Targeting the Life Cycle Stages of the Diamond Back Moth (*Plutella xylostella*) with Three Different Parasitoid Wasps

F. O. Faithpraise, J. Idung, C. R. Chatwin, R. C. D. Young, P. Birch

Abstract—A continuous time model of the interaction between crop insect pests and naturally beneficial pest enemies is created using a set of simultaneous, non-linear, ordinary differential equations incorporating natural death rates based on the Weibull distribution. The crop pest is present in all its life-cycle stages of: egg, larva, pupa and adult. The beneficial insects, parasitoid wasps, may be present in either or all parasitized: eggs, larva and pupa. Population modelling is used to estimate the quantity of the natural pest enemies that should be introduced into the pest infested environment to suppress the pest population density to an economically acceptable level within a prescribed number of days. The results obtained illustrate the effect of different combinations of parasitoid wasps, using the Pascal distribution to estimate their success in parasitizing different pest developmental stages, to deliver pest control to a sustainable level. Effective control, within a prescribed number of days, is established by the deployment of two or all three species of wasps, which partially destroy pest: egg, larvae and pupae stages. The selected scenarios demonstrate effective sustainable control of the pest in less than thirty days.

Keywords—Biological control, Diamondback moth, Parasitoid wasps, Population modeling.

I. INTRODUCTION

THERE is a requirement for an environmentally friendly sustainable solution to pest infestation of food crops to improve the quality of life through healthy living via the achievement of improved food security and quality. The quest for the eradication of pest infestation led to the introduction of pesticides as a means to control the damage wrought by crop pests. In some instances this approach resulted in acute poisoning of humans, which caused seizure disorders, rashes, gastrointestinal illness and chronic effects such as cancer and adverse reproductive outcomes as reported by [1]-[3]. Their research shows that pesticides have harmful effects on human health, wildlife, plants and naturally beneficial insects. References [4], [5] demonstrate the dietary effects of the intake of fruits, vegetables, contaminated meat, fish, rice, and dairy products. Pesticide exposure has a significant detrimental effect on all levels of human development: foetus, infants and children [6]-[14]. References [15]-[18], have demonstrated statistically and experimentally that excessive exposure to pesticides causes a severe risk of cancer. As a result of the side effects of pesticides, many new pesticides were developed based on a greater understanding of the biological / biochemical mechanisms; these are based on synthetic light-stable pyrethroids. Researchers used a modified approach with a reduced risk of pesticide poisoning based on microbial and other biological pest control methods by considering the host-pest interactions as a means to reduce pesticide application. Early detection and pest-problem assessment is critical for propitious control of infestations; Giacomelli developed an automated plant monitoring system in greenhouses [19]. Pydipatiused machine vision and artificial intelligence to propose an intelligent farming system with the goal of achieving early detection of diseases in citrus groves with selective fungicide application on diseased citrus leaves [20]. Dae developed a colour imaging system to acquire RGB images of grapefruits with normal and five common diseased peel conditions, the algorithm developed is based on stepwise discriminant analysis [21]. Bauch proposed a complex vision-based system to measure white fly density within plant stands [22]. Skaloudova used computer vision to quantify symptoms of powdery mildew weed control and spider mite attacks [23]. Boissard combined image processing and machine learning to achieve *in-situ* early detection of a bio-aggressor on mature white flies [24]. A scale invariant feature based approach was developed for monitoring of white fly [25]. Jiang experimented with a GSM based remote wireless automatic monitoring system for the oriental fruit fly, *B. actroceradorsalis* [26]. Ruizhen created a pest classification system design based on Blackfin DSP and 3G wireless communication technology [27], Datt focused on using imaging spectroscopy to detect disease caused by pests on vegetables [28]. Samanta tried to classify tea insect pests using artificial neural networks [29]. Pokharkarb demonstrated pest detection (white fly) using image processing techniques [30], Jamal-Aldin and Faithpraise designed an automatic pest detection and recognition algorithm that is able to detect and recognise all classes of pest [31], [32]. The concept of integrated pest management (IPM) was developed with respect

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to environmental impacts according to the United States Environmental Protection Agency, [33]-[36] as a means of improving the efficiency of pest control whilst keeping the cost and damage to the environment as low as possible.

