SUSTAINABLE CONTROL OF INFESTATIONS USING IMAGE PROCESSING AND MODELLING

By

FAITHPRAISE, FINA OTOSI

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ENGINEERING & DESIGN RESEARCH
SCHOOL OF ENGINEERING AND INFORMATICS
UNIVERSITY OF SUSSEX
BRIGHTON
UK

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DEDICATION

To the almighty God, for his mercy, strength and wisdom to reason out solutions rationally.

To my spouse, Mr. Bassey Otosi Faithpraise, for his love, support, dedication, encouragement and tolerance for the successful completion of this research work.

To my beloved children (Princewill, Godswill, Favour and Success) for all their sacrificial love and effort.

To my Late Father, Mr Mbang Opla for dedicating his time to persuade me to desire the pursuit of higher academic degrees.

To God be the Glory, Great things he has done:
Take a look at the world of insects, what lesson do you learn?
It is only a fool that will say "there is no God"
If insects could obey the laws of nature, scientifically we called them nuisance. Pause, ponder over your life!
How will you rate your relationship with God and human?
Remember now your creator, the almighty God.

Faithpraise Fina Otosi

All knowledge with no reverence to the almighty God through Jesus Christ is vanity as the preacher had said "what profit hath a man of all his labour which he taketh under the sun?"

Ecclesiastes 1:2-3

UNIVERSITY OF SUSSEX

FAITHPRAISE, FINA OTOSI – PHD ENGINEERING

SUSTAINABLE CONTROL OF INFESTATIONS USING IMAGE PROCESSING AND MODELLING

SUMMARY

A sustainable pest control system integrates automated pest detection and recognition to evaluate the pest density using image samples taken from habitats. Novel predator/prey modelling algorithms assess control requirements for the UAV system, which is designed to deliver measured quantities of naturally beneficial predators to combat pest infestations within economically acceptable timeframes. The integrated system will reduce the damaging effect of pests in an infested habitat to an economically acceptable level without the use of chemical pesticides.

Plant pest recognition and detection is vital for food security, quality of life and a stable agricultural economy. The research utilises a combination of the k-means clustering algorithm and the correspondence filter to achieve pest detection and recognition. The detection is achieved by partitioning the data space into Voronoi cells, which tends to find clusters of comparable spatial extents, thereby separating the objects (pests) from the background (pest habitat). The detection is established by extracting the variant and distinctive attributes between the pest and its habitat (leaf, stem) and using the correspondence filter to identify the plant pests to obtain correlation peak values for the different datasets. The correspondence filter can achieve rotationally invariant recognition of pests for a full 360 degrees, which proves the effectiveness of the algorithm and provides a count of the number of pests in the image.

A series of models has been produced that will permit an assessment of common pest infestation problems and estimate the number of predators that are required to control the problem within a time schedule. A UAV predator deployment system has been designed.

The system is offered as a replacement for chemical pesticides to improve peoples' health opportunities and the quality of food products.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

ACRONYMS

AAW	African Armyworm
APDR	Automatic Plant pest Detection and Recognition
APDRS	Automatic plant Pests Detection and Recognition System
ARDMS	Automatic Robotic Drone Management System
ASPC	Automated Sustainable Pest Control
GPU	Graphics Processing Unit
GPS	Global positioning system
CDF	Cumulative distribution function
CPU	Central Processing Unit
CS	Control Station
INS	Inertial Navigation System
IPM	Integrated Pest Management
LSS	Left Side Slider
LIDAR	Light Detection and Ranging
NBI	Naturally beneficial insects
MACE	Minimum Average Correlation Energy
MVSDF	Minimum Variance Synthetic Discriminant Function
OT-MACH	Optimum Trade-Off Maximum Average Correlation Height Filter
OSPC	Optimization Statistical Pest Control
PUCB	Pest UAV NBI Dispenser Carriage Box Design

PUS	Pest UAV NBI Dispenser System
PUSP	Pest UAV NBI Despenser system Payload
RSS	Right Side Slider’
SDF	Synthetic Discriminant Function
SSC	Solenoid Switching Circuit .
UAV	Unmanned aerial Vehicle
USEPA	United States Environmental Protection Agency
USPA	United States Protection Agency

LIST OF PRINCIPAL SYMBOLS

In the following principal symbols the superscript attached to the variable refers to the life cycle stage of the pest or NBI which class is indicated by the subscripts for instance superscript h, e, l, and p refers to the adult, eggs, larva, and pupa stages of the insects (pest and NBI). The subscript m, d, e,c,a and b for instance refers to the class which is mosquito, dragonfly, elephant mosquitoes (Toxorhynchites), ladybug, aphids and beetles for some examples.

N_m^h	Population density of pest mosquito adult
N_m^l	Population density of pest mosquito larva
N_m^e	Population density of pest mosquito egg
N_m^p	Population density of pest mosquito pupae.
K_m^h	Population carrying capacity of the environment for adult mosquito
N_d^n	Population density of *Odonata* nymph
m_e^l,	Predator mortality rate of the larva
ξ, ζ, η	The efficiency of turning prey into parasitoid wasps offspring
β_m	Number of eggs per day from pest
ε_m	Fraction of eggs hatching to larva
a,b,c	Probability that the parasitoid finds and paraitizes a prey
f	Fraction of pest laying egg
μ_d	Fraction of nymphs changing into *Odonata*
λ_m	Fraction of larvae changing to pupae
ρ_m ρ_m, ρ_e	Fraction of pupae turning into adult

N_{lw}	Population density of wasps parasitizing host{larva}
μ	Leaf-larvae coupling coefficient
${}_iN_{lf}$	Initial Population of leaves
N_{lf}	Population of leaves
γ	Fraction of leaves eaten by one larva per unit time
δ	Leaf growth rate
ξ, ζ, τ	Frequency the predator attack its prey
α	Leaf impact factor
η	Efficiency of parasitism
p_{lm}	Wasps mortality rate (larval)
a, Beta	Probability of parasitism
ψ	Slope
θ	Characteristic life
x	Life span
$Q_{(x)}$	63.2th Quantile of a Weibull distribution
V_1	Valve control
D_d	Hinged door
σ	Variance
e,f,g	Frequency a predator attack another predator
r	Number of success
P	Probability of success in a single trial
X	The number of trials needed to achieve a particular success

CHAPTER -1- INTRODUCTION TO SUSTAINABLE PESTS CONTROL SYSTEM

CHAPTER -1- SUSTAINABLE PESTS CONTROL SYSTEM

1.1 BACKGROUND TO THE PROBLEM OF CROP PESTS

Agricultural crop cultivation has seen rapid development in both the quantity and quality of food production, however, the presence of pests and disease on crops has hampered the quality of agricultural produce. This threatens to destabilise global food security due to the threat posed to crop production by plant pests and diseases. (Pimentel, I997) reporting on production losses, gave an estimated average of 21% losses on selected vegetable crops caused by pests. (Cock, 2011) revealed that scientific warnings have forecast more losses in global production as a result of the pest threat. Therefore crop pests need to be controlled properly and an adequate lasting solution provided, to achieve food security, with good quality and quantity of food produce; this will reduce poverty and lower the human mortality rate.

The problems of insect pest management are not new; indeed they are endemic throughout the history of the world’s agricultural development. One major problem for agriculturists and growers is to reduce or control the effect of pests on crop yields. The most common pests affecting plants and mammals are, Aphids, Fungus, Gnats, Flies, Thrips, Slugs, Snails, Mites, Beetles, Caterpillars and Mosquitoes. There is therefore a need to detect these pests at all stages of their lifecycle: either at an early or advanced stage and suggest remedies so that much of the damage can be avoided so as to increase the quality and quantity of crop production.

1.2 WHY THE STUDY OF CROP PESTS

Pests cause periodic outbreaks of diseases, which lead to famine, considerable reduction in the world food supply and starvation. Sometimes in some nations of the world, there are recurrent cases of epidemics as a result of pest infestations, for instance (Haggis, 1996) and

(Harvey et al., 1995) reported cases of armyworm outbreaks to have started in Tanzania in 1970 and migrated to nearby nations, (Kenya Agricultural Research Institute, 1986) noted the extensive damage, with up to 90% losses of crops and pasture as a result of the outbreak. Also in north eastern India 1943, (Nisikado, 1943), (Chandwani, 1963) there was an outbreak of helminthosporiose pests on rice, which led to a heavy loss of food grains and claimed millions of lives. (Williams, 2011) estimated that in 2007 crop losses in Georgia (USA) were approximately $653.06 million. (Dowell and Krass, 1992) gave an account of 67% of all crop losses in California; (Pimentel, 1993a) estimate about $13 billion of yearly crop losses due to pests and about $1.2 billion spent on pesticides to control pests each year in the US. (Liebold, et al., 1995) noted the losses caused by pests are approximately 9% of forest products, which is equivalent to $7 billion each year in the US. (Hall and Moody, 1994) estimated the annual Canadian losses attributed to pests to be about $2.1 billion per year. (Campbell and Schlarbaum. 1994), established the U.S. Forest Service expenditure of about $11 million annually on gypsy moth control. In Nigeria (Booker, 1964), estimated 78% value of crop losses from pests. (Youdeowei, 1979), (Oerke, 2006) also estimated yield losses for cereals to be between 15 and 25% and for coffee between 31% and 78% in some regions in the world. This endemic pest problem is not found only in US, Canada, and Nigeria, it affects many nations in the world, although reliable estimates of the losses may not be available now. (Pimentel, 1997) noted the great adverse effect on any nation's economy. Pest insurgence can greatly affect any nation's economy especially those where 70% of the population depend solely on the proceeds from the agricultural sector for their livelihood and for survival. Pest insurgence had led to alien diseases and death to human beings and livestock as noted by (Ken et al., 1992), and growing environmental degradation as a result of the application of poisonous chemicals (pesticides). Therefore there is a need to raise awareness of the deadly effects of pesticides on human health.

1.3 CHEMICAL PESTICIDES

Pest classification requires a lot of technical expertise; therefore an automated insect identification method is needed. Due to rapid development of digital imaging technology, there is a growing trend towards using machine vision systems to help solve major pest problems. Pest management in most parts of the world is through regular spraying with chemical pesticides, which is based on schedules and assumptions, rather than an accurate assessment of the numbers of pests present in the field. This approach by farmers had led to secondary pest outbreaks, pest resurgence and pest resistance, which has caused great economic losses to growers and to agriculturally based nations. This has resulted in food insecurity, social anxiety, and life threatening diseases caused by exposure to pesticides.

1.3.1 THE EFFECT OF PESTICIDES ON HUMAN HEALTH

Pesticides are hazardous chemicals (Birkhoj et al., 2004), with a very high risk assessment (Reffstrup et al., 2011) designed mixtures of pesticides to repel different classes of rodents, insects, pest, fungi and weeds, which limit food security and intensive agricultural practice. However despite the benefits in controlling agricultural pests, plant diseases and organisms that constitute a nuisance to the environment; the abundance of food production is not guaranteed because pesticides are very harmful to human health, wildlife, plants, and useful insects via exposure "through surface water, ground water, soil, food and drinking water" (Wissem, et al., 2011), (Wissem et al., 2011), and (Kolpin et al., 2000).

(Wissem, 2011) explain the several routes through which Exposure to pesticides can take place as thus: "household use of pesticide products, dietary exposure to pesticide residue", which is due to "intake of fruits, vegetables, contaminated meat, fish, rice and dairy products" – (Iñigo-Nuñez et al., 2010) and (Osman et al., 2010) and exposure to pesticide drift (the airborne movement of pesticides, away from the intended target).

1.3.2 SOLUTION TO PESTICIDES USAGE

Early detection of the symptoms of pest infestation of crops is critical for timely and targeted application of naturally beneficial enemies of pests, instead of using pesticides. Precise knowledge of the areas or crops where pest activities originate is important to control the spread of infestations within a limited time frame. Due to their visual appearance, colour and physical geometry, research has demonstrated several ways of identifying and counting the populations of different pest species; several pest monitoring systems have been designed to achieve pest identification and detection.

1.4 METHODS OF CROP PEST DETECTION

(Patil et al., 2011) illustrated the different methods used by several research workers for plant disease detection and analysis, which includes self- organizing maps & back propagation neural networks with genetic algorithms for optimization & support vector machines for disease classification, (Zulhaidi et al., 2009); image analysis integrated with the Central Laboratory of Agricultural Expert System (CLASE) diagnostic model, (Mohammed et al., 2004); image recognition system to detect pest damage with the use of a wavelet based image processing technique and neural network on Braeburn apples, (Woodford et al., 1999); combination of morphological features of leaves, image processing, feed forward neural network based classifier & a fuzzy surface selection technique for feature selection, (Tzionas et al., 2005); combination of image growing, image segmentation & a Zooming algorithms for the detection of plant diseases, (Meunkaewjinda et al., 2008); Support vector machines for developing weather based prediction models of plant diseases – (Rakesh et al., 2006); Airborne hyper-spectral imagery & the red edge techniques, (Al-Hiary et al., 2011); Multispectral image sensing technologies developed for automatic detection of crop diseases – (Cui et al., 2010); (Ruizhen et al., 2012) and (Datt et al, 2006) focused on the use of imaging spectroscopy to detect disease caused by pests on vegetables. Automatic spray is a “new method of pest detection and positioning based on binocular stereo to get the exact positional information of the pest, which is used as a guide for the robot to spray the pests with pesticides” (Chunlei et al., 2009); Chunlei’s proposal could not consider pest distortion or angular transformation in the orientation of the pests on the crops. Once there is a shift in the orientation or position of the pests on the leaf, the robot will definitely miss the target and spray on unaffected areas of the leaf. I therefore partially disagree with this proposed method because of the negative effect of pesticides on human health, plants, naturally beneficial insects and the environment. However, pest control is one of the most difficult challenges to be over-come by world growers (Ruizhen, 2012) noted. The few works covered in pest control includes (Umeozor et al., 2003) proposal to use chemicals, plant extracts, improved plant varieties, cultural control methods and the use of biological agents to manage agricultural pest in Nigeria. (Jiang et al., 2008) and (Ruizhen et al., 2012) considers a "GSM based remote wireless automatic monitoring system of the oriental fruit fly-B*actrocera Dorsalis* (Hendel)". This system automatically reports environmental conditions and traps pest in real-time. (Solis-Sanchez et al., 2001) demonstrates a "scale invariant feature approach for insect monitoring" basically on white fly by using a "pest classification system design based on DSP and 3G wireless communication technology" using Cnaphalocrocis medinalis Guenee . (Samanta et al., 2012) tried to classify tea insect pests using Artificial Neural Network. (Pokharkar et al., 2012) verified pest detection white fly in particular by the use of image processing techniques. (Boissard et al., 2010) validated a cognitive vision approach to early pest detection in greenhouse crops, his work concentrated on low infestation cases, which is crucial to agronomic decision making, particularly still on white fly's. His work was very good though focused on only particular specie of pest (white fly), he did not consider pest positional or orientation changes. His work did not offer a solution on how to control and suppress the spread of the detected pest species.

One of the best methods of pest control that has gained recognition and interest as regards to environmental impacts according to (USPA, 2011), (Standler, 2010) and (USEP, 2012) is the integrated pest management system (IPM). The IPM system is a prophylactic, long-term, low toxicity means of controlling pests. It has low toxicity because the quantity of chemical recommended for use is less, so some chemical usage is not completely discouraged. IPM is a good scientific method of pest control that can be made into an autonomous system to grow with the pace of sustainable technology especially on pest control; pest identification and the deployment strategies for the naturally beneficial enemies of the pests is nevertheless an open question.

1.5 RESEARCH OBJECTIVES

- Assessment of the impact of current control systems and pesticides in particular.
- Recognition of insects within their habitat independent of size, shape, scale, colour, texture, position and orientation.
- Use of recognition systems to estimate the population of pest images acquired from the snap shot photography obtained from a robotic drone surveillance system (UAV).
- Raised awareness of the immense range of pests that threaten agricultural crops and the devastation that they can cause, and provide the means to reduce and control the their spread.
- Understand the pest and the naturally beneficial insects (NBI) lifecycle.
- Offer a sustainable solution, to achieve food security and control pest infestations, thereby discourage completely the use of pesticides in the agricultural environment.
- Identify useful pest predators, parasitoid wasps and understand their lifecycle.
- Produce a statistical model of the interaction of pest and their corresponding predators and parasitoid wasps lifecycles.
- Develop models to enable estimation of the required population of predators and parasitoid wasps to control pest population density within a specified time period.
- Design a naturally beneficial insect deployment system and e-database for pest control.
- Explore automation methods for NBI filling of the dispenser box and dispensing process.

1.6 BACKGROUND METHODOLOGY FOR CROP PEST DETECTION

The eradication of crop diseases has yielded unfavourable results because of incorrect procedures in handling pest control methods. To facilitate viable plant pest control an

Automated Sustainable Pest Control system (ASPC) is articulated. The ASPC is made up of a combination of executable systems: an automatic pest detection and recognition system using k-means clustering in combination with a correspondence filter (APDRS).

Automatic detection and recognition of plant pests is very important as it demonstrates the advantage of maintaining regular surveillance over a large crop field by automatically detecting the various stages or symptoms of pest invasion.

The detection of rotationally distorted indeterminate shaped targets, or crop pests is a complex problem, effective solutions capable of realizing recognition of all species of crop pests in agricultural environments (pest territory) still requires a lot of research. A filter is required that achieves distortion invariant recognition and detection of crop pests especially in its habitat under any circumstances. We are looking at a system that can classify, detect and recognize the pest images in any complex scene containing other objects and even within the background noise (leaves, crops and stems). To deal with this task, we decided to combine algorithmic processes; the k-mean clustering, and a correspondence filter.

The procedures for pest recognition and control were split into two broad categories. The 1st category was to combine set rules of k-means clustering and the OT-MACH filter to form a correspondence filter for the detection and recognition of crop pests. The 2nd category was to incorporate an optimal statistical biological pest control algorithm to further enable, by simulation, the capability of the APDRS system to detect and control harmful crop pests.

To create an autonomous system, all the algorithms are built into a UAV drone controller using an expert system as illustrated in chapter 4, Fig. 4.2. This system has the capability to automatically detect pests in their habitats, recognize and classify ecologically natural beneficial insects species based on their images and can assist in the deployment of these natural pest enemies into the agricultural environment in an optimised manner so as to deploy the correct numbers of predators or wasps to avoid an ecological disaster.

1.7 ACHIEVEMENTS

- Discovery of the negative impact of pesticides to mankind and living organisms
- Understanding the impact of pesticides residues on crops.
- The detection of pest images in their habitats no matter what their size, shape and colour
- The evaluation of the number of pest images present on crops at any given time
- The position invariance recognition of several classes of pest
- Determination of the mortality rates of pest and their corresponding predators and wasps
- Determination of prey capture probabilities by predators and parasitoids
- Understanding of the biology and lifecycles of both pest, predators and parasitoid wasps
- Construction of e-database for the: pest, predators and parasitoid wasps
- An interactive models for the control of different pest species
- The design of a deployment mechanism for pest control
- A complete surveillance system for pest detection and automated control
- Solution to the problem of transmission of diseases by the reduction of mosquito populations.

1.8 THESIS ORGANIZATION

In this chapter we have opened up the problem of pest infestation and its negative influence on human health and security. The problems caused by chemical pesticides were explained and it was concluded that their application should be entirely prohibited. Finally replacement of chemical pesticides, with predatory insects and wasps was described as a workable pest control system; it uses a set of rules combined with k-mean clustering and correspondence filter. The main approach to solve the problem of pest detection is described and control is provided by a dedicated optimal statistical biological control system.

