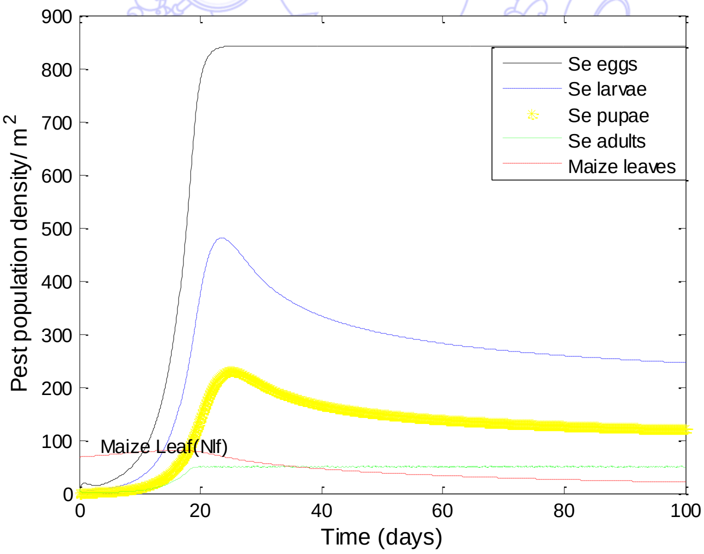



Fig. 10 The effect of Spodoptera Exempta (Se) visiting the maize field habitat

### 5.3. *Introduction of a control measure*

Immediately the pest surveillance system captures a snap shot of the pest on the maize leaves, it was decided to explore the effect of deploying different numbers of the larval parasitoid wasps into the affected habitats to understand the control strength of the wasps and the most economical approach to control the pest population to an economically acceptable level.

Using the same initial population densities of: $N_e = 0$, $N_l = 0$, $N_p = 0$; 7 Se moths and 68 leaves. We assume that each Se moth lays 150 eggs per day. The first step was to deploy five *Cotesia Flavipes* (*Cameron*) ($N_{lw}$) wasps to determine their control strength on the pest population density; the result is shown in Fig. 11. In Fig. 11, the leaf population increases slightly to 84 leaves within the first 19 days and falls to a minimum of 69 after 35 days. The wasp population drops to three after 20 days, which reduces their effect in controlling the pest larva. As the wasp population multiplies to a peak of 47, significant leaf growth was experienced to 111 within the 100 day period, during this period the Se larvae population dropped to a value of 42. The maximum pest population grows to: 843 eggs in 29 days and drops to 179 eggs after 100 days, 379 larva in 24 days dropping to 42 larva in 100 days, 177 pupa in 25 days dropping to 21 pupa in 100 days and 50 Se moths in 22 days dropping to 11 Se moths, which are economically viable values but the moth egg density is still high at 179.

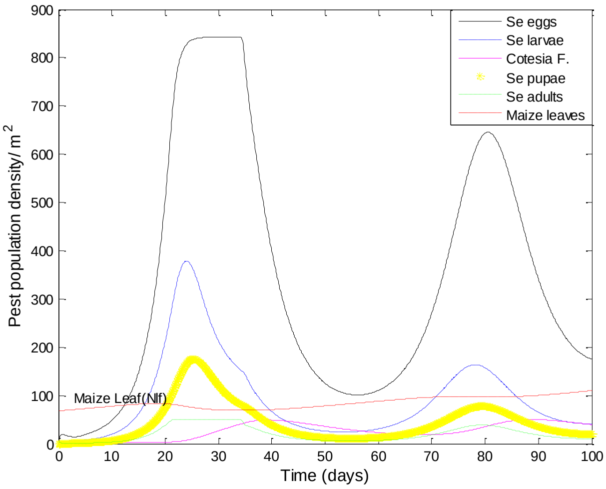



Fig. 11 Effect of deploying five *Cotesia Flavipes (Cameron)* larval wasps

Step 2: due to the losses observed in the leaf population of Fig. 11, and the failure to suppress the Se moth egg population, twenty five *Cotesia Flavipes* (*Cameron*) wasps were introduced into the habitat.