To implement IPM strategic guidelines for pest control, an optimized biological system for pest control is required. Statistical optimization of biological control requires the use of the optimum numbers of living organisms to suppress and manage pest populations below an economically acceptable population threshold, thus reducing the damage to crops. The goals of statistical optimization of a biological control system are:

i) Maintain the density of the pest population at an equilibrium threshold below the economic damage level.

ii) Reduce the pest population to a low level but not to completely destroy them as can occur with pesticides.

iii) Publicize the effectiveness of biological control systems and their sustainable control capabilities.

iv) Maintain the density of the pest population at an equilibrium threshold below the economic damage level.

v) Reduce the pest population to a low level but not to completely destroy them as can occur with pesticide application.

vi) Publicize the effectiveness of biological control systems and their sustainable control capabilities.

The existence of pest natural enemies (parasitoids) worldwide and how they can be nurtured in laboratories and released in bulk as biological control agents for crop pests was illustrated in [37]. In order to efficiently and effectively optimize a biological system of pest control; the dynamics of the pest and its natural enemy populations have to be understood to avoid an ecological disaster. Modelling is an important tool, which when applied to the problems of biological pest control allows a qualitative and quantitative evaluation of the impact of predator population densities on the pest population density. The research of: [38]-[45] experimentally and mathematically illustrate the application and a comprehensive review of host–parasitoid models for biological control.

As an illustration of the effect of targeting different life cycle stages of a pest, we propose a continuous time mathematical model of the interaction between a population of diamondback moths (N_h) and its life cycle stages: the egg (N_e), larvae (N_l) and pupae (N_p) with parasitoid wasps, namely: egg parasitoid (N_{ew}), larval parasitoid (N_{lw}) and pupal parasitoid (N_{pw}). For this model, a typical moth life cycle is illustrated diagrammatically in Fig. 1, row 2.
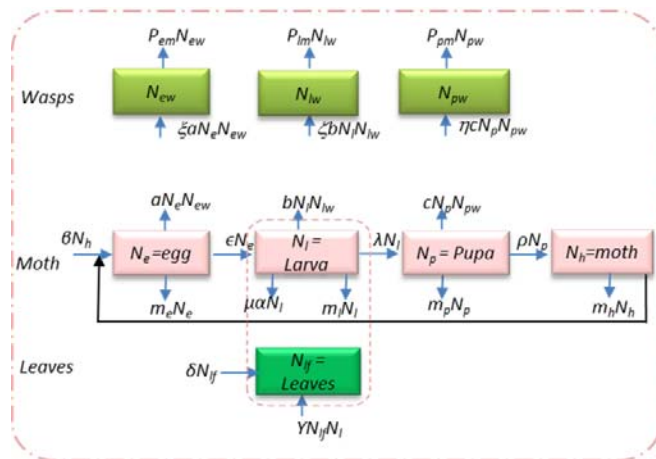

Fig. 1 Life cycle of the three species of parasitoid wasps demonstrating the requirement for a pest population for their existence Population dynamics for wasp-pest-crop interaction model describing the detailed activities of how the eggs, larval and pupae wasps exercise control over pest diamondback moth population in its habitat

TABLE I
DIAMONDBACK MOTH LIFE CYCLE AS OBSERVED BY [46]-[48]; SUMMARIZING THE MAXIMUM NUMBER OF EGGS LAID BY A TYPICAL DIAMONDBACK MOTH AND THE EXPECTED LIFE SPAN OF ALL THE LIFE CYCLE STAGES

Diamondback moth Life cycle & expectancy in days	
Maximum no of eggs per day	2-30
Life expectancy of moth	5-16
Life expectancy of egg	2-6
Life expectancy of larva	2-10
Life expectancy of pupa	5-15