Chapter two focuses on the implication of pesticides to the health and economy of any nation. It was noted that for a nation to achieve good health and save costs, pesticide application should be discouraged in its totality due to the significant risk to the environment and non-target organisms ranging from beneficial soil microorganisms, to Naturally Beneficial Insects (NBI), plants, fish, birds and mammals including humankind. Contrary to common delusions, even herbicides and larvicides can be harmful to the environment.

Chapter three provides the overview of all the strategies and the algorithms that are used to achieve the detection and the recognition of the pests in their various habitats irrespective of their colour, form, size, shape, scale, texture and orientation. The pest filter formation as well as the processes to design and construct the correspondence filter to enable pest recognition, discrimination and identification of different species of pests is presented.

Chapter four illustrates the use of unmanned aerial vehicles (UAV) for pests surveillance activities. A design of a dedicated delivery box, that will enable the smooth carriage and deployment of several classes of the natural beneficial insects to be automatically dispensed was modelled. This automatic robotic drone management system (ARDMS) is dedicated to keep the population of both beneficial and harmful pests under control and reduce the stress on typical farmers by automating the major work of inspection, surveillance, control and NBI deposition; this is performed automatically by the robotic system.

Chapter five explains how predatory insects can be used for pest population density control, the strategies on how to exploit beneficial insects to control or maintain pest population are presented, the economic importance of NBIs and why they should be protected. We have identified several classes and species of both pest and natural beneficial insect (NBI) in an e-databases, to enable a successful detection and control via the Automatic Pest Sustainable Control System (APSC).

Chapter six combines the simultaneous, nonlinear ordinary differential equations (ODE) for population modelling, the Weibull probability distribution and Pascal distribution functions to create a numerical model of the interaction between all classes of pest and all species of NBI lifecycle stages. Via systematic application of the numerical model, it has been demonstrated that it is possible to optimize biological pest control strategies by monitoring the activities of the pest. This pest control planning tool provides agriculturists with the means to estimate the number of NBIs to deploy in any pest infested habitation in order to suppress the pest population within a predicable time frame.

Chapter seven concentrates primarily on the materials and methodology for the various designs of all the sub-systems that make up the pest control system. The steps initiated to implement the model and experimental simulation results. Most importantly, the detailed design and estimation of the required payload for the transmission of the NBIs to the points of dispersion (field).

Chapter eight displays the results and discussion of all the components of the automatic sustainable control system. Finally the usual and regular method of crops inspection or monitoring with the naked eyes is seen to be replaced with a surveillance system for crop monitoring and offers a lasting solution to the problem of pest infestations.

Chapter nine discusses the future prospects for the entire system. The achievements of the work presented, applications in which the system could be utilised and makes suggestions for future work to improve the algorithms and the entire system using dedicated processors

Chapter nine is followed by Appendix and a list of the references used by this research.

CHAPTER -2-
PESTICIDE IMPLICATIONS: ECONOMICS & HEALTH OF A NATION (NIGERIA).

CHAPTER -2- PESTICIDE IMPLICATIONS: ECONOMICS & HEALTH OF A NATION (NIGERIA).

2.1 INTRODUCTION

Agricultural food production, environmental quality and human health are closely interrelated for the developed and developing nations of the world. Pesticides are widely recognized for their immense contribution in agricultural food production but their application is frequently linked with environmental pollution and health challenges of farm workers and consumers.

The impacts from pesticide application in relation to economics and health are an incessant worry among all nations of the world whether developed or developing countries. The Nigerian population is our particular focus, therefore a serious evaluation and examination of pesticide application and policy needed to be reviewed. To quantify the impact of pesticide damage to the populace and the environment, several research works from the different geo-political regions are explored; for instance, (Prabhu et al, 2005) demonstrated how indiscriminate pesticide usage can result in health impairment directly and indirectly. He further enumerated the various means by which pesticides can spread and impact mankind via: "exposure to hazardous chemicals, contamination of ground and surface water" through runoff and leakage, transmission of pesticides through the food chain from farmers to the end users or consumers, persistence resistance of pest population density to pesticides consequently resulting in new pest outbreaks, destruction of naturally beneficial insects, with the consequent reduction in natural pest predators and the difficulty of using natural pest control strategies

2.2 CONSEQUENCES OF PESTICIDES EXPOSURE

The magnitude of exposure to pestcides in humans has been associated with several problems including: "birth defects, learning disorders, respiratory illness, brain cancer, leukemia, non-Hodgkins lymphoma, neurological disorders including Parkinson's disease, brain damage, hyperactivity, attention deficit disorder symptoms, low sperm count, testicular cancer, male infertility, immune system problems, and hormonal activity" (www.turi.org). (Ekundayo, 2003) on the effect of common pesticides application in the Niger Delta Basin of Southern Nigeria on soil microbial populations demonstrated the reduction effect of pesticides on the existing soil microorganisms, which function is to sustain soil fertility; while discouraging the application of chemical pesticides and fertilizers and stressing the need of creative awareness of farmers on the rules of pesticides usage. (Udoh et al., 2011) demonstrates poor adherence to correct utilization of pesticide application by farmers in the south-south region of Nigeria- Akwa Ibom state in particular. This is a very dangerous signal for the population of a nation considering the harmful effect of pesticides on health.

(Oluwole et al., 2009) reports on the Health and environmental impacts of pesticide application confirmed poor levels of literacy as nearly all the farmers (94.7 per cent) in Ekiti State, the south-west geo-political zone of Nigeria, had received no formal training on the safety precaution measures for pesticide application, therefore they mixed incompatible pesticides products. Oluwole's work shows that farmers in this region still require creative awareness regarding the use of protective equipment and correct procedures when handling pesticides, as their pest control decisions do not consider the damage to their own health and the environment.

(Adeola, 2012), experimentally demonstrated the wide usage of pesticides by farmers in Obgomoso, the south-west geopolitical region of Nigeria. His works show the degree of understanding of pesticide effects on the environment by farmers as thus: "soil destruction (54.7%), harming beneficial insects (28.1%); decrease biodiversity (61.7%) and contribution to air pollution (48.1%); pesticide pollution of streams, rivers and wells (70%), harmful effects of pesticides on non-target animals, birds and earthworms (80.5%). Adeola's studies further confirmed the awareness of farmers on the risks of using pesticides but lamented that the continuous application of pesticides in this region by farmers is as a result of insufficient pest control alternatives.

A report given by (NFRA, 2008) revealed that the total land area cultivated by small holding farmers and their output of cowpea in northern Nigeria (Kaduna State), has dropped drastically in recent times and the low quantity of harvest obtained in most cowpea producing areas of West Africa is largely due to field insect pests, which feed on the reproductive plant parts causing major economic damage thereby necessitating appropriate control measures (Karungi et al., 2000). (Omolehin et al, 2011) demonstrated the effective control of cowpea by the use of pesticides, a study conducted in Northern Nigeria (Kano). In his works he noted the use of pesticides for the control of pests by cowpea farmers. Omolehin works shows that the maximum output yield of the product is directly proportional to the amount of pesticides (insecticides) applied. By implication, the greater the quantity of pesticides purchased, the more the cost of pest maintenance or pest control and the greater the negative effect on both crops and humans. His study demonstrated the mean cost of pest control of cowpea farm per hectare to be ₦7,870.52 (£29.7975). The work further demonstrates a high average net return of ₦ 48,308.8 per hectare as a result of pesticide application to eradicate the pest from the cowpea farm. Omolehin regards the net returns as profit without considering the harmful effect on the health of the farmers who needed training on the handling and application of pesticides. (Tijani, 2006) analysed the carelessness of farmers working in cocoa farms in Ondo state as they refused to take the necessary precautions to prevent hazards associated with the pesticide use. Such an attitude had resulted in farmers and farm workers in this region suffering from several discomforts and illnesses associated with pesticide application.

The main limitation in assessing human health impacts from pesticides in several geopolitical regions of Nigeria is related to the lack of systematic application data for all the substances used and also a lack of resources for accurate assessments of external pesticide costs. Therefore more research is required on the health impacts of pesticide usage on all the Nigerian populations

2.3 PESTICIDES IMPLICATIONS

It is important to understand the impact of pesticides on the: Environment, human health, food commodities, air, soil, water and crops

2.3.1 ENVIRONMENTAL AND HUMANS HEALTH IMPACT

(Miller, 2004), noted that the World Health Organization and the United Nations Environment Programme estimated that 3 million agricultural workers each year in the developing nations experienced severe poisoning from pesticides, from which about 18,000 people are likely to die. (WHO, 1990) noted the vulnerability of all the populations exposed to pesticides with the potential for serious health problems in the developing countries. (Environews Forum, 1999) estimated that "the world-wide deaths and chronic diseases due to pesticide poisoning is about 1 million per year" (Md. Wasim et al., 2009). (Jeyaratnam, 1990) further confirmed that as many as 25 million workers in developing nations suffered from mild pesticide poisoning each year.

Pesticides have merits in enhancing food production but the demerit is a serious negative impact on the health of humankind and the environment. (Forget, 1993) and (Igbedioh, 1991) illustrated the overwhelming evidence of the potential risks that some of the chemicals pose to beneficial insects, animals, humans and the environment.

2.3.2 FOOD COMMODITIES PESTICIDES IMPACT

(Adnan & Reuters, 2013), recently in July 2013 reported that several children were found dead in India as a result of pesticide contamination on food.

The categorical statement by WHO on the dangers of the increase to the used of pesticides and their effect on humankind has never been overstated, since every human being lives in the environment and eats food stuff. To determine the degree of food stuff contamination by pesticides, in 1996 the European Union established a Monitoring of Pesticide Residues in Products of Plant Origin. "Apples, tomatoes, lettuce, strawberries and grapes were analysed and found to contain an average of about nine thousand seven hundred (9,700) samples of seven pesticide groups (acephate, chlopyriphos, chlopyriphos-methyl, methamidophos, iprodione, procymidone and chlorothalonil). In 1997 about six thousand (6,000) samples of 13 pesticides groups (acephate, carbendazin, chlorothalonil, chlopyriphos, DDT, diazinon, endosulfan, methamidophos, iprodione, metalaxyl, methidathion, thiabendazole, triazophos) were found in mandarins, pears, bananas, beans, and potatoes. In 1998, four thousand seven hundred (4,700) samples of 20 pesticides groups (acephate, benomyl group, chlopyriphos, chlopyriphosmethyl, deltamethrin, maneb group, diazinon, endosulfan, methamidophos, iprodione,metalaxyl, methidathion, thiabendazole, triazophos, permethrin, vinclozolin, lambdacyalothrin, pirimiphos-methyl, mercabam) were found in oranges, peaches, carrots, spinach, cauliflower, peppers, wheat grains, and melon" (European Commission, 1998), (Md. Wasim et al., 2009).

2.3.3 FOOD POISONING IMPACT

(Eddleston, 2000) reported that besides the death toll from food contamination, most deaths recorded in hospital surveys are the result of self-poisoning through the use of pesticides, (Wasim et al., 2009). Murray and (Lopez, 1996) noted that about 75% of the estimated deaths of seven million nine hundred and eight thousand people were from deliberate self-harm in 1990, were from developing nations. (WHO's, 2001) estimates showed that in the year 2000 over five hundred thousand "(500,000) people died from self-harm in Southeast Asia and the Western Pacific" (Wasim et al., 2009). (Karunakaran, 1958)**,** illustrated **"**the first report of poisoning in India due to pesticides was from Kerala in 1958, where over 100 people died after consuming wheat flour contaminated with parathion" (pesticides)**.**

2.3.4 WATER CONTAMINATION

Generally water pollution with pesticides is a very serious issue as water is used by all humankind for domestic activities. (Kole et al., 2001 & 2002), (Sardar et al., 2005) and U.S. (Geological Survey, 1999) demonstrated water contamination by analysing pesticide components in fish samples collected from 90% of water sources. “Pesticides were found in all samples from major rivers with mixed agricultural and urban land use and on major river basins across the country” (Wasim et al., 2009). The concentration of insecticides in running rivers and streams was found to exceed the guidelines for protection of aquatic life.

2.3.5 SOIL CONTAMINATION

(Savonen, 1997) noted that substantial treatment of the soil with pesticides is capable of causing a decline in the population of beneficial soil microorganisms. Soil degradation occurs when chemical pesticides are over used on soil; these results in the loss of both bacteria and fungi as there aren’t enough beneficial soil organisms to hold onto the nutrients. Plants depend on a variety of soil microorganisms to transform atmospheric nitrogen into nitrates, which plants can use. Common landscape herbicides disrupt this process: triclopyr inhibits soil bacteria that transform ammonia into nitrite (Pell et al., 1998); glyphosate reduces the growth and activity of free-living nitrogen-fixing bacteria in soil, (Santos & Flores, 1995) and 2,4-dichlorophenoxyacetic acid, reduces nitrogen fixation by the bacteria that live on the roots of bean plants, (Fabra et al., 1997). (Chakravarty & Sidhu, 1987) illustrated the toxic nature of Triclopyr to some species of mycorrhizal fungi). (Andreu & Pico, 2004) illustrated the importance of soil pH in terms of the absorption rate for ionisable pesticides as adsorption increases with decreasing soil pH (e.g. 2,4-dichlorophenoxyacetic acid, 2,4,5-Trichlorophenol, picloram, and atrazine) The Acute (short-term) dermal exposure to 2,4,5-trichlorophenol may burn skin in humans. It also irritates the eyes, nose, pharynx, and lungs in humans and the liver and kidneys of rats.

2.3.6 CONTAMINATION OF AIR, AND VEGETATION

(Glotfelty & Schomburg, 1989) demonstrated the extend to which “pesticide sprays can directly hit non-target vegetation, or evaporate from the treated area and contaminate air, soil, and non-target plants”. Some pesticide drift occurs during every application, even from ground equipment (Wasim et al., 2009). (Dreistadt et al., 1994) stated the killing of both target and non-target plants outrightly by pesticide exposure. Phenoxy herbicides, including 2, 4- dichlorophenoxyacetic acid, can injure nearby trees and shrubs if they drift or volatilise onto leaves. Many pesticides have been detected in air at more than half the sites sampled nationwide. (Straathoff, 1986) “Herbicides are designed to kill unwanted plants, so it can injure or kill desirable species if they are applied directly to such plants, or if they volatilise onto them. Many ester- formulation herbicides have been shown to evaporate off treated plants with vapours sufficient to cause severe damage to other innocent plants” (Wasim et al., 2009).

2.4 ECONOMIC AND FINANCIAL IMPACT OF PESTICIDES

When the population density of pests exceeds the pest density economic threshold level, it is financially attractive to manage and control the pest problem. This financial burden is a serious factor to any nation’s economy as significant funds are diverted into purchasing pesticides. (Candel, 2012) Agrochemical Company Limited has lamented the expenditure of over ₦35 billion, which placed a drain on Nigeria’s foreign reserves due to its dependence on importation of agricultural pesticides. (Aktar et al., 2009) demonstrated the impact of pesticide usage considering the benefits and hazards to humankind and the environment.
From Candel’s reports on the statistical importation of pesticides, we can use the available estimated data of the impacts of pesticides on the third world nations and relate this to the events on the developing nations as more research is still required to confirm the health impacts of pesticides usage in Nigeria.

However considering the other regions of the world (Fantke et al, 2012) have quantified " health impacts and related damage costs from exposure to 133 pesticides applied in 24 European countries in 2003 adding up to almost 50% of the total pesticide mass applied in that year. Only 13 substances applied to 3 crop classes (grapes/ vines, fruit trees, vegetables) contribute to 90% of the overall health impacts of disablement cases, which is estimated to be about 2000 cases, which corresponds to annual damage costs of 78 million Euro per year. He further illustrated the banned of 33 of the 133 assessed substances that accounted for 20% of health impacts in 2003 from the European market" (Fantke et al, 2012).

2.5 ENVIRONMENTAL AND ECONOMIC EFFECTS OF REDUCING PESTICIDE USE IN NIGERIA

The adversarial environmental and health effects of pesticides has inspired cities in USA, Sweden, Denmark, Netherlands and Norway to take a stand on the reduction of the quantity of pesticides application. (NBA, 1999) and (Wattiez et al., 2003) confirmed the plan for pesticide reduction by 50% in Sweden, Denmark, Netherlands and Norway. Several organizations that have risen to the challenge of recommending the avoidance of pesticide exposure are "the American Academy of Paediatrics, American Public Health Association, Lymphoma Foundation of America, American Brain Tumour Association, March of Dimes, National Academy of Sciences, Massachusetts Senate and House of Representatives, General Accounting Office, and the Environmental Protection Agency.

The United States Environmental Protection Agency promotes alternatives to pesticides under the Integrated Pest Management and Bio-pesticide programs. Because of the abuse of pesticide application, the General Accounting Office has charged the EPA and the USDA with the promotion of pesticide reduction through integrated pest management programs (IPM)" (www.Turi.org), which control pests without pesticide application but rather promotes the improvement of the soil and the protection of the naturally beneficial insects.

"The National Academy of Sciences, the American Crop Protection Association and others have concluded that IPM leads to more effective long-term pest management" than chemical control. (www.turi.org)

2.5.1 ECONOMIC IMPACT OF PESTICIDE REDUCTION

2.5.1.1 MONEY BACK

There are significant economic benefits derived from the reduction of pesticide application, thus: (Pimentel et al., 1993b) noted direct benefits on the reduction of financial cost of pesticide purchase, as farmers estimated the gain of pence for every £1 invested in the use of pesticides.

2.5.1.2 GAIN IN CROP LOSSES

(Pimentel, 1991) noted with dismay the increase in crop loses despite pesticides application and stresses on the resistance developed to pesticides for a family of crops. "Pesticide-control in US measures cost approximately $4.1 billion annually, not including the in-direct environmental and public-health costs, which total more than $2.2 billion annually" (Pimentel et al., 1991). Therefore the reduction in pesticide application is sure to guarantee revival in crop growth since pest resilience and resistance will be avoided.

2.5.1.3 SECURITY OF LIFE AND FOOD

Healthy life and high quality of food is guaranteed as pest control will no longer be left in the hands of chemical pesticides but be achieved by the deployment of naturally beneficial insects (predators and wasps). Most of the illness and disease from the effect of chemical pesticides directly or indirectly will be avoided.

2.5.1.4 HEALTHY ENVIRONMENT

Environmental friendliness devoid of pollution will definitely promote the survival of the naturally beneficial insects as illustrated in the following simulation experiments: sustainable control of Anopheles mosquitoes, sustainable control of diamondback moth, beetles and the control of Aphids, by the deployments of naturally beneficial insects (predators and parasitoid wasps). Also the activities of all classes of pest species will be controlled and maintained below the minimum allowable threshold level for the existence of the pest.

2.6 CONCLUSION

Nothing good comes easy; to achieve a good health, friendly environment and save cost, pesticide application should be discouraged in its totality. Pesticides are often considered a quick, easy, and inexpensive solution for controlling weeds and insect pests in farms and urban landscapes. However, pesticide use comes at a significant cost. Pesticides have contaminated almost every part of our environment as the residues are found in soil and air and in surface and ground water across all the countries of the world. Pesticide contamination poses significant risks to the environment and non-target organisms ranging from beneficial soil microorganisms, to insects, plants, fish, and birds. Contrary to common misconceptions, even herbicides can cause harm to the environment.

The high risk groups exposed to pesticides include: production workers, chemicals formulators, sprayers, mixers, loaders and agricultural farm workers. During manufacture and formulation, the possibility of hazards may be higher because the processes involved are not risk free. In industrial settings, workers are at increased risk since they handle various toxic chemicals including pesticides, raw materials, toxic solvents and the consumers of food and the general populace including children as a result of house hold usage of insecticides treated nets and insecticide-spray used to eliminates indoor pests.