Using the same initial population densities of: 7 Se moths, $N_e = N_l = N_p = 0$; and 68 leaves and with the assumption of 150 eggs laid per day per Se moth. Twenty five *Cotesia Flavipes* (*Cameron*) ($N_{lw}$) wasps were deployed into the maize field habitat, the result is shown in Fig. 12. In the result of Fig. 12, the control activities of the Cotesia wasps is overwhelming as observed in the growth values of the Se moths and its life cycle stages. It took the Se moths 33 days to reach 50 which is the environmental carrying capacity value. This also affected the life cycles stages as it took them longer to reach their peaks. The result shows the maximum pest population grows to: 843 eggs in 39 days, 316 larvae in 32 days, 147 pupae in 33 days and 50 Se moths in 33 days. Due to the control exerted by the *Cotesia Flavipes* (*Cameron*) wasps on the Se moths larva their population dropped to 26 in 60 days, the eggs, pupae and moths population dropped to 186 for eggs, 13 pupae and 6 Se moths in 60 days and the population of the pest continued to dwindle across the 100 day period while there is constant growth of the maize leaves from 68 to 94 in 30 days, there is a slight drop to a minimum of 84 leaves by day 50' after which the leaves regained their growth to 128 for the 100 day period.

From the Fig. 12, we observe that most of the leaf destruction occurred at the peak of the larva population, when the wasp population dropped from 25 to 6 as there were no initial larvae or host to be parasitized. So as the Cotesia wasps population increases to 55, there was a significant drop in the larvae population with corresponding impact on the rest of the pest populations (eggs, pupae and Se moths).

This interesting oscillatory relationship observed between the *Cotesia Flavipes* (*Cameron*) wasp population and the pests tends to control the pest population to a metastable value, as the population density of the egg, larvae, pupa and moth were controlled to 186, 44, 22 and 11 respectively; which are economically viable values. The populations move towards equilibrium as the leaf growth increases to 128 for the 100 day period. The oscillatory relationship observed is the result of the lack of direct control of the other pest life cycle stages (egg and pupae). So every larva that escapes attack transforms into a pupa, which metamorphose into adults, which continue the reproduction of the egg stage.

### 5.4. Model reliability

From the result of Fig. 10, there were severe leaf losses from the 19th day, when the life cycle of the Se moths completed and there was a rise in the larvae population after the visitation of the Se moths to the maize farm. An initial leaf growth of 81 from the initial leaf starting value of 68 was observed in the first 18 days. Significant constant leaf destruction was noted when the larvae population grew to a peak of 481 in 24 days.

From the result of Fig. 11, it was observed that, the presence of *Cotesia* wasps introduced early into the habitats has significant effect on the activities of the caterpillar. For instance it was observed that the initial leaf growth peaks at 83 in the first 19 days. The caterpillar population peaks at 379 in 24 days, the impact was observed in the leaves within a period of 34 days (from 20th to 54th day). The negative impact on the leaves lasted a long time because of the limited number of wasps deployed. As soon as the wasp population increased to the peak of 46 Cotesia wasps, significant control of the Se larvae was achieved to a minimum value of 25 in 60 days, and 42 in 100 days as the leaf population increased to 111.

In Fig 11 and 12 an initial drop was observed in the population of the *Cotesia Flavipes* wasps from 5 to 2 in the first 16 days and 25 to 6 in the first 23 days respectively, this was due to the lack of host larvae to be parasitized, until the moths eggs transformed to larvae, then there were hosts for the wasps.