TABLE II
PARASITOID WASPS LIFE SPAN AS REPORTED BY [49]-[52]; THE TABLE RECORDS THE MAXIMUM NUMBER OF EGGS LAID BY THE EGG, LARVAL AND PUPAL PARASITOID WASPS AFTER IT PARASITIZES ITS HOST (PEST), THE INCUBATION PERIODS, THE LENGTH OF TIME IT TAKES FOR THE WASPS TO EMERGE AND THE WASPS LIFE SPAN IN THE PRESENCE AND ABSENCE OF FOOD

Parasitoid wasps life span in days			
Trichogramma (egg wasps)		Diadegma Demiclausum (larval wasps)	Diadromus Collaris (pupal wasps)
No of eggs laid	1-2	1-2	2
Egg incubation period	1-2	1-3	1-2
Larva stage	1-3	3-6	2-6
Pupa stage	4-5	6-9	6-9
Total time adult wasps emerge	6-11	9-11	10-12
Wasps lifetime in the presence of food	8-11	21-26	12-31
Wasps lifetime in the absence of food	3-5	3-5	3-7

From Fig. 1, we can observe the reproductive life cycle of a typical diamondback moth. Every life-cycle stage has a population density dependent upon the population inflow (new birth or transformation) and outflow (transformation and mortality). In Fig. 1, an example of population inflow and outflow is demonstrated as the moth lays the eggs that with

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time change into larvae, which pupate and then metamorphose into adult moths; for each developmental stage there is a natural mortality rate as illustrated in Table I. In the case where there is interruption of the life cycle by the interaction with external forces, like parasitoid wasps, the populations are altered as illustrated in Fig. 1 – row 2, where there is a reduction in the population density of the pest due to parasitoid activity and natural death with time, as illustrated in Table II.

From Fig. 1, it is observed that parasitoid wasps cannot exist without their pest host.

Row 2- Fig. 1, displays the reproductive life cycle of a moth. The arrows show the state flow from the adult moth after she has laid her eggs, which hatch into larvae with time and transition to pupa and metamorphose into adults as the cycle repeats.

Row 2, Column 1- Fig.1, demonstrates the life cycle of an egg parasitoid, the adult wasp exploits the pest egg by depositing its own eggs into the moth egg, which after a time hatch into larvae. They pupate inside the moth egg, then metamorphose emerging from the moth egg as adult egg parasitoid wasps (N_{ew}) and the cycle repeats as long as the moth does not stop laying eggs. For our purposes this can be modelled using one equation; that is we do not need to model the wasp developmental life stages.

Row 2, Column 2- Fig. 1, illustrates the life cycle of the larval parasitoid, as the adult wasp introduces its own eggs into the larvae of the moth (caterpillar). After a time some eggs hatch into wasp larvae transform into pupa and then metamorphose into adult larval parasitoid wasps; the cycle repeats as long as the moth does not stop laying eggs that will transmute to larvae for the larval parasitoid (N_{lw})to parasitize. The wasp's life cycle is completed inside and adjacent to the pest larva, so this can be captured using one equation.

Row 2, Column 3- Fig. 1, shows the life cycle of the pupal parasitoid; the adult wasps deposit their eggs into the moth pupae. After a time the eggs hatch into larvae, which transform into pupa and metamorphose into adult pupal parasitoid wasps that emerge as adults from the pest pupa and the cycle repeats as long as there are caterpillars that will change into pupae population for the pupal parasitoid wasp (N_{pw}) to exploit.

II. MODEL, MATERIALS, AND METHODOLOGY

A 700m^2 cultivated field has 2,100 to 3,500 typical Cabbage plants, with each plant having 26 to 35 open leaves [53]. The environment contains: host diamondback moths (*Plutella xylostella) and* its offspring: eggs, larvae and pupae, the egg parasitoid wasp *(Tricho gramma)*, the larval parasitoid wasp (*Diadegma semiclausum),* and the pupal parasitoid wasp *(Diadro muscollaris).*

Cabbages are chosen because they are economically important and it is one of the oldest vegetables grown with broad recognition across nations. It belongs to the *Brassica* family and is related to broccoli, cauliflowers and brusselssprouts. Cabbage plants are susceptible to attacks by beetles, aphids, cabbage white butterflies, thrips, diamondback

moth – *Plutella xylostella* (L); imported cabbageworm – *Pieris rapae* (L); and cabbage looper – *Tricho plusiani* (Hubner) as described by [54]. For illustration purposes we only consider the diamond back moth (D. moth).