CHAPTER -3-
CROP PEST DETECTION & RECOGNITION

CHAPTER -3- CROP PEST DETECTION & RECOGNITION

3.1 CROP PEST DETECTION & RECOGNITION OVERVIEW

The complexity and challenge of recognizing crop pests when they change position, orientation and scale is a major and difficult task that still requires serious breakthroughs in pattern recognition as illustrated by (Kypraios et al., 2003) and (Bone et al., 2005).The problem of recognition is complicated by changes in the: size, shape and different orientations of plant pests in their habitat or environments (farm). (Faithpraise et al., 2013a), showed that image processing can assist in the identification of the insect pests and that this is a first step in assisting the sick plants. The moment the pest that is attacking the plant is identified, the cure can be determined. Fig. 2.1 illustrates the most common but harmful crop pests considered in this research work.

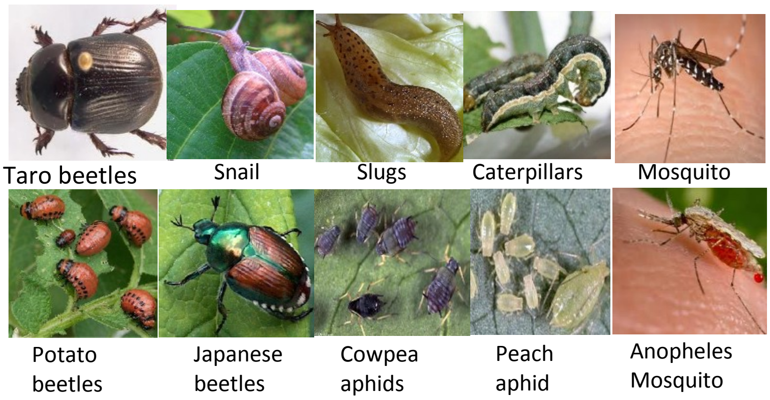


Figure 3. 1 Most common but destructive crop pests in agricultural habitats.

Plants pest images are complex, therefore direct detection and recognition of the object in its environment (habitats) is difficult without first segmenting the image in order to gain access to the useful identifying features.

It is not possible to consider object recognition without dealing with image segmentation, because of its vital role in object recognition, (Lucchese et al., 2001). Image segmentation is thought of as a "process of assigning a label to every pixel in an image, such that pixels with the same label share certain visual characteristics. The result of image segmentation is a set of partitions that collectively cover the entire image, or it may be a set of contours extracted from the image" as illustrated by (Cristobal et al., 2011), (Balaji & Sumathi, 2013). For reliable recognition the plant pest datasets are very large, hence, some method of data consolidation is required in order to reduce the size of the dataset whilst still retaining the essential features of the pest images. All consolidation methods sacrifice some detail as expressed by (Faber et al, 1994). The most desirable methods like the continuous k-means clustering algorithms are computationally efficient and yield practical application results that represent the original data quite reliably. Due to the efficiency and the practical application on the state–of–the–art, the k-means clustering algorithm is regarded as the method of segmentation chosen to implement pest characterisation and detection.

3.2 CROPS PEST K-MEANS CLUSTERING

K-means is a popular clustering algorithm that has been used in a variety of image segmentation domains as demonstrated by (Marroquin et al., 1993). K-means clustering found useful application specifically for the clustering of large crop pest datasets in the laboratory, (Orloci, 1967) . (Amir & Lipika, 2005) "Clustering involves partitioning a set of data points into non-overlapping groups" with similar characteristics or proximity. When a crop pest dataset is clustered, "every point is assigned to some cluster, and every cluster can be characterized by a single reference point, usually an average of the points in the cluster".

However, the main purpose of clustering a crop pest dataset is for size and complexity reduction, "which is realized by the replacement of the coordinates of each point in a cluster with the coordinates of that cluster's reference point" (Amir & Lipika, 2005). A clustered dataset requires a small amount of space to store and can be operated faster than the original dataset. The Orloci, 1967 method identifies the least distance measure in between two elements within a cluster, this means that a fewer number of clusters are obtained by increasing the distance between the elements. The algorithm can converge when all the observations are individual clusters as illustrated by equation 3.1 and equation 3.2

$$\mathbf{d(r,c)} = |\bar{\mathbf{x}}_\mathbf{r} - \bar{\mathbf{x}}_\mathbf{c}|^\mathbf{2} \qquad \text{Eqn. 3.1}$$

Where

$$\bar{\mathbf{x}}_\mathbf{r} = \frac{\mathbf{1}}{\mathbf{n_r}} \sum_{\mathbf{i=1}}^{\mathbf{n_r}} \mathbf{x_{ri}} \qquad \text{Eqn. 3.2}$$

$|\quad|^2$ is the Euclidean distance, $|\overline{x_r}\ and\ \overline{x_c}|$ are the centroids of clusters $r\ and\ c$

n_r = number of objects in cluster r. x_{ri} = the i^{th} object in cluster r.

“When clustering is done for the purpose of data reduction, as in the case of the crop pest images, then iterative-partitioning algorithms are most suitable, the goal is not to find the best partitioning but we want a reasonable consolidation of N data points into k clusters” as demonstrated by (Faber et al., 1994).

“Iterative algorithms begin with a set of k reference points whose initial values are usually chosen by the user. First, the data points are partitioned into k clusters: A data point x becomes a member of cluster i if z_i is the reference point closest to x” (Faber et al., 1994).

The positions of the reference points and the assignment of the data points to clusters are then adjusted during successive iterations, (MacQueen, 1967), (Faber et al., 1994)..

Conceptually, the initial partitioning of the crop pest dataset is performed as described earlier: “All the data points are partitioned into k clusters by assigning each point to the cluster of the closest reference point. Adjustments are made by calculating the centroid for each of those clusters and then using the centroids as a reference point for the next partitioning of all the data points. Demonstrative evidence shows that a local minimum of the error measure E corresponds to a “centroidal Voronoi” configuration, where each data point is closer to the reference point of its cluster than to any other reference point, and each reference point is the centroid of its cluster. The purpose of the iteration is to move the partition closer to this configuration and thus to approach a local minimum E_r" (Faber et al., 1994), as shown in equation 3.3

$$E_r = \sum_{i=1}^{k} \sum_{j=1}^{n_i} \left\| x_{ij} - z_i \right\|^2 \qquad \text{Eqn. 3.3}$$

Where

x_{ij} is the j^{th} point in the i^{th} cluster, z_i is the reference point of the i^{th} cluster, and n_i is the number of points in that cluster. The notation $||x_{ij} - z_i||$ is the distance between x_{ij} and z_i.

Therefore, the error measure E_r shows how all the data points are assigned to their reference points. To attain a cluster representative level, Faber noted that E_r ought to be very small and evaluated using an unbiased procedure to compare the partitions thereby making provision for a test to eliminate partitions that are not suitable. This is the primary notion of the system as a technique for clustering data through an uninterrupted space. (MacQueen, 1967) formularization denoted the error measure E_r for individual district d_i as described in equation 3.4

$$\mathbf{E_i} = \int_{\mathbf{x \in R}} \boldsymbol{\rho}(\mathbf{x}) \|\mathbf{x} - \mathbf{z_i}\|^2 \, \mathbf{dx} \qquad \text{Eqn. 3.4}$$

Where

ρ(x) is the probability density function, seen as an uninterrupted operation carried out across the spatial domain, and the sum total of the overall errors E_r is denoted as E_i the total error measure.

After some useful features have been marked and partitioned in accordance with the concept of the k-mean clustering technique, there is still a need to distinguish and recognise the pest from the clustered environment (leaf), a function that can be achieved by the applications of filters. What type of filter can we use to achieve the pest detection and recognition from its habitats? (Gonzalez, 1992) described the mutual relationship between two or more signals as a standard approach to feature detection. The object (crop pests) are deformable and change shape freely, hence a good filter is required to achieve rotation-invariant recognition and detection of such pests. (Sasaki et al., 1998) suggested a system based on a modified logarithmic mellin transform to solve the invariant pattern recognition problem of plant disease. (Young & Chatwin, 1992) gave a clear and distinct analysis of invariant pattern recognition. (Wood, 1996) divided the approach to solving invariant problems into two main categories, image normalization and pre-processing techniques and (Yuceer & Oflazer, 1993) dwelt mostly on other pre-processing techniques to achieve invariance to certain distortions. (Young & Chatwin,) (1992) optically implemented a matched spatial filter (Kumar, 1992), (Kumar et al., 2005) illustrated original matched spatial filters and stated that though the choice of sensors may differ depending on the problem of interest, the approach for the construction of the correlation filters generally remains the same.

3.3 PLANTS PEST FILTER FORMATION

Chronologically, going by the design of filters, (Hester & Casasent, 1980) demonstrates Synthetic Discriminant Functions (SDF), as a filter with the ability to produce a single filter through the imposition of additional constraints as the filter is made to combine linearly with the training images. This filter has the ability to suppress the response to negative training images and upholds responses to positive training images. (Kumar, 1986) proposed the Minimum Variance Synthetic Discriminant Functions (MVSDF), (Kumar et al., 1988) and (Sudharsanan et al., 1990) among other measures, for instance shows the importance of the Horner light efficiency in filter design. The numerical test outcome shows the MVSDF's ability to maximize the noise tolerance by effectively suppressing frequencies corresponding to noise, this filter does not provide a sharp correlation peak as its emphasis is on low frequency. (Mahalanobis et al., 1987) designed the Minimum Average Correlation Energy

(MACE) filter, a filter that emphasizes high frequencies to produce sharp peaks that can be easily detected as it minimizes the average correlation plane energy for the training images. The MACE filter, despite its advantage of producing sharp peaks, is sensitive to noise in the input plane. It is desirable to design filters that provide a compromise between MVSDF and MACE. (Refregier, 1991) then considered the design of the Optimal Trade-off Filter (OTF) that balances the properties between MVSDF and MACE for detecting an undistorted image as illustrated in equation 3.5.

$$\mathbf{D_d} = \mathbf{D_T}\boldsymbol{\alpha} + \mathbf{N}\sqrt{\mathbf{1} + \boldsymbol{\alpha}^2} \qquad \text{Eqn. 3.5}$$

Where $D_d = N$

Such that N is a diagonal matrix whose elements correspond to the power spectrum of the noise,
D_T is a diagonal matrix whose elements corresponds to the power spectrum of the training images, α is the tuning parameter between the noise tolerance MVSDF and the detected sharp peak of the MACE. The discrimination between the four filters (SDF, MVSDF, MACE, and OTF) depends on the value of D_d, such that if $\alpha = 0$, the filter behaves like an SDF filter, when $D_d = 1$ (identity matrix) and if $\alpha = 1$, the filter behaves like a MACE as $D_d = D_T$.
The four classes of filters as shown above have the same similarity in each of the training images as it uses a '0' value to represent the target constraint and a '1' for a non-target constraint. (Mahalanobis et al., 1994) in his work on unconstrained correlation filters vehemently discouraged the use of hard constraints especially in the production of vigorous or tough correlation filters. Mahalanobis further suggests the use of unconstrained correlation filters to increase the numbers of possible solutions so as to obtain a filter with better performance and great correlation response to the mean training images. This method is computationally simple and the proposed filters offer improved distortion tolerance and produce sharp peaks, which he called the maximum average correlation height (MACH). The resulting filter is optimal because it can "yield a smaller value of the optimized performance measure while holding the other two at specified levels" (Kumar,

1992). Thus, the name optimal trade-off filters, (Kumar & Hassebrook, 1990) saw the inadequacy for characterizing the performance of the composite filters with a single figure of merit, he then proposed six measures, “signal to noise ratio (SNR) to measure noise tolerance, the peak-to correlation energy (PCE) to measure peak sharpness, the modified Horner light efficiency, distortion invariance, discrimination ability, and accuracy in correlation peak location. The three performance measures of interest are the SNR, the PCE, and the Horner efficiency to measure the light-throughput efficiency of the filter” (Kumar, 1992). Based on Refregier’s approach with Optimal Trade-off Filters, (Faithpraise et al., 2013a) designed the Correspondence Filter for crop pest recognition.

3.3.1 CORRESPONDENCE FILTER FOR CROPS PEST RECOGNITION

The name Correspondence is used due to the filter’s capability to pick on the smallest features with close similarity to the target object to classify the object (pest) in spite of its orientation. Correspondence “filters have been extensively used in the world of detection and security. Their ability to discriminate objects from cluttered backgrounds makes correlation a very powerful tool that can be used for demanding, real time applications” (Alkandri et al., 2011). Correspondence filters are known for their shift-invariance and distortion tolerance, which makes them suitable and attractive for pest pattern recognition applications.

The correspondence filter is a powerful algorithm with the following three important features:

(a) The ability to control the correlation peak localisation. (b) Good distortion tolerance. (c) the ability to suppress noise/clutter.

In this research work the correspondence correlation filter is applied in the frequency domain, with the transfer function given by (Mahalanobis, et al., 1994) as shown in the following equations.

$$\mathbf{Z_T} = \frac{\mathbf{m_T}}{\alpha\mathbf{N} + \beta\mathbf{D_T} + \gamma\mathbf{S_T}} \qquad \text{Eqn. 3.6}$$

Where

α, β and γ = the filter parameters that are non-negative, $\mathbf{m_T}$ = the overall mean of the trained images, $\mathbf{N}$ is the additive noise, $\mathbf{S_T}$ = the similarity matrix of the trained images and $\mathbf{D_T}$ = the diagonal average power spectral density of the trained images.

Where D_T is given by

$$\mathbf{D_T} = \frac{1}{n}\sum_{i=1}^{n} \mathbf{x_i^*}\mathbf{x_i} \qquad \text{Eqn. 3.7}$$

also, S_T is given by

$$\mathbf{S_T} = \frac{1}{n}\sum_{i=1}^{n} (\mathbf{x_i} - \mathbf{m_T})^* \, (\mathbf{x_i} - \mathbf{m_T}) \qquad \text{Eqn. 3.8}$$

Where $\mathbf{x_i}$ is a diagonal matrix of the $\mathbf{i^{th}}$ trained images

In filter design, additive noise has always been estimated by the use of the white noise covariant matrix (Zhou & Chao, 1999) expressed it as given below

$$\mathbf{N} = \boldsymbol{\sigma}^2\mathbf{I_m} \qquad \text{Eqn. 3.9}$$

Where

σ^2 is the variance and I_m is the identity matrix. He further stated that other methods used an image as the added noise/clutter, which usually results in a better correlation performance. A power spectrum density technique has also been used in other filters to set the additive noise value – (Tan et al., 2002)]. We therefore use image information such as the standard deviation and the mean to set the additive noise value (Kypraios et al., 2004).

The input image statistical information, the variance and mean are used to set the value of the additive noise in the filter design. The N value according to (Alkandri et al., 2011) is given as:

$$\mathbf{N} = \frac{\boldsymbol{\sigma}}{\boldsymbol{\mu}} \qquad \text{Eqn. 3.10}$$

Where

σ is the input image standard deviation and μ is the same image mean. It is also called the coefficient of variation; a good value of the additive noise is in the range between 0 and 1. Usually, the parameter α will adjust the N value to give the best correlation result, but in this case the filter will adjust itself so α will be equal to 1. Considerable research work has been completed to optimize the tuning parameters or to set the additive noise as described by (Oliver et al., 2009). The parameters' range between a zero and a one. The new technique will minimize the search value that lies between 0 and 1 by selecting the best starting point and also by setting α = 1 will leave us with only two parameters, β and γ to change in order to get the best correlation output.

The test has also shown the direct effect of the new technique on the β value, were it stays stabilized and fixed at 0.1 throughout the test. The new technique optimizes the filter to leave us only with γ to shape up the correlation peak result. It has given the filter a great automation advantage and faster processing time with fewer parameters to adjust.

3.4 MEASUREMENT METHOD

(Kumar et al., 2005) uses Peak-to-side lobe ratio (PSR) & Peak-to-correlation Energy (PCE), among the several measures to enumerate the correlation filter performance

3.4.1 PEAK-TO-SIDE LOBE RATIO (PSR)

This method provides a measure of the correlation peak quality. The peak height is compared to the surrounding values and is given as:

$$\mathbf{PSR} = \frac{\mathbf{Peak} - \boldsymbol{\mu}}{\boldsymbol{\sigma}} \qquad \text{Eqn. 3.11}$$

“Where μ is the mean and σ is the standard deviation of the correlation plane pixel intensities. It is a common way of describing the peak quality and how good the match is between the target and the input image” (Alkandri et al., 2011).

3.4.2 PEAK-TO-CORRELATION ENERGY (PCE)

“The Peak-to-Correlation Energy (*PCE*) is defined as the energy of the peak correlation (E_{peak}) normalized to the total energy of the correlation plane (E_{corr_plane})” (Alfalou & Brosseau, 2010):

PCE will measure the correlation sharpness and is given as:

$$\mathrm{PCE} = \frac{\sum_{ij}^{n} E_{peak}(i,j)}{\sum_{i,j}^{m} E_{corr\_plane}(i,j)} \qquad \text{Eqn. 3.12}$$

Where *n* denotes the size of the peak correlation spot, and *m* is the size of correlation plane.

It compares the peak height relative to the correlation plane energy. Low PCE values indicate a better correlation peak output and thus a better detection of the true target.

The correspondence filter has demonstrated better discrimination between targets and background (noisy environment, the leaves, plants and background), as the filter is still effective at detection and recognition of pest images at varying degrees of rotation.

Since our goal and objective is a system design, in which its range of tracking is multidimensional in operation, that is a system with broad detection and recognition capabilities of all species of insect classes (which includes all manner of pests and gives discrimination and classification between pests and naturally beneficial insects), a more rigorous system that goes beyond correlation filters was incorporated.

The main concept of the correspondence techniques as expressed by Bolme, is to learn filters with the optimal goal of mapping source images of insects to their perfect output. Filters trained using this method, will literally discriminate between noisy backgrounds as they learn to restrain response to all sorts of distractors while producing greater response for target objects.

Combining the correspondence filter with the k-means algorithm, maximizes the detection and recognition of all classes of insect species despite the colour, shape, form, size, scale and orientation of the insect.

By all classes of insect species, we mean all forms of crop pests as shown in Fig. 3.1, and two classes of the natural beneficial insects (NBI-parasitoid wasps and predators) which are essential in biological pest control and in fulfilment of the objectives set herein.

3.5 CONCLUSION

Chapter 3 gives an overview of all the strategies and algorithms that are used to achieve the detection and the recognition of the pests within their various habitats using: colour, size, shape, scale, texture and orientation.

A detailed overview of the crop pests dataset was analysed to select the most useful and vital features to achieve detection. The pest filter formation as well as the processes to design and construct the correspondence filter to enable reliable pest recognition, discrimination, classification and identification of different species of crop pests was discussed.

CHAPTER -4-UNMANNED AERIAL VEHICLE (UAV) DATA SAMPLING SYSTEM & POPULATION ESTIMATION

CHAPTER -4- UNMANNED AERIAL VEHICLE (UAV) DATA SAMPLING SYSTEM & POPULATION ESTIMATION

4.1 UNMANNED AERIAL VEHICLE (UAV) EVOLVEMENT

An Unmanned Aerial Vehicle (UAV) is an aircraft that can fly independently based on pre-encoded flight plans or a more complex active automation system or they can be remotely controlled by a pilot at a ground control station, (Dempsey, 2010), (Frampton & Keirl, 2006). With reference to the past events, the evolution of Unmanned Aerial Vehicle (UAV) technology can be traced back to the armed forces, (Muttenz & Bento, 2008). The foremost application of UAVs has been in the field of intelligent supervision, reconnaissance and surveillance, (Gaszczak et al., 2011); commercial aerial surveillance, (Reg, 2010), (Frampton, et al., 2008); military surveillance (Sauer et al., 2012) and (Wilson, 1991). UAV's are used for disaster monitoring, crude oil pipeline examination, site surveillance, real-time control or supervision (Eugster & Nebiker, 2008), traffic monitoring, mapping, cultural heritage, movie production, forestry (Eisenbeiss, 2004), and Defence (Cyber Aerospace, 2004).