From the result of Fig. 12, it was observed that the greater the number of wasps deployed, the higher the leaf growth and the smaller the impact of the pest on the leaf population. For instance in Fig. 12 when 25 *Cotesia Flavipes (Cameron)* wasp were introduce, there was uninterrupted leaf growth from 68 to 94 in the first 29 days with negligible leaf growth drop to 83 within 21 days (between the 31st to 52th days) though the leaf growth value is still higher than the initial starting value of 68. The wasps regain control within a short period and subdue the pressure from the caterpillar to achieve a leaf growth to 129 after 100 days with a significant drop to the population of the larvae to 44.

### 5.5. Established infestation

In a scenario where an infestation is already established as illustrated in Fig. 13, using initial population densities of: 7 Se moths, $N_e = 150$, $N_l = 120$, $N_p = 90$ and 68 leaves. We assume that each Se moth lays 150 eggs per day. It was observed in Fig. 14 that 5 *Cotesia Flavipes* (*Camero*n) population started to rise contrary to our previous observations in Figs 12 and 13, where the population was observed to drop first before rising. This increase in the wasp population contributed to the earlier suppression of the Se moth larvae from 274 to 100 larvae, which definitely causes a reduction in the population of the pupae from 129 to 45, with a subsequent fall in the population of the Se moth from 50 to 22, which also affected the production of eggs from a maximum value of 843 down to 333 eggs. It is interesting to note that, in an established infestation, the control impact on the larvae stage by the wasps could cause instability on the Se moth population, despite the Se moths reaching the environmental carrying capacity, significant suppression was observed, which also reflects in the reduction in the pest egg population. But what we are interested in is the total suppression of both the other stages (eggs and pupae) to the barest economically acceptable threshold, which should be below 100 per $m^2$. In order to achieve our goals, several quantities of *Cotesia Flavipes* (*Cameron*) *wasps* were tried on the pest infestation to evaluate the quantity, which can actually suppress all the pests population to a symbiotic level. The most favourable result was observed when twenty five *Cotesia Flavipes (Cameron)* wasps were introduce as indicated in Fig. 14.

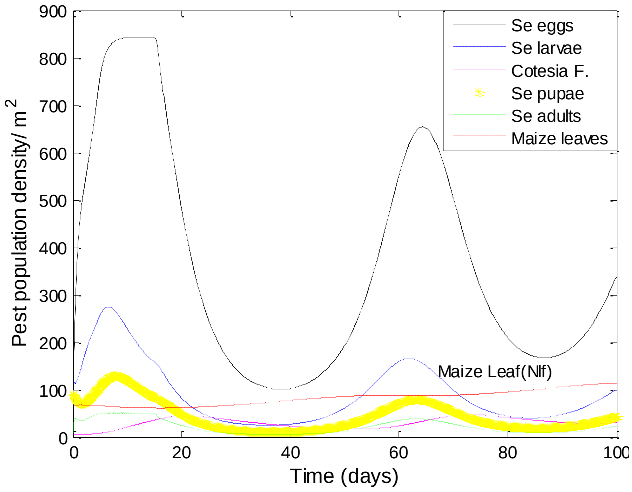



Fig. 13 Effect of five Cotesia Flavipes (Cameron) wasps on an established infestation

In a scenario where an infestation is already established as illustrated in Fig. 13, using the initial population densities of: 7 Se moths, $N_e$ =150, $N_l$ = 120, $N_p$ = 90 and 68 leaves. Twenty five (25) *Cotesia Flavipes* (*Cameron*) wasps were introduced. The result shows a maximum population growth to 463 eggs, 104 larvae, 55 pupae, and 25 Se moths . The effective control of the *Cotesia* wasps was observed by the significant drop in the population of all the pest life cycle stages to 330 eggs, 79 larvae, 40 pupae and 20 Se moths for the 100 day period. There was no actual destruction of the maize leaves across the 100 days to less than the initial leaf starting population of 68. Effective control by the *Cotesia* wasps was observed on the pest suppression values with a constantly increasing leaf growth to 127 for the 100 days. The result shows the value of the egg population 330, has still risen above the minimum allowable economic threshold whereas the larvae, the pupae and the Se moth population is maintained to a metastable values as the leaf growth rises to 128.