The *Tricho gramma*egg parasitoid wasp is chosen because of its affinity to parasitize insect eggs. It has the ability to attack 10 hosts in a day, and an average of two adults emerge from a single parasitized egg, [49]. The *Diadegma semiclausum* larval parasitoid wasp lays a single egg in the host larva and can deposit an egg in fourteen larvae in a day. It has the ability to parasitize 164 host larvae in its life span, as demonstrated by [55]. The *Diadro muscollaris* pupal parasitoid wasp carry eight matured ova at any given time, and the female oviposit within one or two days after its emergence from the pest egg, the wasp parasitizes up to 46 host pupae in its life span as reported by [56], [51]. Using data from the cited publications we modelled the interaction of the three different wasp species with the pest: egg, larva and pupa using a negative binomial distribution sometimes known as a Pascal distribution [38].

A continuous time numerical model of interactions between the host diamondback moth and parasitoid wasps is now developed. Consider a square metre with 4 – 5 cabbage plants growing with 26 open leaves per plant, $(_iN_{lf})$. Consider an equilibrium population (some arriving, some leaving) of ten female diamond back moths (N_h) laying (β) number of eggs once per day on a leaf (N_{lf}) of the cabbage plant. After a time some eggs hatch into larvae (εN_e), where ε is the fraction of eggs hatching, while some are parasitized by the introduced egg parasitoid wasp (*Trich ogramma*) (aN_eN_{ew}),where a is the probability (evaluated from the negative binomial distribution that the female wasp finds and parasitizes a pest egg. Some pest eggs die naturally (m_eN_e), where $m_e$is the egg mortality rate – (1). The egg wasp offspring (ξaN_eN_{ew}), where ξ is the efficiency (evaluated from the Weibull distribution [57], [58] of turning prey into wasps, suffer a natural death rate $(p_{em}N_{ew})$, (2), where p_{em} is the egg wasp mortality rate, the egg wasps life cycle is completed within the pest egg as they emerge from the pest egg as adult wasps, hence we only need (2) to model the wasp population. Some pest larvae (εN_e) that escaped attack as eggs change into pupae (λN_l), where λ is the fraction of larvae changing into pupae, some larvae are parasitized by the larval parasitoid wasp (*Diadegma semiclausum*) (bN_lN_{lw}), where b is the probability (evaluated from the negative binomial distribution) that the female wasp finds and parasitizes a larva. Other larvae may die (m_lN_l) naturally, where m_l is the larva mortality rate. Some larvae do not have sufficient food and starve (μaN_l), (3), where α is the leaf impact factor and μ is the leaf-larva coupling coefficient [59]. The larva wasp offspring (ζbN_lN_{lw}), where ζ is the efficiency (evaluated from the Weibull distribution) of turning larva into wasps produces the first term in the equation, the larva wasps suffer a natural death rate $(p_{lm}N_{lw})$, where $p_{lm}$is the larva wasp mortality rate, the larva wasps life cycle is completed within and adjacent to the pest larva, hence we only need (4) to model the wasps. Some of the larvaethat changed to pupae (λN_l) transform into adult moths (ρN_p) (diamondback