The autonomy of a UAV is defined by its degree of intelligence and its ability to make decisions without human intervention. This autonomy is aimed at teaching the machine to be smart and function more like humans. Fig. 4.1, illustrates typical subsystems and components of an autonomous UAV. All the components of a UAV can be grouped into Air Vehicle and Mission control element.

Air Vehicle: - this is the flying platform that carries a sensor package that can be supervised from a control station or independently. It is made up of an airframe, power plant guidance and control system, navigation equipment and an on board recorder vehicle (Vikram, 2010)

Mission control element (MCE):- This system comprises of the elements that are responsible for key mission planning, this includes flight, communication, sensor, and dissemination planning; sensor processing; aircraft and mission payload control.

At the moment the UAV airborne, the Landing and Recovery Equipment (*LRE)* hands off the aerial vehicle to the *MCE* for command and control.

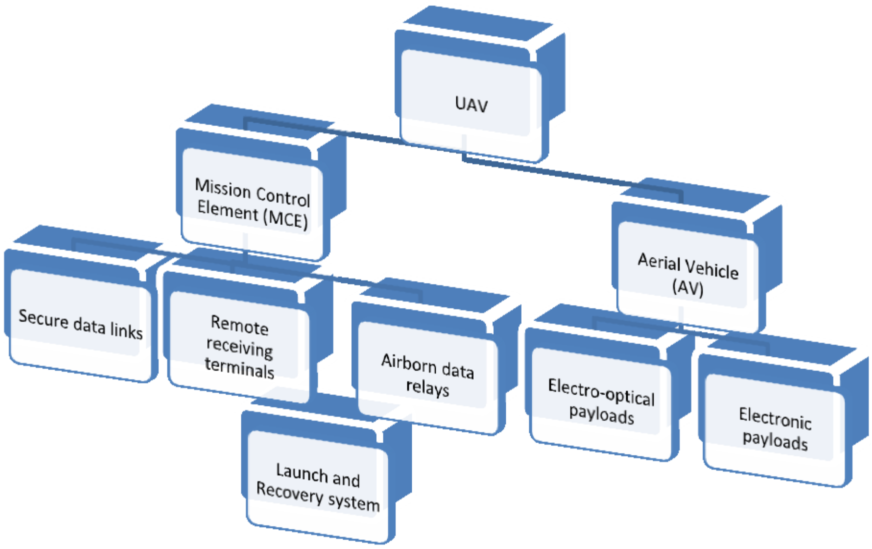


Figure 4. 1 Subsystems and components of an autonomous UAV.

4.1.1 UNMANNED AERIAL VEHICLE (UAV) CATEGORIES

UAVs are categorised according to their dedicated functions as thus:

Target and Decoy: - this is a UAV whose function is to simulate an enemy aircraft or missile for ground and aerial gunnery.

Reconnaissance: - this is a UAV equipped for battlefield intelligence.

Combat:- this is a UAV that is used to acquire useful facts about attack capability for high risk missions.

Research and Development: - this is a UAV that is used for further development and research of UAV technologies.

Civil and Commercial UAVs: - these are UAVs that are usually very small and dedicated for commercial and civil purposes (Hausamann, 2002).

UAV technology design has witnessed tremendous development over the years from large UAVs, (Coronado et al., 2003), through to small UAVs (Johnson et al., 2003), and to very small UAVs (Annen et al., 2007).

4.1.2 SIGNIFICANCE OF UNMANNED AERIAL VEHICLES (UAV)

The importance of UAVs over the years from the largest to the micro should not be under estimated, as they are often preferred for dangerous, hard, dull, dirty environments and tasks that require a high level of accuracy or precision (Neitezel, 2011).

A great deal of research on the use of pest management systems for the control and eradication of disease and pests using biological means instead of pesticides has been completed. (Daane et al., 1996) used the lacewing to control the population of leaf-hopers; (Mills & Daane, 2005) demonstrated the benefits of deploying parasitoids or naturally beneficial insects to control pest population; Mills strongly prohibited the application of toxic pesticide and insecticides.

The search for more reliable methods for pest eradication, led to the establishment of a pesticides production plant near Calcutta in India 1952, (Wasim et al., 2009), which has great potential risk to mankind, (Forget, 1993). As part of a creative solution to avoid the use of pesticides, most growers carryout visual inspections of their field weekly by observing the leaf properties to understand plant health based on the leaf 's appearance, the colour, the size of leaves and the number of pests per plant. This qualitative method is too labour intensive, and only helpful and successful for a very small field size. Visual inspection has completely failed and is unreliable, especially when the field size is very large. To improve upon visual inspection (Dorigo et al., 2007), proposed Optical satellite-based remote sensing for agro-ecosystem modelling. The algorithms were successful in supporting large scale field tests but show an inability to support small scale tests on the activities of pests. Meanwhile our interest is on a system that will prevail on both small test plots to hundreds of acres and a reliable system that can survey the field, communicate the negative activities of pest and finally offer a control measure for the identified problems. This quest for a dedicated control measure for the pest environment motivated our desire for a UAV design for pest surveillance.

A strong demand now exists in many countries of the world for non-chemical pest control methods; hence, this area still requires a lot of research.

This research expands the civil role of UAVs to pest monitoring in agricultural environments and total control by means of the deployment of the naturally beneficial enemies of the pest.

Our focus in this work is on early pest detection and control to achieve pest free habitats. This implies regular observation of the plant habitats; interpretation of the image data and planning the required action to be taken.

The above objective can be accomplished using the proposed automatic robotic drone management system (ARDMS) as illustrated in Fig. 4.2.

4.2 AUTOMATIC ROBOTIC DRONE MANAGEMENT SYSTEM (ARDMS)

The ARDM system is made up of three sub-systems

- UAV camera Drone, which provides regular monitoring and surveillance of the plant habitats.
- APDR system, which is necessary to interpret image data from the camera Drone system in order to identify objects corresponding to potential pests.
- Pest Predators/Parasitoid wasps' Statistical system (APS), which defines the pest control strategy to be taken.

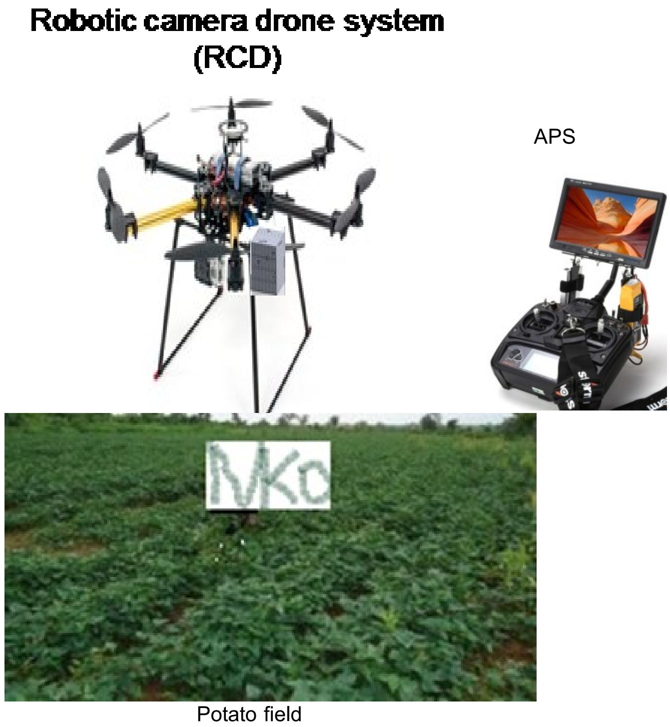


Figure 4. 2 **Proposed Automatic Robotic Drone Management System (ARDMS)**

4.2.1 THE AUTOMATIC ROBOTIC DRONE MANAGEMENT SYSTEM (ARDMS) STRUCTURE

The ARDMS is designed with the following sub-systems: Storm Drone 6 GPS **(www.helipal.com);** Pest UAV Carriage Box (PUCB); Walkera DEVO 7 7-Channel 2.4Ghz Digital Radio System; Control system; Naturally Beneficial insect's e-database (NBI).

4.2.2 THE AUTOMATIC ROBOTIC DRONE MANAGEMENT SYSTEM (ARDMS) PLAN

ARDMS is a Pest surveillance system. It is designed just like the usual UAV camera drone systems, made to operate locally with negligible legal restrictions, with minimum take-off weight of 1250g to 2.5kg and the maximum flight altitude of 50m to 200m, endurance will be 30 minute to 60minute and the data link range will be from ½ km to 5 km. The Robotic Drone used in this simulation analysis is the *Storm Drone 6 GPS system.*

The storm Drone 6 GPS is a light weight Hexa-copter platform with Carbon Fibre Landings Skids, it provides excellent stability above the ground level. It has a large ground clearance, which allows additional payload to be mounted underneath. It has dynamic balancing of the propellers, which offers ZERO vibration from the drone. It is made up of the following subsystem components and has dimensions of 550mm x 550mm x 280mm. It has a frame and landing gear with Jello Killer (a vibration free mount base).

Flight controller board - The DJI NAZA Lite with GPS Module (Setup for DEVO 7 transmitter): a system that supports remotely controlled navigation and can automatically stabilise the platform. The flight control board has a built in altitude sensor, Gyroscopes, Accelerometers, Barometer, Signal transmitter and Advanced Algorithm for positioning and stability. This is the brain that guards the Robotic drone to maintain its stability in the air

Autopilot: a system which combined with programmable image acquisition allows flights to be pre-programmed with already defined waypoints, a global positioning system (GPS), navigation-grade GPS receivers, barometers, and magnetic compass, cameras, light detection and ranging (LIDAR) technology to navigate through the environment and be able to adjust to unforeseen obstacles and situations in the habitat without human intervention.

***Navigation Systems*:-** the navigation system uses a GPS module and an Integrated UAV Navigation System Based on Aerial Image Matching. Integrated UAV Navigation System Based on Aerial Image Matching is a vision based navigation system, which integrates inertial sensors, visual odometer and registration of a UAV on-board video to a given geo-referenced aerial image, with the purpose to provide functional position information from aerial imagery even when the UAV is flying at low altitude (Gianpaolo et al., 2007). We decided that the ARDMS system should use this combination on the Robotic drone because of the possibility of GPS signal interruption or failure. If the GPS signal for some reason becomes unavailable or corrupted, the state estimation solution provided by the inertial navigation system *(*INS) alone drifts in time and may be unusable after a few seconds (especially for small-size UAVs, which uses low-cost INS). Multi-path reflections sometimes may cause the GPS signal to become irregular when operating close to obstacles. GPS is quite vulnerable to jamming (especially for a GPS operating on civilian frequencies). Therefore UAVs, which rely blindly on a GPS signal alone are quite vulnerable to malicious actions (Barber et al., 2006), (Duranti et al., 2004).

Propeller: Carbon Fibre Propeller (Clockwise and Counter Clockwise) and 2212 Brushless Motor, Tarot T-2D Brushless motor Gimbal has (Gyroscope built-in)

Power: The ARDMS system components are powered by Rechargeable Batteries

Cameras: there is a lot of on-going research work on the best lightest airborne digital camera system to use on UAVs. (IGI, 2007) disclosed the availability of a 5 kg DigiCAM-H39 multispectral camera systems with a CIR option and Tetracam's have released a 1.8 kg multichannel Camera MCA4 and 500 g ADC2. The 500 g ADC2 camera appears to be very stable for all operations based on the UAV specification but the disadvantage is the endurance and the quoted interval of not more than 12 seconds between two individual images. This camera type will only allow stationary image acquisition and not video streams.

To satisfy the goal of this work a GoPro 3 Camera is used because it provides crystal clear 1080p@60fps video, 5.8 GHz FPV video transmitter system, it also provides a high quality single shot mode. GoPro 3 Camera frame (AnDMK-301) has a weight (battery +GoPro) that will not exceed 1.5kg and Storm SD-8 Brushless Camera motor Gimbal and Storm 20A ESC.

Digital Transmitter:- It has a 2.4Ghz digital transmitter Walkera Devention 7 (or we call it DEVO 7), which offers longer transmission distance, less interference, more stable radio transmission and less legal issues, high performance and low cost. DEVO 7 is a 7-Channel 2.4Ghz DSSS Transmitter, which carries all the basic features that are needed for any 6-Channel aircraft, Throttle and Pitch curve, 3 flight modes (Normal, IDLE 1, IDLE 2), Dual Rate (DR) and EXP settings, Servo reverse, Swashplate mode and Gyro sensitivity. This transmitter has the following specification, ARM micro computer system as the encoder; 2.4Ghz（DSSS） operational frequency; -5dBm~20dBm Output power; 1.2VX8 NiCad or 1.5VX8 AA dry batteries and Current Drain: ≤170mA and a suitable Laptop for field work.

Communication - The transmission medium is at radio frequency at a distance between 100m to 10 km, with flexible transmission data rates of (62 kbps to 744 kbps) (Agogino et al., 2012). The communication link between the sub-systems is done via Wi-Fi and cellular network.

Integration and Test- the ARDMS system is a complex assembly deployed into a complex environment (pest habitats). Therefore all the multiple sub-systems are designed and developed independently before being integrated into a single entity, and a remote control system is used to manipulate and control the system's operation. Significant emphasis is placed on the UAV weight, size and power management to fulfill the goals of the system.

4.3 PEST UAV NBI DISPENSER CARRIAGE BOX (PUCB) APPROACH

PUCB is designed with carbon fibre composite material. The fibres are extremely stiff, strong, and light, and are used in many systems that are required to be reliable and lightweight. Carbon fibre composites are useful in applications where high strength to weight and high stiffness to weight are desirable as required by UAVs, aeroplanes, wind turbines etc. Its electrical conductivity, as well as high thermal conductivity in addition to the basic mechanical properties (Asuquo et al., 2010), creates a unique and attractive surface finish (Battiste et al., 2000). The carbon fibre composite properties are the factors that make it the best material for the construction of the naturally beneficial insect (NBI) carriage box.

4.3.1 PEST UAV NBI DISPENSER CARRIAGE BOX (PUCB) COMPONENT

The '*Left side slider*' has a valve control (V_1), which is activated to open and close via a Solenoid Switching Circuit (SSC). A dispenser hinged door (D_d) located at the bottom of the box has a control valve (V_2), which is also triggered to open and close by the SSC.

This carriage main box has network connection points to facilitate communication between all its components as shown in Fig. 4.3, and the UAV. The carriage box uses a weighing system at the refilling station to weigh and be sure that the right quantity of Naturally Beneficial Insects (NBI) is automatically deposited into each of its 52 small boxes,

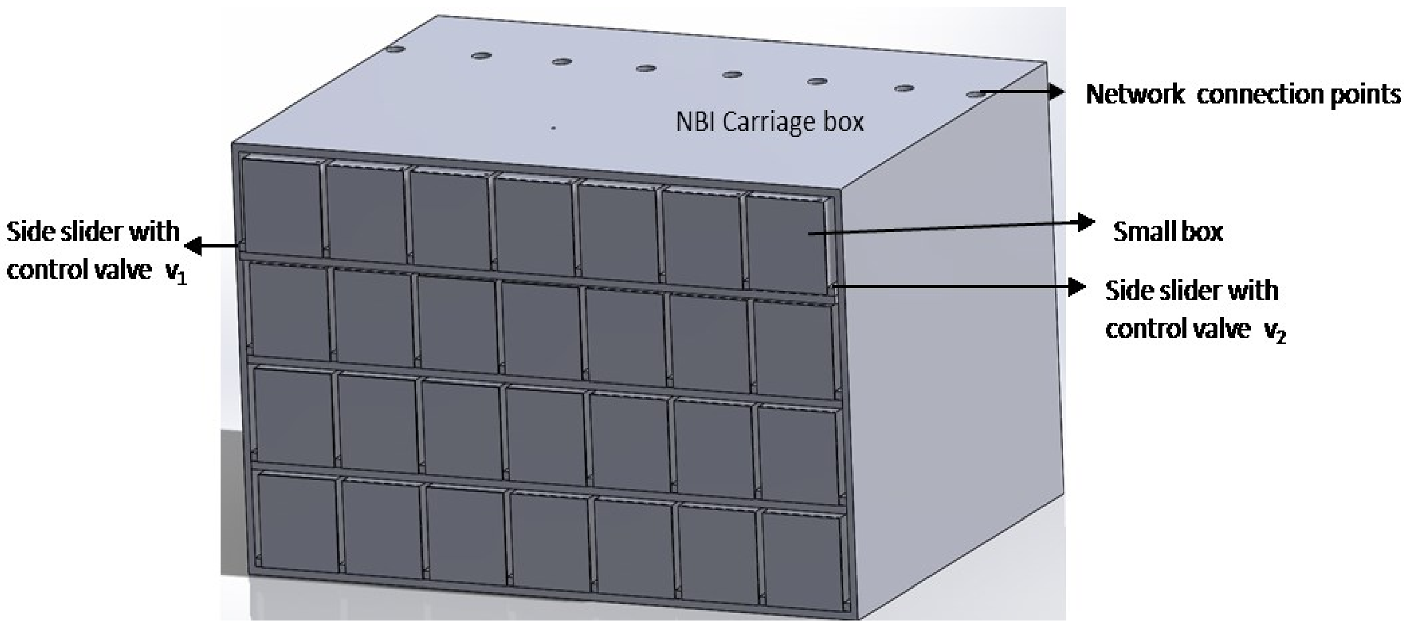


Figure 4. 3 The box assembly is attached to the UAV using simple snap connectors.

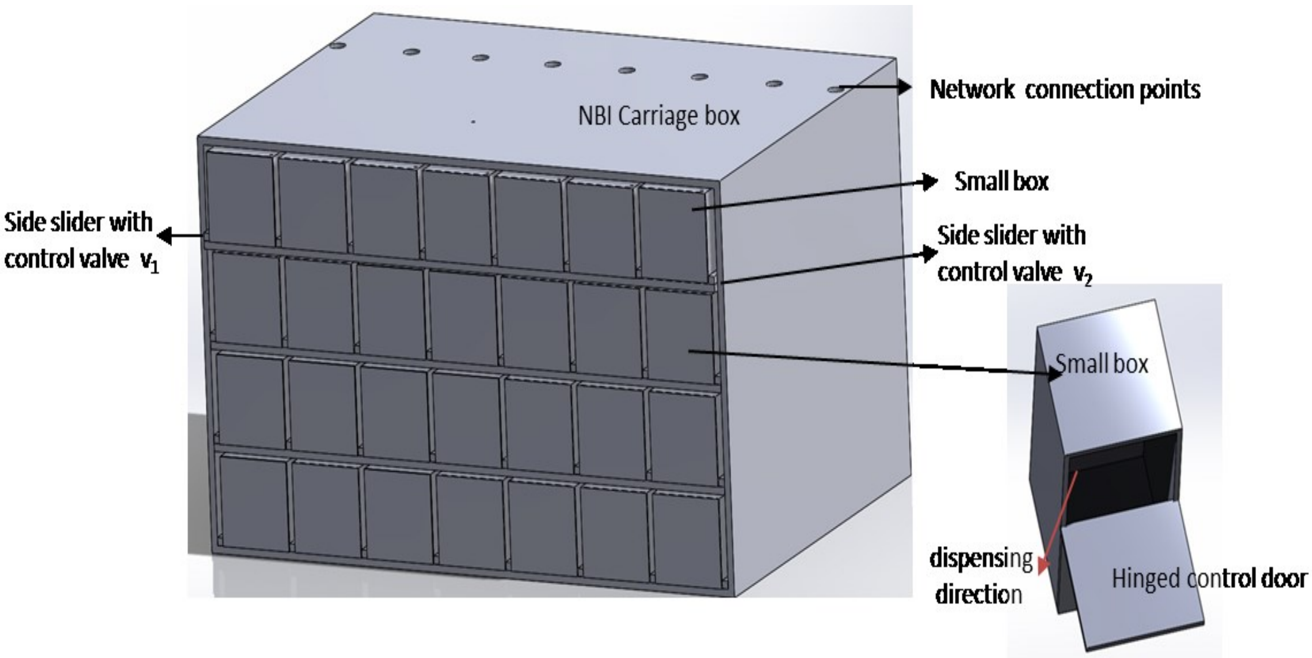


Figure 4. 4 **Proposed Pest UAV NBI Dispenser Carriage Box (PUCB) design**

4.3.2 PEST UAV NBI DISPENSER CARRIAGE BOX (PUCB) WORKING PROCEDURE

The 52 individual boxes are filled with the required quantity of NBIs automatically in the refilling station, and then loaded into the NBI carriage main box as shown in Fig. 4.4.