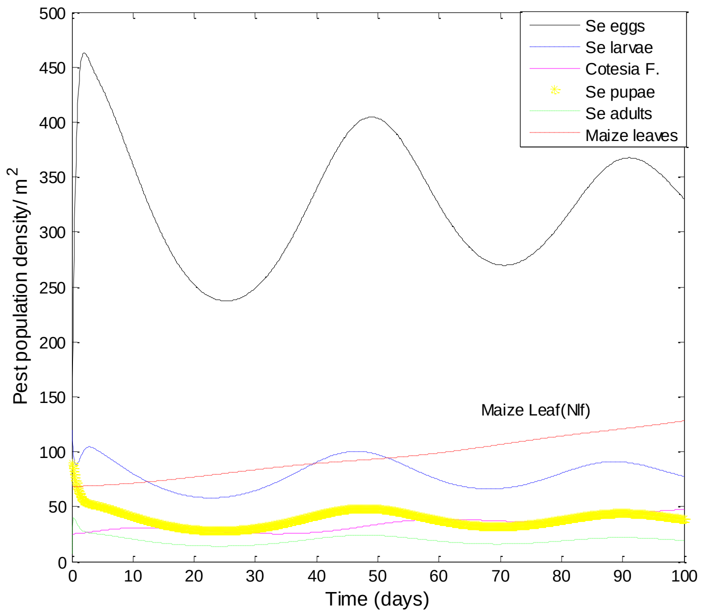



Fig. 14 Effect of twenty five Cotesia Flavipes (Cameron) wasps on an established infestation

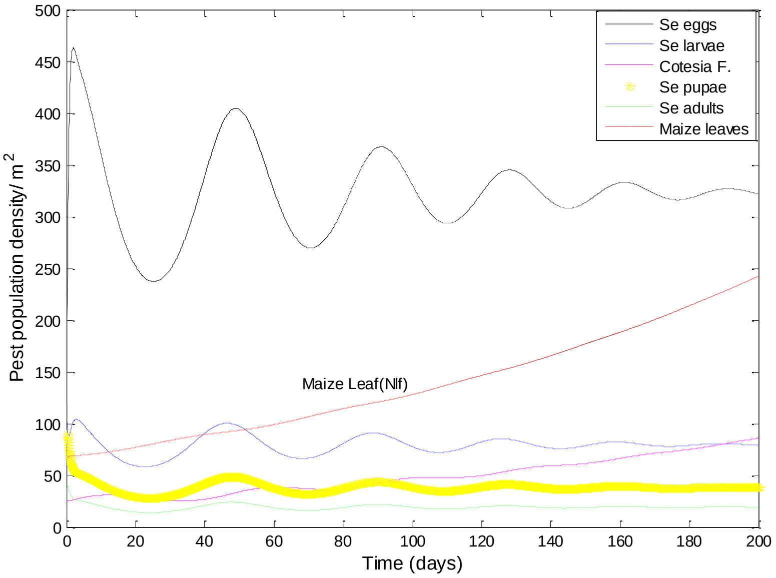



Fig. 15 System stability and equilibrium

The long term effect of none application of chemical pesticides will result in stability and symbiotic existence within the insect kingdom as observed in Fig. 15 where the plant-pest–wasp interaction becomes stable as the pest population was maintained at the minimum threshold value of 322 eggs, 79 larvae, 38 pupae, and 19 moths with corresponding increase to 239 leaves over the 200 days.

Note: Corn or maize takes 60 to 90 days to grow depending on the variety, (Mierzejewski [41], so stopping the simulation experiment within a 100 day period is in line with this. However, to prove the stability of the system, the graph of Fig. 15. shows that a stable system is obtained when wasps established their abode in an ecosystem as shown when the simulation experiment was extended to 200 days.

The result of Fig.15 shows that the system is stable, as the deployment of the larvae wasps alone had provided reasonable control without the deployment of chemical pesticides.