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moths), where ρ is the fraction of pupae turning into moths, some pupae are parasitized by the pupal parasitoid (*Diadro muscollaris*) *(cN_pN_{pw})*,where *c* is the probability (evaluated from the negative binomial distribution) that the female wasp finds and parasitizes a pupa. Some pupae may die naturally *(m_pN_p)*, where $m_p$is the pupae mortality rate, (5). The pupa wasp offspring *(ηcN_pN_{pw})* from the parasitized pest pupae, where η is the efficiency (evaluated from the Weibull distribution) of turning pupa into wasps, suffer a natural death rate *(p_{pm}N_{pw})*, where p_{pm} is the pupa wasp mortality rate, the pupa wasp's life cycle is completed within the pest pupa as they emerge from the pest pupa as adult wasps, hence we only need (6). Some of the pupae metamorphose into moths *(ρN_p)* and some moths die naturally *(m_hN_h)*, where m_h is the moth mortality rate, hence the net moth population growth rate is *{(ρN_p − m_hN_h)}*, which controls the moth population N_h, which is also limited by the moth environmental carrying capacity K_h, (7). The leaf population increases due to their growth *(δN_{lf})*, where δ is the leaf growth rate, some leaves are eaten by the larvae *(γ N_{lf}N_l)*, where γ is the fraction of leaves eaten by one larva per unit time, (8).

The following simultaneous, ordinary differential equations provide a continuous time dynamic model of the evolving pest, parasitoids and leaf populations per unit volume.

$$\frac{dN_e}{dt} = \beta N_h - \varepsilon N_e - aN_eN_{ew} - m_eN_e \qquad (1)$$

$$\frac{dN_{ew}}{dt} = \xi aN_eN_{ew} - p_{em}N_{ew} \qquad (2)$$

$$\frac{dN_l}{dt} = \varepsilon N_e - \lambda N_l - bN_lN_{lw} - m_lN_l - \mu\alpha N_l \qquad (3)$$

$$\frac{dN_{lw}}{dt} = \zeta bN_lN_{lw} - p_{lm}N_{lw} \qquad (4)$$

$$\frac{dN_p}{dt} = \lambda N_l - \rho N_p - cN_pN_{pw} - m_pN_p \qquad (5)$$

$$\frac{dN_{pw}}{dt} = \eta cN_pN_{pw} - p_{pm}N_{pw} \qquad (6)$$

$$\frac{dN_h}{dt} = \{\rho N_p - m_hN_h\}\left[N_h\left(\frac{K_h - N_h}{K_h}\right)\right] \qquad (7)$$

$$\frac{dN_{lf}}{dt} = \delta N_{lf} - \gamma N_{lf}N_l \qquad (8)$$

where:

N_h, N_e, N_l, N_p = Population density of moth, egg, larvae and pupae.

N_{ew}, N_{lw}, N_{pw} = Population density of wasps parasitizing: eggs, larvae and pupae, respectively.

K_h = Moth carrying capacity of the environment.

m_h, m_e, m_l, m_p = Moth, egg, larvae and pupae mortality rate, respectively.

p_{ew}, p_{lw}, p_{pw} = Egg, larval, and pupal parasitoid wasps mortality rate, respectively.

ξ, ζ, η = Efficiency of turning prey into parasitoid wasps offspring: eggs, larvae and pupae, respectively.

a, b, c = Frequency with which parasitoid finds and parasitizes a prey: eggs, larvae and pupae, respectively.

β = Number of eggs per day from each moth

ε = Fraction of eggs hatching into larvae

λ = Fraction of larvae changing to pupae

ρ = Fraction of pupae turning into moths

α = Leaf impact factor

δ = Leaf growth rate

γ = Fraction of leaves eaten by one larva per unit time

$_iN_{lf}$ = Initial population of leaves

N_{lf} = Population of leaves

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

Equation (8) models the leaf population and leaf growth rate, which is determined using the relative growth rate equations [58]. The proposed model consists of eight simultaneous non-linear, ordinary differential equations (1) to (8), which are solved using a 4th order Runge –Kutta method as described by [60]-[63].Using the average life span of all the insects and their mortality rates as displayed in Tables I & II and more details in [64].

For this illustration it is important to note that from Tables I and II, the diamondback moth and its life cycle forms (egg, larvae and pupae) and the parasitoid wasps have a unique death rate, which is already established from the literature and several research papers. The parasitoid wasp mortality rate was determined by the use of a distributive function as described by Chatfield and Ostle in their work on the Weibull distribution. Hence, the mortality rate can be modelled using the Weibull distribution function [65], as summarized in Table III.