After the loading phase, the UAV surveillance system then shuttles the PUCB to the field dispensing points. By automation, at the dispensing terminals, the solenoid switching circuit (SSC) sends an 'ON' signal to control valve (V_1) which triggers the '*left side slider(LSS)*' to pull the small box ¼ way out of the main carriage box to enable the hinged door to open as shown in Fig. 4.5, due to the force of gravity (Obu et al., 2011), then the NBIs are released to the various preprogramed points in the field. An 'OFF' signal is then sent to control valve (V_2), which triggers the '*right side slider(RSS)'* to close the hinged door as shown in Fig. 4.6, which returns the box to its initial position. At each preprogramed location, the side slider rod spins to position the next box that is required to dispense the NBI, this an on and off, pull and push process which repeats until all the 52 boxes are empty, and returned back to their initial position, as illustrated in the flowchart of the algorithm for the box operation of Fig. 4.7.

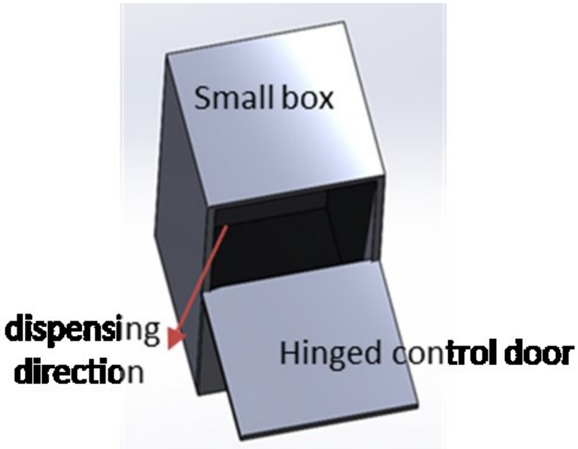


Figure 4. 5 **Pest UAV NBI Dispenser small box with hinged door mechanism**

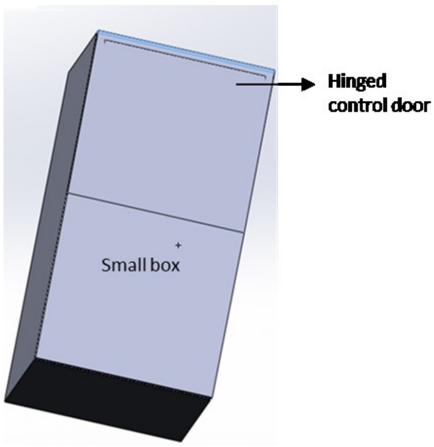


Figure 4. 6 **Pest UAV NBI Dispenser small box with hinged door closing mechanism**

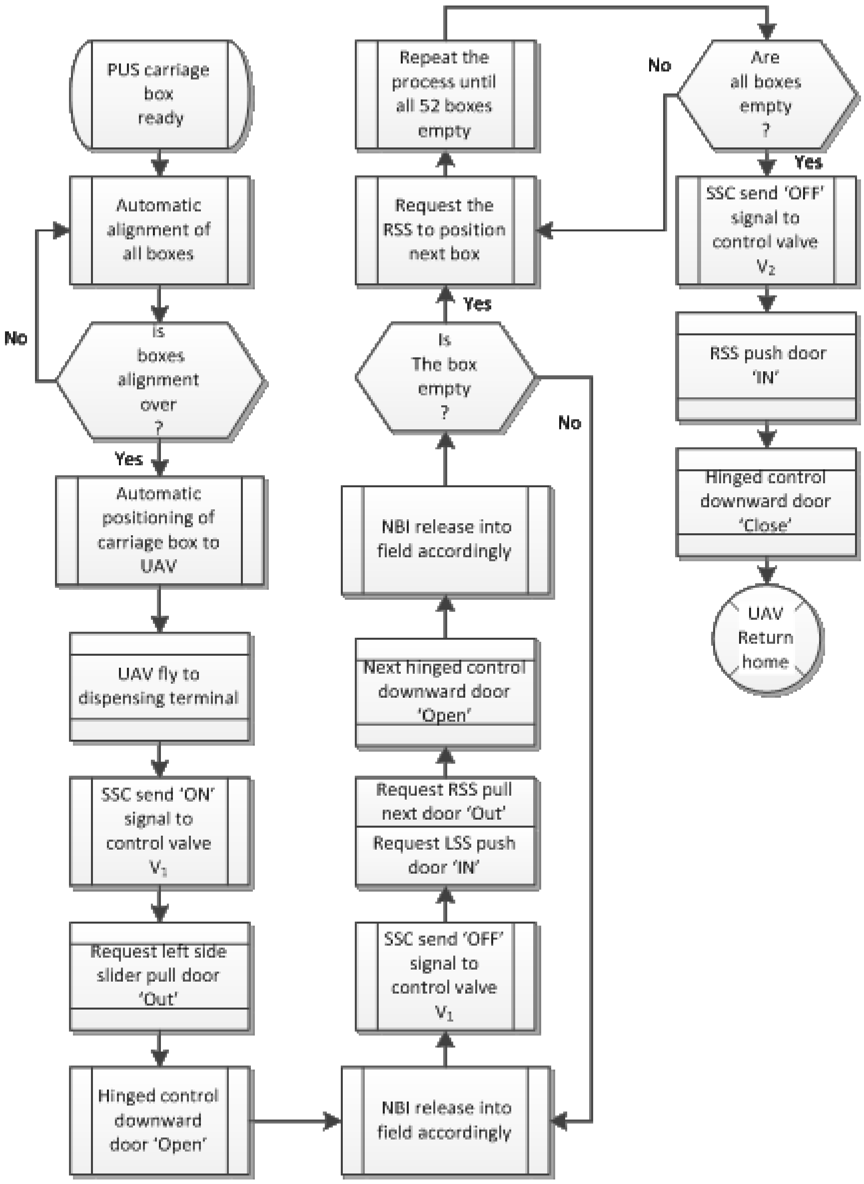


Figure 4. 7 **Proposed flowchart for Pest UAV Carriage Box (PUCB)**

4. 4 AUTOMATIC ROBOTIC DRONE MANAGEMENT SYSTEM (ARDMS) CONTROL SYSTEM

The control system consists of the image processing and recognition algorithms for all the classes of pest, the statistical algorithms for pest classification and control, the e-database of all known pests and naturally beneficial insects images , the interface programs for the control of the UAV mission and the digital radio transmitter to control and monitor the operation of the UAV.

4.5 NATURAL BENEFICIAL INSECTS E-DATABASE (NBI)

This is a database that contains information and images of all economically important pests and naturally beneficial insects that are considered very useful to our studies. The NBI database is subdivided into groups, the parasitoid wasps and the predators. The parasitoid wasps are further classified into ecto-parasitoid and endo-parasitoid wasps for ease of locating it when the need arises.

4.6 AUTOMATIC ROBOTIC DRONE MANAGEMENT SYSTEM CONFIGURATION

The main task of the UAV Robotic Drone is to carry the mission payload to its point of application (the farm). These payloads include the communication link (wireless signals), stabilization and control equipment as illustrated above and Parallel Li-Po battery pack. What determines the UAV design and configuration are the operational range, air speed and endurance demanded of it by the mission it is required to perform, (Frampton & Keirl, 2006). The Paraellel Li-Po battery pack load to be carried will provide 30 min endurance and a 5 metre height required by the mission. The robotic drone is required to fly at a speed lower than 10km/hr to obtain the most efficient hovering and low-speed performance we desire to capture the activities of the pest.

The ARDMS has a computer on board and is monitored by humans on the ground, using industrial wireless technology and digital radio frequency (RF) signals. The Automatic Robotic Drone can fly and navigate itself using software instructions that are fed to the system before its launch. The software instructions have the mission plan downloaded into the Automatic Robotic Drone software. The operator on the ground can change the mission plan by sending a new set of instructions using the digital RF signals. The instructions are used to decide the flight path, take static photographs, mark target, transmit and dispense wasps to the affected plant areas and return to base.

The UAV mission which includes Ariel surveillance of farm lands, videoing the activities of the pests, taking static images of the pest on the crops, transmitting the images via data links, refilling of the NBI carriage box, and for better control of the affected crops dispensing the appropriate beneficial insect to the affected crops, using a pre-planned schedule implemented at the control station (CS) of Fig. 4.2, or may be planned from a central command centre with mission data sent to the CS for it execution. At the control station the operators communicate with the UAV via the communications system up-link in order to direct its flight profile and to perform the various types of mission. Likewise, the UAV returns information and images to the operator via the communication down-link. These information include data from payloads, status information of the UAV itself (known as housekeeping data), and position information, (Johnson et al., 2003). CS may sometimes control the launching and recovery of the UAV.

The Pest surveillance UAV Design, as observed above, is similar to a drone from the usual UAV camera drones systems design in the market with all the subsystems listed. Our added system element is the attachment of a Proposed PUCB, which is designed to accomplish the pest control processes and management functions.

4.7 ARDMS MECHANISM OF OPERATION

The early detection of the symptoms of all pest invasions at all their distinct life cycle stages is essential to control and avoid permanent infestation. As analysed by (Meihls et al., 2004) and (Mondor et al., 2010) during their investigation on the high reproductive growth rate of aphids pests on a leaf or plant under normal and varying conditions. Their investigation and analysis forecast a constant increase in growth rate of pest (aphids) in any infested ecosystem, as all pests reproduce in great numbers under favourable conditions. Therefore the UAV Robotic drone is built with a camera platform that enables safe operation of a constant surveillance video system and at the same time takes snapshots of the plants and leaves, within the area of the farmland. The camera drone will operate five meters above the field level to maintain complete surveillance of the crop within the habitat. The UAV robotic drone flies a pre-programmed flight path as illustrated in Fig. 4.8, taking images of the plants' leaves at different points within the field as demonstrated in Fig. 4.9. The leaf images taken at various points in the field are sent to the automatic plant pest detection and recognition system (APDRS) via the signal transmission unit (Wi-Fi) for interpretation of the image content in order to identify objects corresponding to potential pests and the specie of pest dominating the habitat. For a more detailed description of the operation of the ARDMS, view the flow chart of Fig. 4.10.

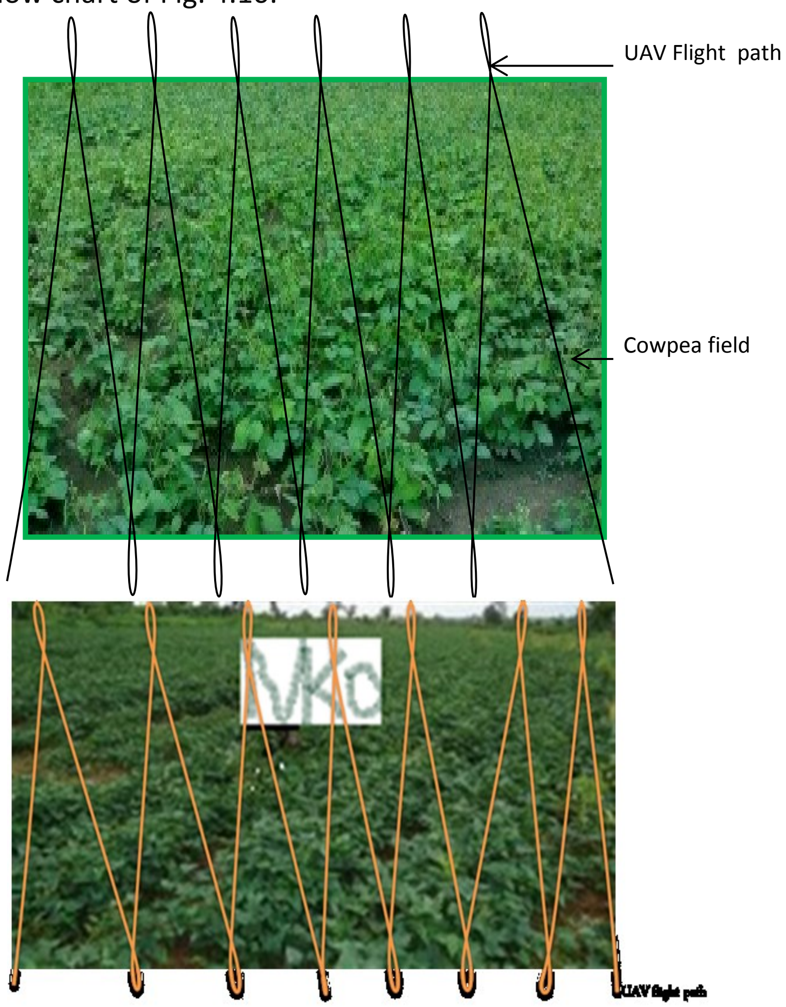


Figure 4. 8 UAV Robotic Drone flight path on different crop field

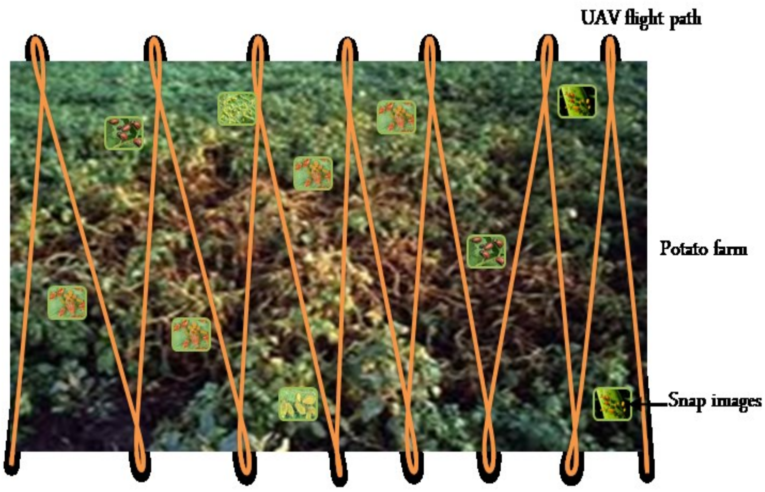


Figure 4. 9 **UAV Robotic Drone snapped shots on infested field**

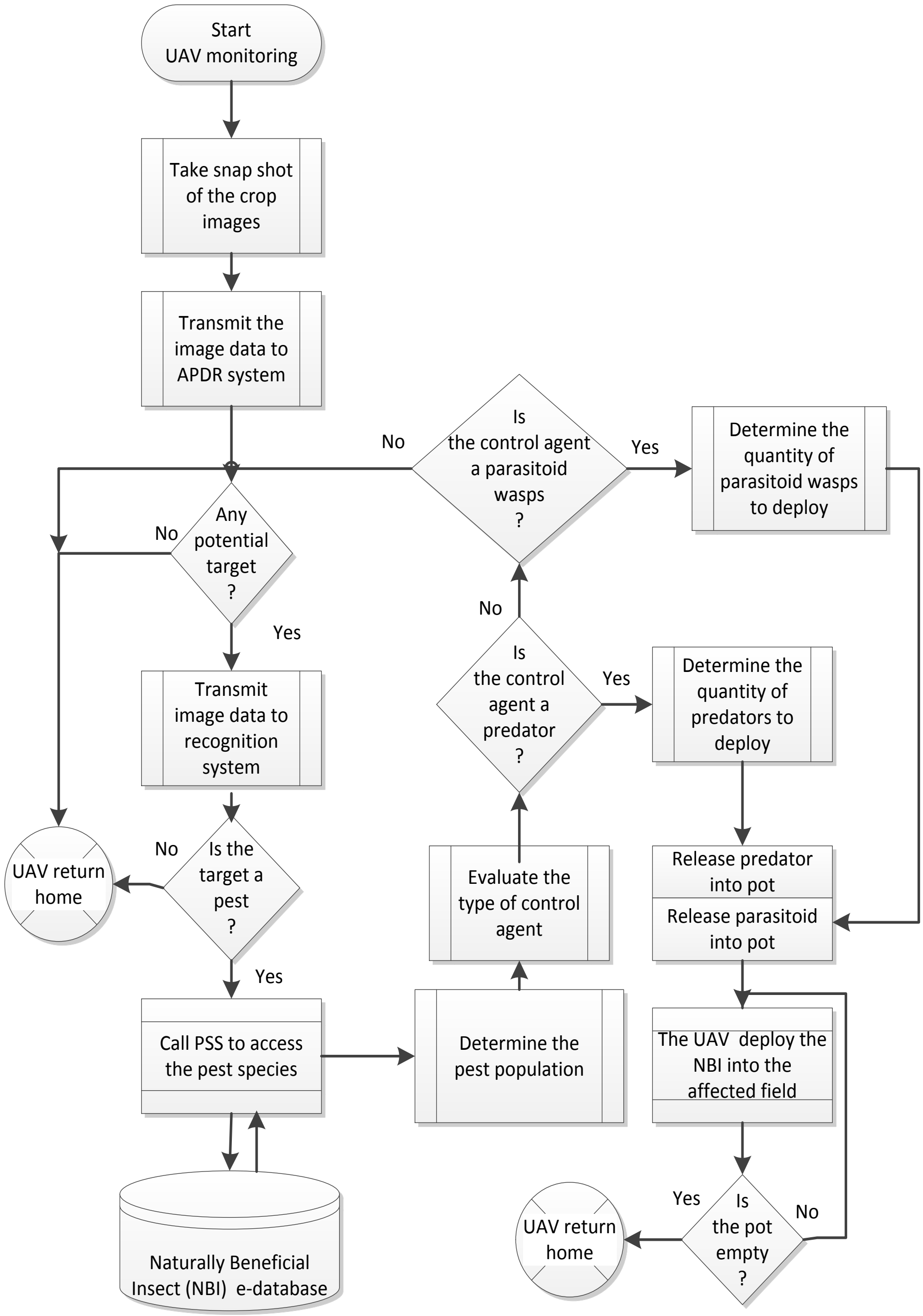


Figure 4. 10 Proposed flowchart for the operation of the ARDMS

The UAV Robotic drone function is to survey the crop field as shown in Fig. 4.2, through the programmed flight path, taking images as shown in Fig. 4.8 to Fig. 4.9.

Thereafter, send the snapshot of the images taken from the field to the Automatic pest Detection and Recognition algorithm (APDRS) and the Automatic Pest Predators/ Parasitoid wasps Statistical system (PSS) for processing and analysis. After the statistical estimation of the possible pest population density by the PSS system, the UAV robotic drone is expected to convey and deploy all the natural beneficial enemies (NBIs) of the pest that will be necessary for the total control of the pest population through the same flight path to the field.