## 6. Results analysis

In Fig. 9, there is uninterrupted leaf growth of the maize crop over a 100 day period; due to the absence of pests the leaf population density increased from 68 leaves/m$^2$ to 281 leaves/m$^2$ within a 100 day period. Once the Se moth enters the environment they lay eggs, which hatch into larva, which eat the leaves and the leaf growth is attenuated. This is illustrated in Fig. 10, which also shows that there is a rapid increase in larva population density that attenuates as the food supply becomes inadequate to support the over population. In Fig. 11, the leaf population dropped slightly after 34 days, as the density of *Cotesia Flavipes* (*Cameron*) larval parasitoid wasps introduced was inadequate to suppress the rapidly growing pest population; Fig. 13 also illustrates the destructive nature of caterpillars in the established infestation of Fig. 14 and Fig. 15 shows the control effect when the right quantity of wasps is deployed into the habitat, the pest outbreak will be minimized and food security will be achieved as the relationship between the pest, wasps and the habitat becomes symbiotic.

Via systematic application of the numerical model it has been demonstrated that it is possible to optimize biological pest control strategy. The model demonstrates the symbiotic existence, at a sustainable level, of the parasitoid wasps and the caterpillar over a longer period as demonstrated in Figs. 12 and 14. Clearly we do not want to completely eradicate the larvae population because the absence of larvae means that the wasps cannot survive, as shown in Figs. 11 & 12 , when the wasps were deployed in the absence of an initial larvae starting population, the wasp population dropped from 5 to 2 and 25 to 6 in the first 16 and 23 days, respectively. This pest control planning tool provides agriculturists with the means to calculate the number of parasitoid wasps to deploy in any pest infested environment and the timing schedule in order to suppress the pest population. This approach offers a replacement for pesticides to enable the quality of life for all of humankind to be improved by using parasitoid wasps for the sustainable control of pests. For rapid response to an established pest infestation, this study illustrates that it is advantageous to deploy a sizable number of *Cotesia Flavipes* (*Cameron*) larval parasitoid wasps as illustrated in Fig. 12, and Fig. 14. When a sizable number of larval wasps were introduced leaf growth was sustained, the population of the larvae was under control within a short time and the leaf destruction was less over the first few days as well as the population density of the caterpillars being drastically reduced by the *Cotesia Flavipes Cameron* larval parasitoid wasps. This pest control approach will result in the production of a high quality of crops with good yield. Furthermore, there will be a great reduction in health hazard and difficulties triggered from contact with the caterpillar.

## 7. Conclusion

This research contributes to the development of an autonomous integrated pest management system for farmers across the globe with the goal of discouraging completely the application of conventional pesticides that pose risks to our immediate environment and human health. The research demonstrates the use of *Cotesia Flavipes* (*Cameron*) larval parasitoids wasps (natural enemies) to control and eradicate the problems resulting from the spread of caterpillars in our environment and farms without actually coming into direct contact with any of the species whether stingers or non-stingers, our interest is to make the environment friendly and habitable. We have created a strategy for managing the caterpillar pest generally by deploying a proposed parasitoid delivery system that deploys wasps based on statistical evaluation of the problem; this tool will enable farmers or growers to know exactly the number of *Cotesia Flavipes* (*Cameron*) larval parasitoid wasps to deploy and the period it will take to achieve control of the pest. These results agree with the initial findings of Faithpraise [11] which proves that larval parasitoids are capable of managing a pest infested habitat without the application of pesticides despite the continuous reproduction of the adult stage. Future work will investigate the possibility of combining egg and larval parasitoid wasps stages to observe the effect on the field and to achieve greater crop productivity in terms of food quality and quantity for economic benefit.

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## Dedication

We dedicate this paper to memory of Dr Ming-Yaw Huang who completed his Doctorate with us in the United Kingdom in 1994 and subsequently worked in Taiwan as a highly innovative and adventurous Engineer.