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TABLE III
THE MORTALITY RATES OF THE WASPS AND PEST WERE OBTAINED FROM THE AVERAGE LIFE SPAN BY APPLYING THE WEIBULL PROBABILITY DISTRIBUTION FUNCTION

Symbol	Life span (x) days	ln (x)	$\psi = b_1$	(b_0/b_1)	$\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$	Mortality
p_{ew}	3-10	1.7918	1.4411	-1.7259	5.6176	0.26
p_{lw}	3-24	2.5953	0.6675	-2.4529	11.6218	0.055
p_{pw}	5-25	2.7014	0.9148	-2.5976	13.4317	0.068
m_h	5-12	2.1282	1.9249	-2.0786	7.9933	0.25
m_e	2-6	1.4110	1.3916	-1.3427	3.8294	0.37
m_l	2-11	1.8405	0.8707	-1.7314	5.6484	0.15
m_p	5-11	2.0669	2.1836	-2.0234	7.5640	0.30

Our aim is to find a lasting solution to the damaging effect of the pest larvae, which are very harmful to the crop. In this illustrative simulation we consider a $1m^2$ area of cabbage growing habitat with 4- 5 plants each with 26 – 35 leaves per plant. We assume an initial equilibrium population density (that is, the entry and leaving rate of moths and larvae is equal) of pests: 10 adult female moths, 150 eggs, 100 larvae and 85 pupae; the carrying capacity (K_h) was set at 50 adult moths; this value was used for all the results reported herein. We assume that each moth lays eggs in clusters of 15 per day. Using the model it is possible to produce copious simulation results but clearly we are restricted in how much can be presented.

The model can just be run with only an assumption about the number of invading moths, with no eggs, larva or pupa but the results are less interesting than considering an established infestation. We assume that the initial estimates of infestation population density are provided using a machine vision system or the data may be collected by manual counting. After some eggs transform into larvae, a significant effect is noticed on the growth of the leaves, as indicated in Fig. 4. To prevent the destruction of the cabbage crop we introduce parasitoid wasps into the cabbage growing habitat. The results illustrate a number of wasp deployment combinations, which will be discussed below. For this illustration we set the initial female wasp populations to: 30 egg parasitoid (*Tricho gramma*), 30 larval parasitoid (*Diadegma semiclausum*), and 30 pupal parasitoid (*Diadro muscollaris*); the simulation results are presented in Figs. 3 to 7.

III. EXPLORING THE POSSIBILITIES

This section explores the effect of deploying parasitoid wasps in different combinations to try to understand the most economical approach to control the pest population to an economically acceptable level.

A. A Pest Free Environment

Fig. 3 illustrates a scenario where there is an absence of pests in the crop habitat (cabbage 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. 3 show the normal uninterrupted growth rate of the crop over an interval of 100 days, the leaves increased from 130 to 324 per cubic meter.
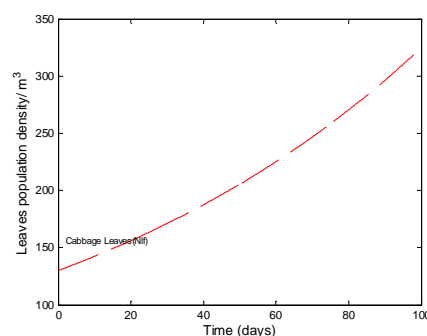