After an interval of one week, the UAV Robotic drone will still be expected to repeat the surveillance activity and repeat all the processes to ascertain the level of pest control achieved by the natural beneficial insects deployed earlier. For more information on the ARDMS mechanism of operation, view the ARDMS mechanism of operation flow chart of Fig. 4.10.

4.8 CONCLUSION

This chapter describes the capability of the Automatic Robotic Drone Management System (ARDMS) for use in controlling the invasion of several categories of harmful pests in the agricultural environment. A dedicated box that enables the smooth carriage and deployment of several classes of the naturally beneficial insects automatically was designed, it uses solenoids switching circuits (SSC) to control NBI delivery. This chapter has added a new feature to the existing UAV designs.

This system can be used to keep the population of harmful pests under control. This system is able to reduce the stress on typical farmers as the major work of inspection, surveillance, control and NBI deposition is performed automatically by the robotic system. This system also promotes increased food security, increasing the quality and quantity of food produced as chemical pesticides and insecticides should no longer be used in the agricultural environment. This system is efficient, reliable, cost effective and safe. The expansion of this research will centre on complete automation of all the subsystems and further development of advanced hybrid algorithms.

CHAPTER -5-
PEST POPULATION DENSITY CONTROL

CHAPTER -5 - PEST POPULATION DENSITY CONTROL

5.1 PEST POPULATION DENSITY

Pest population density control refers to a formidable means of controlling the density of pests that has reached its Economic Injury Level (EIL). EIL is a level at which the damage induced by the pest can no longer be tolerated thereby initiating control measures. The growth of pest population in any habitat depends upon a simple birth, death, immigration and emigration process and the control of the growth is considered over a finite time interval.

The amount of damage done by the pest at any given time depends on the size of the population at that time, which depends greatly on the initial pest population, the birth and death rates, and the rates of migration and emigration within the habitat.

In real time when pests invade and start destroying a field, the immediate control action might consist of treating the field with chemical pesticides, and spraying the crops. The cost implication of the pest population include the cost of the action taken to eliminate the prevalent pest, the cost of the loss of crops, cost of the labour and materials (amount spent to purchase insecticides). If the pest is an intermediate disease carrier like the mosquito, it can also spread infectious disease, (Wilcox and Ellis, 2006); yellow fever virus, (Souza et al., 2010); dengus fever, (Whitehorn and Farrar, 2010), (Reiter, 2010); Chikungunya fever, (Caglioti et al., 2013), (Hawman et al., 2013), Japanese encephalitis, (Ghoshal et al., 2007), (Schiøler et al., 2007); Meningitis, (Ginsberg, 2004), (van de Beek, et al., 2006); Urticaria, (James et al., 2005), (Champion et al., 1969); West Nile virus, (Nash et al., 2001), (Klenk et al., 2004) and Dirofilaria immitis, (Cancrini et al., 2003), the canine heartworm disease (*Dirofilaria immitis)* (Ettinger et al., 2010), filariasis (*Wuchereria bancrofti, Brugia timori and Brugia malayi*) (Melrose, 2002), O'nyong-nyong fever (Posey et al., et al., 2005), Brain tumor viruses (Lehrer, 2010) and Malaria (White et al., 2009), (Hay et al., 2005), (De Silva et al., 2012), & (Maguire et al., 2002) all of which causes risk and major challenges, which can possibly result in illness and death.

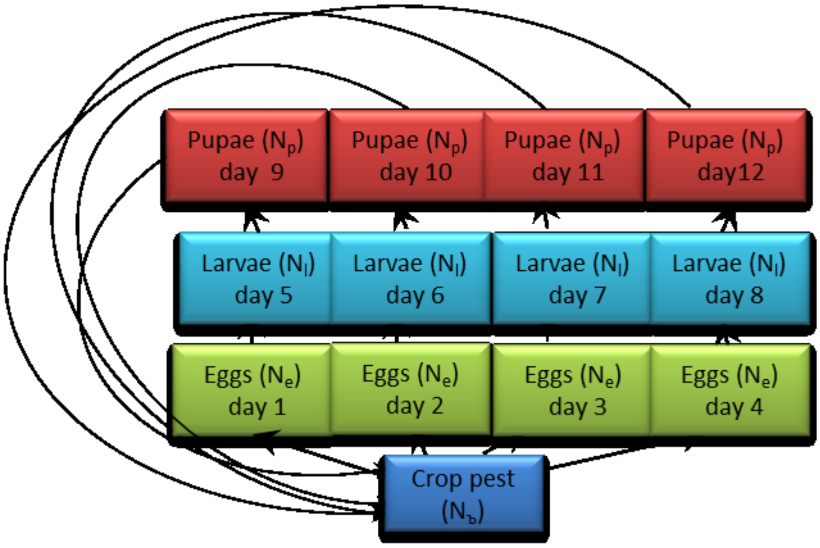


Figure 5. 1 Demonstrative Life cycle of a typical crop pest (Moth).

From Fig. 5.1 we can observe the reproductive life cycle of a typical crop pest (diamondback moth) illustrating how the reproductive stages change with time (in days), if the reproductive cycle continues without interference from environmental forces. In Fig. 5.1, an example of population inflow and outflow is demonstrated as the moth lays the eggs and with time the eggs transform into larvae, then to pupae and finally to adults.

The most difficult challenge to over-come by world growers according to (Ruizhen et al., 2012) is pest control. Growers had used special models like weather–based models to predict the presence of pests and explore the necessary control measures based on the report of the model according to (Jiang et al., 2008). There has been a lot of research on the best methods of pest control, one such control method is predation, (Samit et al., 2013) that leads to oscillation in the density of the pest population. Pesticide application, (Becker, 1990), a method that should be improved upon because of its risk factors to human health. The sterile insect technique (SIT) is a species-specific and environmentally non-polluting method of insect control that relies on the mass rearing, sterilization, and release of large numbers of insects (Krafsur, 1998), a modification to the sterile insect technique by the use of transgenic insects homozygous for a dominant, repressive, female-specific lethal gene system (Thomas et al., 2000). Wolbachia-induced cytoplasmic incompatibility (Bourtzis et al., 2004); (Sterling et al., 1998); (Stimac & O'Neil, 1995) provide evidence recognizing the importance of natural enemies in effecting the regulation of pests. The research based on Sterling (1998), the Integrated Pest Management system (IPM) is gaining interest in regard to environmental impacts according to the (United States Protection Agency, 2011), (BioControl Reference, 2006), (Hilary, 2010), (United States Environmental Protection Agency, 2012), (IPM Guidelines, 2009) and (Solis-Sanchez et al., 2011). The IPM system is a very good scientific method of pest control that can be made an autonomous system to grow with the pace of sustainable technology especially on pest identification and the deployment steps of the natural beneficial enemies of the pests using the proposed Optimisation Statistical Pest Control Model (OSPC).

To solve the pest problems, the chemistry of the various species in question must be made obvious or known. This study has organised the e-database of the most important pests in our studies as shown in Table A0.1 to Table A0.5 - Appendix A0

5.2 PEST E-DATABASE

The Pest e-database in this study consists of the most important pests, which have caused significant threats to food supply and medical concerns for many nations of the world. (Wright, 2005) has acknowledged several classes of such crop pest as illustrated in Table A0.1 to Table A0.5 - Appendix A0

5.3 NATURALLY BENEFICIAL INSECT (NBI)

The system aims to protect agricultural habitats from harmful pests and application of toxic pesticide chemicals that pollute the environment as a result of controlling pest infestation. Pest management requires frequent and accurate observation of plants to detect and control the population of unwanted insects colonising the habitat. The priority is early detection and control of the unwanted pest invasion. This early monitoring of pest outbreak can be achieved using automatic vision systems or manual methods and then controlled by using naturally beneficial insects (NBIs), which are predators of the pest. This avoids the use of toxic chemical pesticides.

The NBI e-database has its insects divided into groups of: endoparasitoid, ectoparasitoid and predators according to the various characteristics the predators or wasps' exhibit. The works of (Potting et al., 1995), (Lemckert, 2000), (Mattiacci et al., 1995), and (New, 1991) have shown that wasps exhibiting particular behavioural characteristics that fall into more than one group. Therefore for easy identification and allocation of the required assignment, based on our work, the insects are classified as shown in Fig. 5.2 to Fig. 5.4

Parasitiod wasps and insect predators play a very important role in pest management and can provide assistance in reducing the environmental damage and harm to human health caused by chemical pesticides. Major ailments like cancer and other life threatening diseases are frequently caused by exposure to pesticides. It is important to understand the problems emanating from environmental pollution and overcome the lack of awareness of its damaging effects, which exposes humans, different species of wasps and beneficial insects to the risk of death and extinction.

It is therefore important to be aware of the different types of parasitic wasps and other beneficial insects, their mode of operation and how they can be protected. We believe that the first step is to build-up an e-database for ecologically beneficial species.

Parasitoid wasps are organisms with predatory and parasitic characteristics. (Quicke et al., 1999), noted parasitic wasps are principally arthropods, some of which belong to the family Braconidae. Parasitic wasps have the tendency to turn the prey (host) into living larders for their larvae, as they lay their eggs in the bodies of other living organisms, with the consequence that the host will be consumed or die. Parasitoids use viruses and bacterium to form an evolutionary alliance with infection to serve as strong biological weapons to subdue its prey (host) as identified by (young, 2009). Parasitoid wasps and predators are beneficial to farmers as they prey on the populations of agriculturally harmful pests. Controlled introduction of appropriate naturally beneficial insects can be made easy for farmers once an e-database is developed.

Historically, parasitic wasps are classified into the insect order Hymenoptera, which are the most species rich group of insects in the world. Hymenoptera have 2 pairs of wings, though some may be wingless, they undergo complete metamorphosis (transformation in four distinct stages). They are carnivorous or insectivorous except for sawflies and gall wasps. Research by (Fitton, et al., 1990), (Crosskey, 1951), (Richards, 1980), (Bolton, B. & Collingwood, 1975), (Morgan, 1984), (Eady, & Quinlan, 1963), and (Blood, 1922), (Greathead, 1976), (Greathead, et al., 1983), (Yu et al., 2011), (Niehuis et al., 2012), (Buffington et al., 2007), and (Gibson et al., 2007) illustrated possible parasitoids classification of some known wasps that are relevant to biological pest control. There are many species of NBI classified into parasites, parasitoid wasps and predators. In this study, we shall limit our findings to some useful parasitoid wasps and predators for biological pest control, as shown Table A0.6-Appendix A0.

5.3.1 THE NBI E-DATABASE CLASSIFICATION

Parasitoids wasps are classified into Endo-parasitoids (those that lays their eggs inside a host) and Ecto-parasitoid (those that lays their eggs outside the host body)

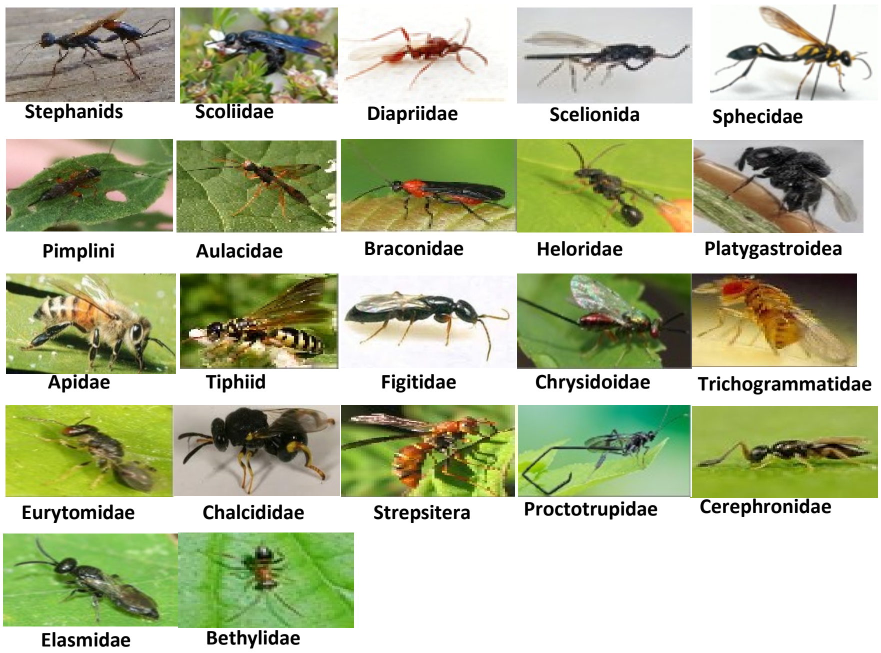


Figure 5. 2 Endo-parasitoid wasp e-database

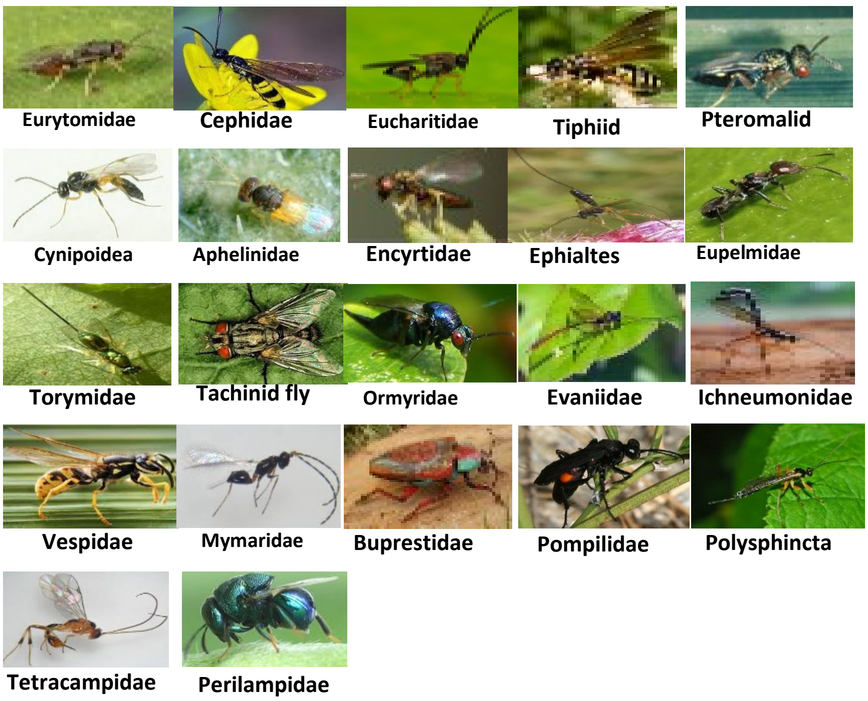


Figure 5. 3 Ecto-parasitoid wasp e-database

Predators are organism that capture and consume other organisms (prey).

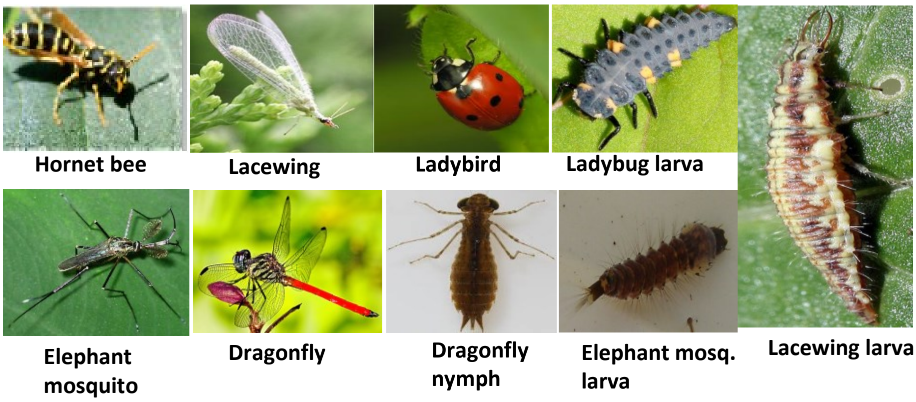


Figure 5. 4 Predators e-database

5.3.2 MECHANISM OF OPERATION OF THE NBI (PARASITOIDS WASPS)

(Maure et al., 2011), showed experimentally how wasps (*Dinocampus Coccinellae*) locate a ladybird then oviposit between the host's abdominal plates, with a single egg laid inside the host. The egg matures and hatches into a larva which feeds off the living beetle. At full age, it severs the host’s leg nerves to paralyze it and makes a tunnel out of its abdomen to weave a cocoon between the host’s legs. Maure noted that “the grub on the host does not consume all of its vital organs at once; it partially paralyses the host and manipulates its behaviour to favour its course of development” (Maure et al., 2011). Once the larva emerges from the host, it spins a silken cocoon between the host’s legs and slowly transforms from the pupa stage into an adult. Meanwhile, the host still remains watchful and vigilant over its own parasite as it sends warning signals using its bright colours of red, yellow and black to deter any invading predators from coming closer to the wasp larvae .

(Grosman et al., 2008) experimentally illustrated the exploitative activities of Braconidae parasitoid (*Glyptapanteles sp.*) wasps as it laid up to 80 eggs inside the host (the caterpillar) on a single pass. *Thyrinteina leucocerae* acted as a lifeguard of the parasitoid pupae. After the parasitoid larvae completed its development in the inside of the caterpillar, it eventually forces its way out from the host to pupate, the host starves whilst keeping watch over the pupae and scaring away creatures that naturally prey on the parasitoid pupae as demonstrated by (Gel & Libersat, 2010), the caterpillar protects the pupae using violent head-swings and finally the host dies without reproducing or reaching adulthood.

(Gess et al., 1980), (Day, 1988) and (Chrisraper, 2013) demonstrated the activities of *Polysphincta tuberosa* (Ichneumonidae: Pimplinae) wasps on its victim the spider (*Araniella cucurbitina)*; (Harmer, 2010) and (Salleh, 2000), demonstrated the activity of the female (*Hymenoepimecis* sp.) wasp sting on the spider (*Plesiometa argyra).* The research work showed how some species of wasps locate (Ngi-Song, et al., 1996) and paralyse their host before they eventually lay their egg on the front side of a spiders abdomen but the egg continue to develop whilst living outside the host's body. When the egg hatches into larva, the larva remains in the same position and pierces the host's skin to drink its blood and suck the vital nutrients from the host's body for its own development.

5.3.3 MECHANISM OF OPERATION OF THE NBI (PREDATORS)

Predators are usually larger and attack the prey in large numbers. Most predators like the dragonfly, ladybird and lacewing feed on wide range of insects *(mosquitoes, aphids, caterpillars, eggs etc.)* while some like the feather-legged assassin bugs are specific as they target particular species of prey (eg ants). There are some that do kill their victim immediately, among these categories are the adult and young species of the praying-mantis, dragonflies and damselflies, lacewings, scorpion flies and alderflies. There are several classes of predation, but this work is limited to the insect feeding predators like the dragonflies and damselflies, lacewings, elephant mosquitoes, ladybird, and beetles, as illustrated in Fig. 5.4 above

5.3.4 STRATEGIES OF OPERATION OF PARASITOIDS AND PREDATORS

(Edson et al., 1981) illustrated how parasitoids inject venom, which paralysed but also modifies the host's tissues making the host more nutritious for the developing wasp larva and help to overcome the host's immune systems just prior to the egg laying moment. Edson further demonstrated the use of polydnaviruses (also known as Poly-DNA-viruses), which protects the developing parasitoid larvae by targeting and disabling the host's immune system. The parasitoid larva continues to develop inside the body cavity of their host and only kills the host when it pupates.

(Ivanova-Kasas, 1970) illustrated the laying of an egg directly into the host's brain (ganglion), where the immune system is unable to encapsulate it.

(Askew & Shaw, 1986), parasitoid wasps' larvae prevent the death of its host by the release (secretion) of chemicals with antibiotic or antiseptic properties as they move around the host's body cavity damaging and eating non-essential areas like body fat and the reproductive organs.