Fig. 3 Pest free crop habitation

In Fig. 4 a scenario is represented where moths ($iN_h = 10$) are alighting on the 130 leaves and laying eggs in clusters, The initial pest populations are: $N_e = N_l = N_p = 0$; there are no wasps deployed, so the infestation is just starting. After a period of 30 days, there is a significant drop in the leaf population from 130 to 64 and subsequently the leaf population drops to < 20 within a period of 100 days; this is the result of the larvae eating the leaves. After about 11 days the moth population saturates due to the carrying capacity of the environment, this limits the population density of the eggs, which also saturates at the peak of 1154 eggs after about 25 days. The transformation of eggs into larva peaks at 609 larva after 13 days causing a significant drop in leaf population, which then causes the larva population to decrease due to the shortage of food. At about 100 days the leaf population collapses to 19 leaves and the dependent larva population to 226 larvae, this causes the pupae population to fall to a steady metastable value of 164 pupae.
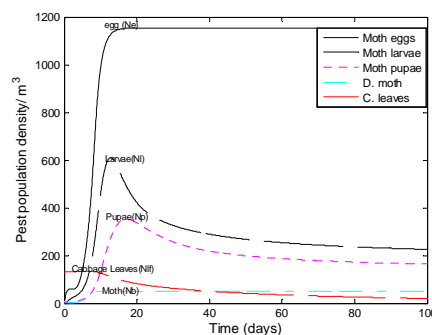

Fig. 4 Effect of moth visitation on the crop habitat

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B. Control Strategy

For the effective control of the crop pests with parasitoid wasps, different strategies are explored to control the pest's reproduction to a level below an economically viable threshold as outlined in the test cases, the best result with two wasp species deployed is the larval/pupal combination. As shown below the deployment of all three parasitoids waspsimproves on this result.

C. Scenario 1 – The Deployment of Two Species of Parasitoid Wasps

Using the same initial population densities of 10 moths, 150 eggs, 100 larvae, 85 pupae, 130 leaves, we assume that each moth lays 15 eggs per day. Two different species of parasitoid wasps were deployed simultaneously; the outcome is as illustrated in Figs. 5 & 6.
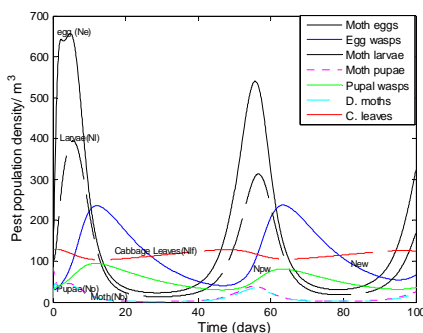

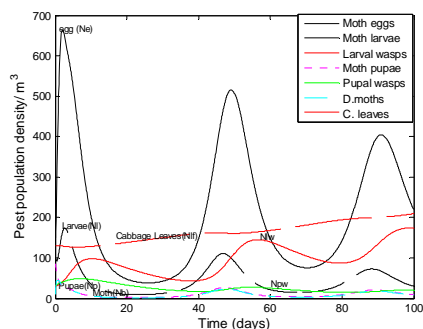Fig. 5 Effectiveness of Egg and Pupal parasitoid wasps in reducing pest population density

Fig. 6 Effectiveness of Pupal and Larval parasitoid wasps in reducing pest population density

In Fig. 5, thirty egg and thirty pupal parasitoid wasps were deployed into the habitat. The result shows the maximum pest population grows to: 654 eggs, 393 larvae, 65 pupae and 39 moths. The results show a reduction in the leaf density to 125 leaves < the initial starting population of 130 after a 100 day period. The population density of the egg, larvae, pupa and moth were reduced to 322 eggs, 156 larvae, 22 pupae and 13 moths respectively.

In Fig. 6, thirty larval and thirty pupal parasitoid wasps were deployed into the habitat. The result shows that the maximum pest population grows to: 663 eggs, 174 larvae, 75

pupae and 28 moths. Due to the control effect of the deployed wasps, there is constant growth of cabbage leaves to 208 for the 100 day period. The population density of the egg, larvae, pupa and moth were reduced to 219 eggs, 30 larvae, 10 pupae, and 8 moths respectively; which leaves an unstable population legacy.

The results of Figs. 5 and 6 show reasonable control of the pest density; when two wasp species are deployed simultaneously. Better control is achieved with the pupal/larval parasitoid wasp combination, as there is an increase in the total leaf population over the 100 day period, Fig. 6.

The result of Fig. 6 shows the pest population was subdued from the 7th day and the number of leaves dropped to 110. The combined efforts of the pupal/larval parasitoid wasps subdue the effect of the pest as the leaf population rises up again; this gives a better performance than deploying the egg/pupal parasitoid wasp combination, as illustrated by Fig. 5 where the leaf population is seen to fall below the starting population due to the massive destruction by the pest larvae. In all cases, as the host population decreases the parasitoid wasp population starts to decrease leading to a slight recovery in the host population, again the model demonstrates the classic prey/predator oscillation in population density, nevertheless, the pest population is decreasing globally. Deploying the larval/pupal parasitoid leaves a better population legacy than the egg/pupal wasp deployment for the control of the infestation.

D. Scenario 2 – Deploying Three Species of Parasitoid Wasps

Using the same initial pest population densities all three parasitoid wasps (30 egg, 30 larval and 30 pupal) are introduced into the cabbage habitat; control is established immediately. The results of Fig. 7 demonstrate a constant leaf growth from 130 to 214 for the period of 100 days. The result shows the maximum pest population grows to: 601 eggs, 160 larvae, 65 pupae and 28 moths. The population density of the eggs, larvae, pupae and moths were reduced to 57, 17, 6 and 3 respectively; which are economically viable values, with the populations moving towards equilibrium
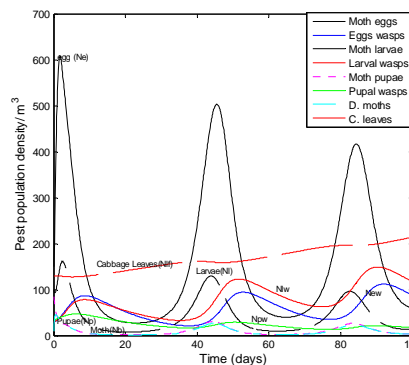

Fig. 7 Effectiveness of all three parasitoid wasps in reducing pest population density

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IV. RESULT ANALYSIS

In Fig. 3, there is uninterrupted leaf growth of the cabbage plants over a 100 day period, due to the absence of pests the leaf population density increased from 130 leaves/m^3 to 324 leaves/m^3.

Once moths enter the environment they lay eggs, which hatch into larva, which eat the leaves and the leaf growth is attenuated. This is illustrated by Fig. 4, 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. The larvae population then drop gradually with a greater leaf destruction rate. The moth and egg population density are limited by the environmental carrying capacity thereby attaining a stable value.

The pupal parasitoid wasps deliver reasonably effective biological pest control when deployed in combination with the larval parasitoid, Fig. 6.

Statistical optimization of biological control implies obtaining effective suppression of the pest population within the shortest period of time so that the pests' destructive effect is controlled. The results of Fig. 4 show that the habitat can never produce a good crop yield when the pest infestation is left unchecked, for in this scenario the ecosystem will remain unbalanced.

The result of Fig. 5 illustrates the control ability of the egg/pupal combination on pest infestation; although there was suppression of the moth eggs and pupae, the rate of leaf destruction is still very high across the 100 day period; whereas in Fig. 6, which uses the larval/pupal wasp combination, there is maximum suppression of the pest population with a corresponding increase in the leaf population over the 100 day period. In Fig. 7, all three wasp species were deployed, giving very effective control of the pest infestation.

To attain maximum effectiveness in any habit, early detection and control with the right quantity and species of parasitoid wasps is necessary, as is observed when all three parasitoid wasps were introduced into the cabbage habitat, Fig. 7.

V. CONCLUSION

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 pests. Clearly we do not want to completely eradicate the pest population because the absence of pests means that the wasps cannot survive, as shown in Fig. 1 and Fig. 5. 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 right parasitoid wasp species combination in order to suppress the pest population within a reasonable time scale. 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 a pest infestation, this study illustrates that it is advantageous to deploy larval/pupal parasitoid wasp combination but maximal control is obtained with the deployment of all three wasp species. This pest management planning system will be integrated with a pest detection and recognition system [32], and an automatic drone deployment system [66] to achieve sustainable pest control, thereby discouraging the use of chemical pesticides for crop pest infestation management.

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