Parasitoids wasps used teratocytes (this are bundles of cells that emerge from the egg with the embryo) to absorb food from the host body cavity that sustains the parasitoid until it is necessary to feed on the host's tissues directly.

According to (Underwood), a single egg may divide to form many new eggs, which developed into larvae, for example about 1500 embryos have been counted after Encyrtidae oviposition into a single caterpillar. (Ivanova-Kasas, 1970), illustrate Polyembryony, a state whereby a single egg continues to divide producing several independent larvae.

(Reed et al., 1995) olfactory response by parasitoid wasps to odor of plants when pest (aphids) invades the plant.

(Adamo, 1997) demonstrated how the parasites altered the behaviour of the host by inducing the host's immune system to produce the appropriate neuromodulators, which gives the animal the behavioral flexibility it needs to survive in a complex changing environment. For instance the parasitic wasp, (Cotesia congregate), according to (Adamo, 2002) in his work on modulating the modulators prevents the host from eating food partially by influencing the host (Manduca sexta) to increase the octopamine concentration in its blood-like fluid or hemolymph, which assist in the starvation of the host by preventing food intake. Polymorphus paradoxus (Acanthocephalan) changes the elude behaviour of its host, (Gammarus lacustris (Crustacea)), possibly through an effect on the host's serotonergic system. The trematode (Trichobilharzia ocellata) restrain egg-laying in its snail host (Lymnaea stagnalis), partially by influencing the host to secrete schistosomin, which decreases excessive sensitivity of the caudodorsal cells.

The host is only partially paralysed by the wasp's venom and soon will recover to protect the developing wasps;

5.3.5 STRATEGIES OF OPERATION OF PREDATORS

The various strategies of NBIs as illustrated by Underwood are thus:

- ✓ Predators can kill and devour as many prey as possible to reach adulthood or maturity.
- ✓ After an initial contact or meal, further searching involves more frequent trials which may result in the predator remaining or living in the same general location.
- ✓ Insect predators like coccinellids, syrphid larvae, and lacewings usually search for their prey randomly
- ✓ Predators like robber flies and dragonflies have enormous compound eyes for detecting their prey even in flight.
- ✓ Many predators use chemical signals and sound produced by the prey for intraspecific communication and location.

- ✓ Odonata larvae rest concealed in submerged vegetation waiting for prey victims to pass by.
- ✓ Predators like dragonfly adults employ one form of ambush hunting tactics to dart out and capture prey on the wing much like the flycatchers of the bird world.
- ✓ Predators with piercing-sucking mouthparts can as well inject enzymes into the prey then suck up all the vital nutrients (pre-digested liquid) (extraoral digestion) from the prey body. This is obviously a more efficient way of killing lots of prey than eating the whole body of the organism.

5.4 ECONOMIC IMPORTANCE OF NBIs (PARASITOIDS WASPS AND PREDATORS) AS A CONTROL AGENT

- ✓ NBI are extremely important in checking and controlling the large populations of pests. Research has shown that in response to an attack by insects, some chemicals are released by plants, which actively attract parasitoids wasps and predators.
- ✓ NBIs encourage nutrient recycling as most of the dead host is decomposed back into the ecosystem.
- ✓ The presence of NBIs in an ecosystem will put the activities of pest and its population under severe check.
- ✓ Indiscriminate application of NBI enemies of the pest will be avoided.
- ✓ Food security and security of life will be guaranteed, that means a healthy nation and a healthy economy as most of the illness being transmitted by pests as a result of pest outbreaks will be minimised.
- ✓ Financial success from crops as well as healthy and friendly environment devoid of chemical pesticide poisons will be attained.

5.5 CONCLUSION

In this section we have concentrated on understanding more about pest population density control, the strategies beneficial insects use to exploit the pest population, the economic importance of NBIs and why they should be protected. We have identified several species of both pest and naturally beneficial insect (NBI) in e-databases, to enable successful detection and control of the Pest .

CHAPTER -6- MODELLING TOOLS FOR PEST CONTROL

CHAPTER -6- MODELLING TOOLS FOR PEST CONTROL

6.1 INTRODUCTION TO MODELLING TOOLS

To implement Integrated Pest Management (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 the pest population below an economically acceptable threshold, thus reducing the damage to crops. The goals of statistical optimization of a biological control system are to:

- Maintain the density of the pest population at an equilibrium threshold below the economic damage level.
- Reduce the pest population to a low level but not to completely destroy them as can occur with the use of pesticides.
- Publicize the effectiveness of biological control systems and their sustainable control capabilities.

(Barclay, 1970) noted 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.

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 predatory population densities on the pest population.

As an illustration of the concept, we propose a mathematical model of the interaction between several pest populations and the appropriate species of NBIs for the various pests. The pest populations considered include: diamondback moths, aphids, Spodoptera Exempta, Scarab beetles and classes of mosquitoes and the species of the naturally beneficial insects considered are parasitoids wasps and predators.

To optimize total control of the pests population density, a model of the interaction between the crop pests and the 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 and predator/prey capture probability based on the Pascal distribution. The crop pest is present in all its life-cycle stages of: egg, larva, pupa and adult. The beneficial insects (parasitoid wasps or predators) may be present in either or all parasitized pest lifecycle stages: eggs, larva, pupa and adult.
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 the Naturally Beneficial Insect (NBI) that target 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 one or two or all of the life cycle stages of the species of the NBI, which permanently or partially destroy pest: egg, larvae, pupae and adult stages. The selected scenarios shown below demonstrate effective sustainable control of the pest within a number of days.

6.2 NUMERICAL MODEL OF THE INTERACTION BETWEEN THE PEST (HOST) AND NBI

The numerical model of the interaction considers several variables and employs several strategies of which single species or combined species of several classes of NBI may be used depending on the case being studied to verify its effect on pest management. To illustrate the concept, we propose a mathematical model of the interaction between populations of the pest's life cycle stages: the egg, larvae and pupae with NBI (parasitoid wasps and predators).

6.2.1 PARASITOID WASPS USED FOR THE MODELLING

The various classes and species of the parasitoid wasps used for the different models include: egg, larval and pupal parasitoid wasps.

The egg parasitoid wasps considered in this research work is the *Trichogramma* wasp*.*

The *Trichogramma* 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, (Knutson, 2005 & 1998). The female egg parasitoid usually locates pest eggs within the crop by the use of chemical and visual signals like the eggs shape and colour, (Davies et al., 2011) and (Polaszek et al., 2012). After inspection (antennal drumming), it will often drill a hole into the chorion and insert an appropriate number of eggs. The adult wasps live anywhere from 7 to 14 days. The females will parasitize up to 300 pest moth eggs in her life span, laying one or more eggs inside each moth egg, (Flanders et al., 1960) and (Smith, 1996)

The larval parasitoid wasps considered are the *Tachinidae, Cotesia Flavipes (Cameron),* Scoliid*,* and *Diadegma semiclausum* wasps.

6.2.1.1 LARVAL PARASITOIDS/ WASPS

The *Tachinidae* larvae parasitoid employs different strategies of oviposition to attack its host, (Imms, 1977) noted *Gonia, Sturmia* and *Zenillia* as a species, which lays many thousands of matured “micro-eggs” on foliage near the host insect, and the eggs are ingested during feeding by the host after which they hatch immediately into larvae. (Imms, 1977) also noted *Winthemia*, *Eutachina, Thrixion*, and *Gymnosoma* species as those that glue eggs to the body of the host, the larva penetrate into the host's body after the egg hatches. (Wood, 1987) identified *Plagia*, *Exorista* and *Voria* female species as possessing a piercing ovipositor, which is used to insert their eggs into the host’s body. In all cases, *tachinid* larvae feed internally in their hosts, after killing its host, the larvae exit the hosts body to pupate, (Stireman et al., 2006). The pupae are commonly oblong and dark, (Hoell et al., 1998). The

Larval development is usually completed in one to three weeks, as the lifecycle lasts for three to four weeks, only one larva survives within each pest (host) depending on the species, (Chaudhari, 2013), (Pickett et al., 1996) and (O'Hara et al. 2008)

The *Cotesia Flavipes (Cameron)* is a braconidae gregarious larval endoparasitoid wasp, which can lay 40 eggs in the host larva, (Kfir, 2002) 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, 1996).

Scoliidae wasps as illustrated by (Bhattacharjee & Raychaudhuri, 2010) are known as ground wasps, as they work their way through the soil, digging burrows in order to locate their prey, sting them (beetle larvae) and lay an egg on the paralysed insect, they cover the burrow on their way out, (Elliott, 2011). It has the ability to sting many grubs that never recover from the paralysis; it then lays a single mature egg on a few hosts, which hatch in about three days to continue their life cycle, (Barrat, 2003). After hatching, the scoliidae larva feeds on its host for approximately one to two weeks and then spins an underground cocoon, (Krombein, 1963) from which the adult wasp emerges in an average of about five weeks, the scoliidae wasp lays eggs continuously for two months and has a life span of 4 -5 months, (Misra, 1996), (Grissell, 2007) and (Yeates et al., 1999)

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 (Khatri et al., 2011, 2008).

The pupal parasitoid wasp considered is the *Diadromus collaris* wasp. This wasp carries eight matured ova at any given time, and the female oviposit them 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 (Lloyd, 1940) and (Liu et al., 2001).

6.2.2 PREDATORS USED FOR THE MODELLING

The species of predators considered are Ladybug *(coccinellidae),* (*Odonata)* and **(***Toxorhynchites).* The *(coccinellidae)* is used because of the predatory nature of the ladybug adult and larvae on the aphid pest population as illustrated by (Houdkova & Kindlmann, 2006), (Noma & Brewer, 2008), (Snyder et al., 2003) and (Kindlmann et al., 1999), (Fergusen et al., 1996). Snyder and Fergusen demonstrated the various strategies that the adult Ladybug and the larvae engage in to feed and kill hundreds of aphids.

The *Odonata* adult and nymph are recommended because the *Odonata* nymph is very effective in reducing the mosquito population by eating the mosquito: eggs, larva and pupa. *Odonata* adults are very important predators and a valuable ally for humanity as they feed on adult mosquitoes, especially when their populations are in abundance. (Singh et al., 2003) experimentally confirmed the feeding ability of the Odonata nymph for the control of several species of mosquitoes. (Dragonfly site, 2014) discussed the frequency of control of the dragonfly compared to mosquitoes and houseflies as thus: "the dragonfly is many times the size of a mosquito or a housefly and only needs to flap its wings a mere 30 times a minute when compared to a mosquito's 600 times a minute and the housefly's 1000 flaps a minute to maintain flight with peak manoeuvrability. Such is its power that the dragonfly is equipped with a low-energy high speed capability, very few insects can escape its basket shaped grabbing limbs that it uses to clutch on to its prey before crushing them into a gooey mass, with its powerful mandibles and swallowing it".

Toxorhynchites are unique in that none feed on blood and, unlike many other mosquitoes, they are harmless to mankind. In fact, the larvae of all *Toxorhynchites* are predaceous on other mosquito larvae or small aquatic arthropods, they are therefore beneficial to humankind. They have the ability to consume 10 to 20 mosquito larva in a day and up to 5000 during their whole larval stage, (Steffan & Evanhuis, 1981), (Focks et al., 1982) and (Goettle & Adler, 1999).

6.2.3 SELECTED CROPS FOR THE MODEL

Several field crops were considered for the model, namely: Cabbages, Sorghum, Maize, and root crop (cocoyam & potato)

Cabbages were 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 Brussels sprouts. 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 - *Trichoplusia ni* (Hubner) as described by (Shelton, 1982). For illustration purposes we only consider the diamond back moth.

Sorghum, also known as "guinea corn," a cereal grain originates from Africa, (Kimber, 2000) and is eaten throughout most nations of the world and is used for making flour, bread, porridge and pancakes (Hugo et al., 2003). Because of its high resistance to drought, it is appreciated in arid terrain, (Jordan et al., 1982. Guinea corn is a nutrient-rich grain with high nutritional and therapeutic benefits for decreasing risk of heart disease by decreasing blood cholesterol levels, (Carr et al., 2005); it is safe for people with celiac disease, (Ciacci et al., 2007); and protects against diabetes (Farrar et al., 2008); and inhibits colon cancer tumor growth, (Yang et al., 2009).

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.

Cocoyam as a root crop has great economic importance across many nations; apart from home consumption and cash crop sales on local markets and export earnings, cocoyam has important cultural attributes: it plays a part in traditional exchanges and social obligations - marriage ceremonies, religious commitments and reconciliations. It is a tropical starchy root crop, which is a staple food in many subsistence communities, particularly in Nigeria and across many nations including the Pacific islands, (Iwuoha, & Kalu, 1995). Cocoyam with its high dietary fiber content is very rich in vitamin B6 and magnesium, which helps control high blood pressure and protect the heart and is good for glucose metabolism. For most of the Nigerian communities, cocoyam is an essential part of their diet, it makes up almost 20% of daily calorific food intake and it is easily digestible, (Fitday, 2014).

Using data from the cited publications we modelled the interaction of the NBI species with the pest: egg, larva, pupa and adult using a negative binomial distribution sometimes known as a Pascal distribution to determine the frequency with which predators capture prey or the probability that a parasitoid wasp locates and attacks its host.

6.3 THE FREQUENCY, EFFECIENCY AND PROBABILITY OF CAPTURING PREY AND HOST

The negative binomial distribution evaluates the distribution of the number of trials needed to get a fixed number of successes (r) (Villarini et al., 2010) and (Hilbe, 2011). The negative binomial distribution has found useful applications in several areas including the fitting of several frequency distributions of different biological data, (Bliss, 1953). The enquiry into the frequency distribution of multiple events with particular reference to the occurrence of multiple attacks of disease or repeated accidents, (Greenwood et al., 1920). The consideration of the problem of mortality curve fitting over the entire life range, (Hewatt, 1960) and (Gray & Bennetts, 1996) analysed organism frequency count data using the negative binomial distribution.

We decided to use a negative binomial distribution since it is an appropriate method when representing sequential sampling when the objective is to continue sampling until a certain number of successes has been achieved. We consider the use of the negative binomial probability distribution function (pdf) of equation 6.1 to 6.4, to determine the frequency with which predators capture prey and the probability that a parasitoid wasp locates and attacks its host or the host search efficiency of attack as shown in the program of Appendix A2

Therefore Efficiency (ξ) may be consider as the lowest amount of energy the host required to attack its prey. This actually implies the search efficiency of contact.

However, to be consistent with a more general interpretation of the negative binomial distribution. The probability that the random variable X takes on a value less than or equal to x is given as

$$F_X(x) = P(X \leq x)$$

Let x be the number of trials needed to achieve a success and r be a fixed number of independent successful trials. If

P(Success) = p which is kept constant in all trials and

P(Failure) = 1- p =q

Then the probability that the r^{th} success is likely to occur on the x^{th} trial is given by equation 6.1.

$$y = f(x|r,p) = \binom{r+x-1}{x} p^r (1-p)^x \; I_{(0,1,2,\dots)}(x) \qquad \text{Eqn. 6.1}$$

$$\binom{r+x-1}{x} = \frac{(r+x-1)\ \dots .(x)}{r!}$$

$$y = F(x|r,p) = \sum_{i=0}^{x} \binom{r+i-1}{i} p^r (1-p)^i \; I_{(0,1,2,\dots)}(i) \qquad \text{Eqn. 6.2}$$

The mean of the probability distribution is $\eta = \frac{r}{p}$ Eqn. 6.3

Equation 6.1 and Equation 6.2, returns the negative binomial "Pdf" and "Cdf" at each of the values of 'x' using the corresponding number of successes, 'r' and probability of success in a single trial, 'p'. Where X is the number of trials needed to achieve a particular success rate 'r' and 'η' is the mean of the distribution and 'σ^2' is the variance.

The simplest motivation for this model is the scenario for the successive random trials that the NBI undertake, with each attempt having a probability of success 'p'. The number of attempts that the NBI must perform in order to capture or parasitize a given number of prey r has a negative binomial distribution, where 'I' is the indicator function, which ensures that 'r' only adopts integer values as shown in Fig. 6.1.

Therefore, considering the life span of the predators *Toxorhynchites* larvae, and *Odonata* adult and nymphs and their feeding habits extracted from research works, the frequency of capturing their prey can be modelled using the negative binomial function as illustrated in Fig. 6.1 as demonstrated in the program code of Appendix A2.

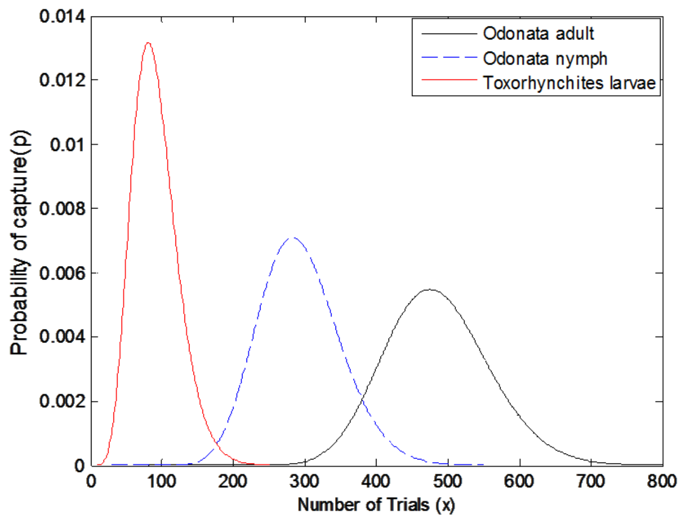


Figure 6. 1 Predation success probability distributions for *Odonata* and *Toxorhynchites*

6.4 MORTALITY OF THE PEST AND NBI

The Weibull distribution is a probability distribution function designed to describe failure, as it is suitable for modelling certain event waiting times. It has been established as the most popular model for describing failure times because it is widely used to model the lifetimes of system components. For this reason, we used this model to estimate the death rate of all the classes of pest and NBI.

To determine the mortality rates of the various stages of the pest and the NBI, to enable accurate development of the pest control model a Weibull probability model was used.

Weibull analysis is frequently used with small sample sizes, for this very reason the slope (ψ) and the characteristic life (θ) are usually estimated by a graphical technique as described by (Chatfield, 1992) and (Ostle et al., 1996) in their work on the Weibull distribution function.

The parasitoid wasp, the predators and pest mortalities (m) used in the design of the pest control system were determined by the use of a distributive function as illustrated in eqn. (6.5) to (6.10) and Table 6.1 column 8.

$$X \sim W(\psi, \theta) \qquad \text{Eqn. 6.5}$$

$$m = \frac{f}{R} = \frac{\psi}{\theta}\left(\frac{x-\gamma}{\theta}\right)^{\psi-1} \qquad \text{Eqn. 6.6}$$

at γ = 0 then

$$m = \frac{\psi}{\theta}\left(\frac{x}{\theta}\right)^{\psi-1} \qquad \text{Eqn. 6.7}$$

Where

θ = scale parameter or characteristic life

ψ = Slope or shape parameter

γ = failure free life or location parameter

x = age factor (life span)

m = mortality

To obtain the intercept of the Weibull distribution, equation 6.8 is applied as

Intercept = $-\psi \ln(\theta)$ Eqn. 6.8

To calculate the least square line equation based on the plotted points $x_{(1)} \ldots. x_{(n)}$, as shown in Table 6.1 column 2, then b_1 will be estimates for the slope (ψ) and b_0 for the intercept $[-\psi \ln(\theta)]$, such that $\psi \approx b_1$ and $\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$ as shown in Table 6.1 column 5 & 7.

A graphical technique as shown in Fig. 6.2 was used to determine the slope (ψ).

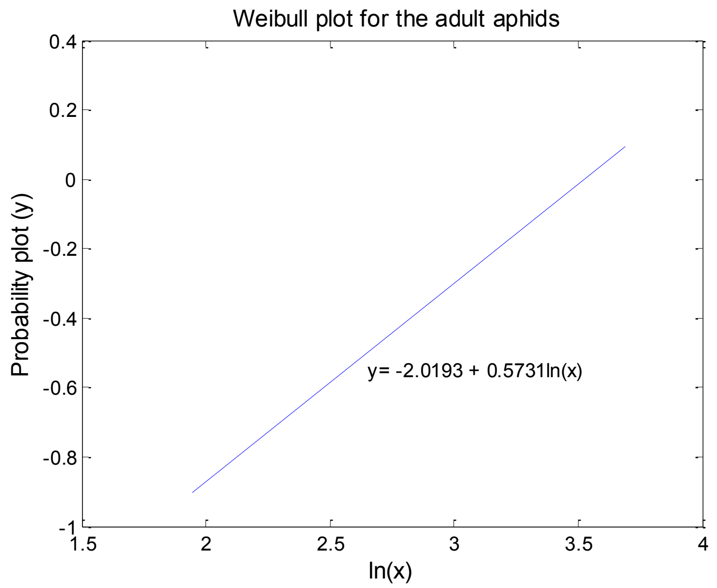
This technique considers the age factor (x) Table 6.1 column 2 and the probability distribution function (y). The variable (x) is estimated using the minimum and maximum life span of the insects, Table 6.2 and Table 6.3. p_i the distributed data points Table 6.1 column 4 are calculated from equation 6.9, while y_i the probability function is determined from eqn. 6.10, where n is the total number of data points. For more details see Table 6.1 and Appendix A5, for the program codes and Fig 6.2.

$$p_i = \frac{i}{n+1} \qquad \text{Eqn. 6.9}$$

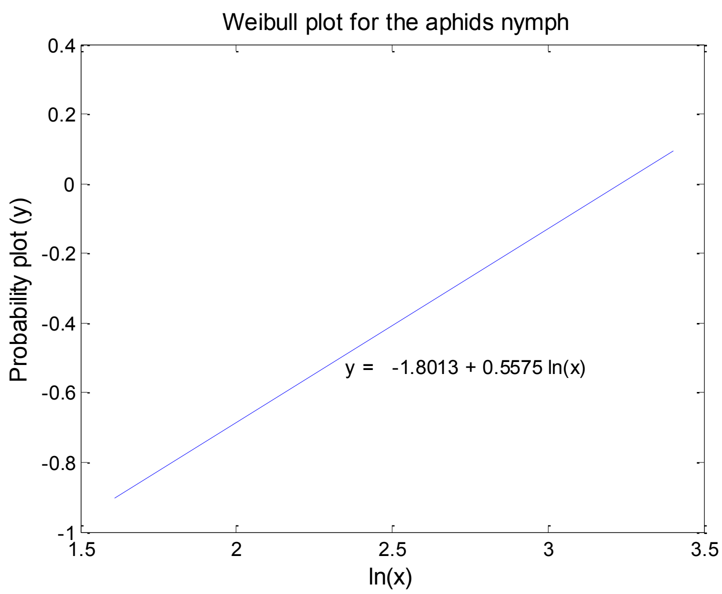
$$y_i = \ln\left[\ln\left(\frac{1}{1-p_i}\right)\right] \qquad \text{Eqn. 6.10}$$

Table 6.1 The mortality rates of the *Ladybug* species and *Aphids* species

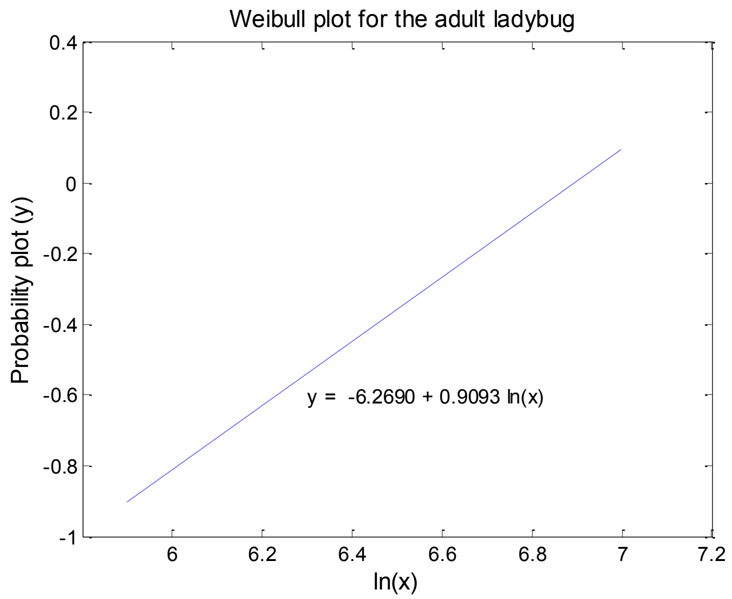
Variable name	Life span	ln (x_1 & x_2)	pi pii	ψ= b1	(b0/b1)	$\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$	Mortality
m_a^h	7-40	1.9459 3.6889	0.333-0.666	0.5731	-3.5235	33.9018	0.0016
m_a^e	120-154	4.7875 5.2204	0.333-0.666	2.3077	-5.1792	177.5454	0.014
m_a^n	5-30	1.6094 3.4012	0.333-0.666	0.5575	-3.2310	25.3057	0.0204
m_c^h	365- 1095	5.8999 6.9990	0.333-0.666	0.9093	-6.8943	986.6490	0.0000091
m_c^e	4-10	1.3863 2.3026	0.333-0.666	1.0903	-2.2154	9.1646	0.12
m_c^l	14-30	2.6391 3.4012	0.333-0.666	1.3109	-3.3286	27.9001	0.0481
m_c^p	7-14	1.9459 2.6391	0.333-0.666	1.4411	-2.5732	13.1083	0.113


Weibull plot for the adult aphids
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Probability plot (y)
y= -2.0193 + 0.5731ln(x)
1.5
2
2.5
3
3.5
4
ln(x)

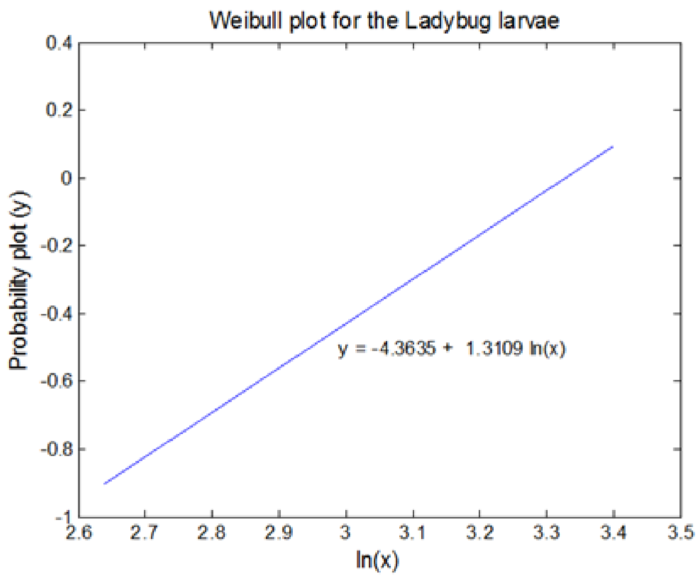
(a)


Weibull plot for the aphids nymph
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Probability plot (y)
y = -1.8013 + 0.5575 ln(x)
1.5
2
2.5
3
3.5
ln(x)

(b)



(c)



(d)

Figure 6. 2 Weibull plots of the aphids and the Predator (ladybug)

To determine the mortality rates of the various pests and NBIs used in the design of the pest control system as illustrated in Table 6.1 for the Aphids and ladybug, the life span of the various stages of the pest life cycle were used as shown in Table 6.2 and Table 6.3 and Table A0.7 to Table A0.15- Appendix A1 for every other pest and naturally beneficial insects.

Table 6.2 The Aphids life cycle stages (Bohmfalk et al., 2011) and (Buss, 2013)

Aphids life cycle and mortality rates	Gestation period
adult	7 - 40
Eggs in fall seasons	120 - 154
nymph	5 - 30

Table 6.3 Ladybug development stage as described by (Community Heritage Initiative) and (Touzan, 2013)

Ladybug development stages in favourable conditions	
Clusters of eggs hatch	= 4 - 10 days
Larva stage lasts	= 10 - 24 days
Pupa stage lasts	= 7 - 14 days
Adult lifetime	= 365 - 1095

6.5 EXPERIMENTAL DEMONSTRATION OF THE EFFECTIVE CONTROL OF THE NBI

To demonstrate the effective control of the various pest species and classes of NBI. Several cases of destructive pest infestation and NBI were simulated as illustrated below:

6.5.1 MODEL OF INTERACTION BETWEEN THE PEST (HOST) DIAMONDBACK MOTHS AND THE PARASITOID WASPS

As an illustration of the concept, we propose a 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 the three species of 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. 6.3, column 2.

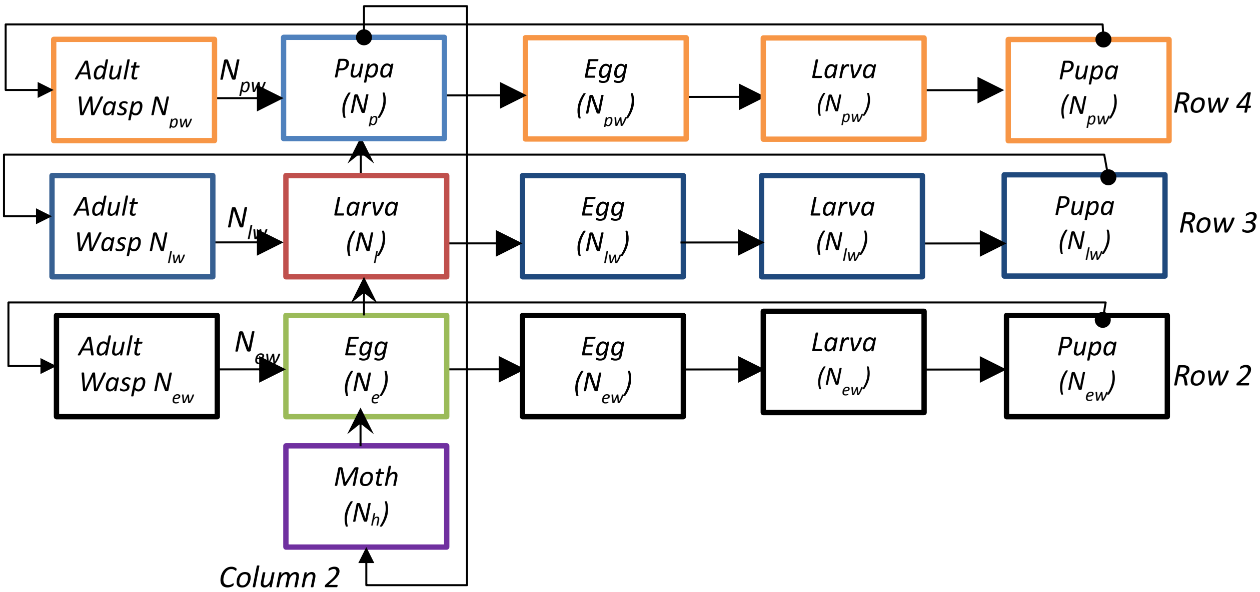


Figure 6. 3 Life cycle of the three species of parasitoid wasps demonstrating the requirement for a pest population for their existence.

From Fig. 6.3, column 2- 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. 6.3, an example of population inflow and outflow is demonstrated as the moth lays the eggs that with 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 A0.7-Appendix A1. In the case where there is interruption of the life cycle by the interaction with external forces, like parasitoid wasps, the population is altered as illustrated in Fig. 6.3 – row 2 to 4, 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 A0.8- Appendix A1.

6.5.1.1 ANALYSIS OF LIFE CYCLE OF THE THREE SPECIES OF PARASITOID WASPS

From Fig. 6.3, it is observed that parasitoid wasps cannot exist without their pest host.

Column 2- Fig.6.3, displays the reproductive life cycle of a moth. The arrows show the state flow from the adult moth after she laid her eggs, which hatch into larvae with time and transition to pupa and metamorphose into adults as the cycle repeats.

Row 2- Fig.6.3, 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, and 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 3- Fig. 6.3, 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 4- Fig. 6.3, 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.

6.5.2 DIAMONDBACK MOTH AND PARASITOID WASPS EXPERIMENTAL MODEL DEMONSTRATION

A 700m^2 cultivated field has 2,100 to 3,500 typical Cabbage plants, with each plant having 26 to 35 open leaves (Tonnang et al., 2010), The environment contains: host diamondback moths (*Plutella xylostella) and* its offspring: eggs, larvae and pupae, the egg parasitoid wasp *(Trichogramma*), the larval parasitoid wasp (*Diadegma semiclausum),* and the pupal parasitoid wasp *(Diadromus collaris).*

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 (*Trichogramma*) (aN_eN_{ew}), where a is the probability (evaluated from the negative binomial distribution, (May & Hassell, 1988) 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 – eqn. (6.11). The egg wasp offspring (ξaN_eN_{ew}), where ξ is the efficiency of turning prey into wasps, suffer a natural death rate ($p_{em}N_{ew}$), eqn. 6.12, 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 eqn. (6.12) 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 ($\mu\alpha N_l$), eqn. (6.13), where α is the leaf impact factor and µ is the leaf-larva coupling coefficient – (Hoffman et al., 2002). 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 eqn. (6.14) to model the wasps. Some of the larvae that changed to pupae *(λN_l)* transform into adult moths *(ρN_p)* (diamondback moths), where ρ is the fraction of pupae turning into moths, some pupae are parasitized by the pupal parasitoid (*Diadromus collaris*) *(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, eqn. (6.15). 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 – (Wang et al., 2002), 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 eqn. (6.16). 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 *$\{(\rho N_p - m_hN_h)\}$*, which controls the moth population N_h ,which is also limited by the moth environmental carrying capacity K_h , eqn. (6.17). The leaf population increases due to their growth *(δN_{lf})*, where δ is the leaf growth rate, some leaves are eaten by the larvae *($\gamma N_{lf}N_l$)*, where γ is the fraction of leaves eaten by one larva per unit time, eqn. (6.18).

6.5.3 THE INTERACTION BETWEEN THE HOST SPODOPTERA EXEMPTA AND LARVAL PARASITOID WASPS

An experimental simulation of a cereal crop (maize) 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. The pest 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) as shown in Table A0.10-Appendix A1, monitoring and treatment to prevent spreading, uncontrollable infestation and out breaks as shown in Figure 6.4.

Figure 6. 4 Pest (*Spodoptera Exempta)* Outbreak on weeds and maize crop
[*source:* Chikwenhere, 2013]

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 & Carl, 2014). We assume an initial equilibrium population density of 7 adult female Spodoptera Exempta (Se), which lay an average of 150 eggs per day.

As an illustration of the concept, we propose a model of the interaction between a population of *Spodoptera Exempta* moths (N_h) alighting on the maize crops 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. 6.5.

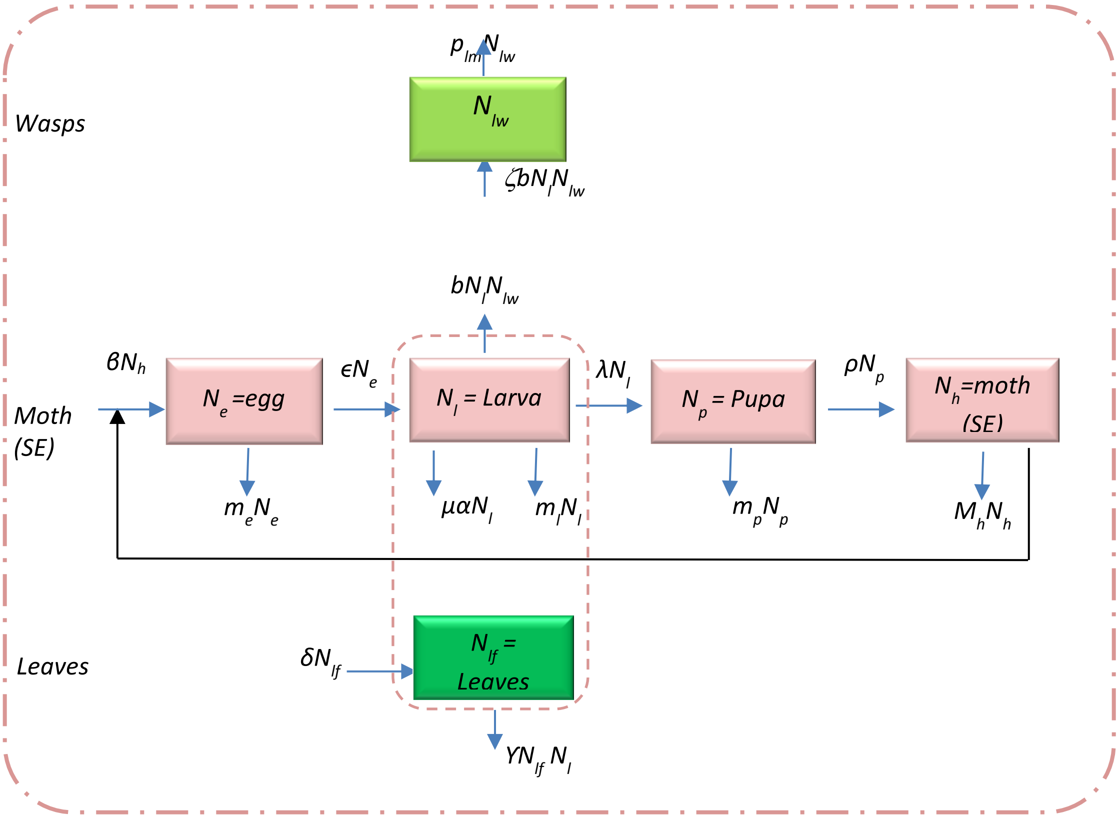


Figure 6. 5 Population dynamics schematic for wasp-pest-crop interaction model describing the detailed activities of how the *Cotesia Flavipes* wasps exercise control over host *Spodoptera exempta*, population in its habitat. (Faithpraise et al., 2014e)

6.5.4 THE INTERACTION BETWEEN THE HOST AFRICAN ARMYWORM AND EGG PARASITOID (TRICHOGRAMMA) AND THE LARVAL PARASITOID (TACHINIDAE) WASPS

We have simulate a habitat with 5 – 7 plants of sorghum per square metre with each plant having 8 to 22 leaves, (Tamworth, 2011), Fig. 6.6(a).

African armyworm moths alighting on newly green growing leaves after some showers of rainfall, Fig.6.6 (a) there is no initial population density of the African armyworm moth (N_h) life cycle stages: the egg (N_e), larvae (N_l) and pupae (N_p) stages are set to zero. To manage the pest invasion we introduce a population of egg parasitoids (N_{ew}) (*Trichogramma)* and the larval parasitoids (N_{lw}) (*Tachinidae*) wasps, using modelling we explore the possibilities for efficient pest control. This scenario is modelled by the following simultaneous, ordinary differential equations 6.19 to 6.25, which provide a continuous time dynamic model of the evolving pest, egg and larval parasitoids and the habitat sorghum field (leaf populations per m^2).To understand graphically how the populations of the pest-wasps-crop model interact see Fig. 6.7.

(a)

(b)

(c)

Figure 6. 6 Sorghum fields (a) newly grown leaves (b) Armyworm moth alighting on the field {*Wayne Bailey*, 2014} (c) Armyworm damage

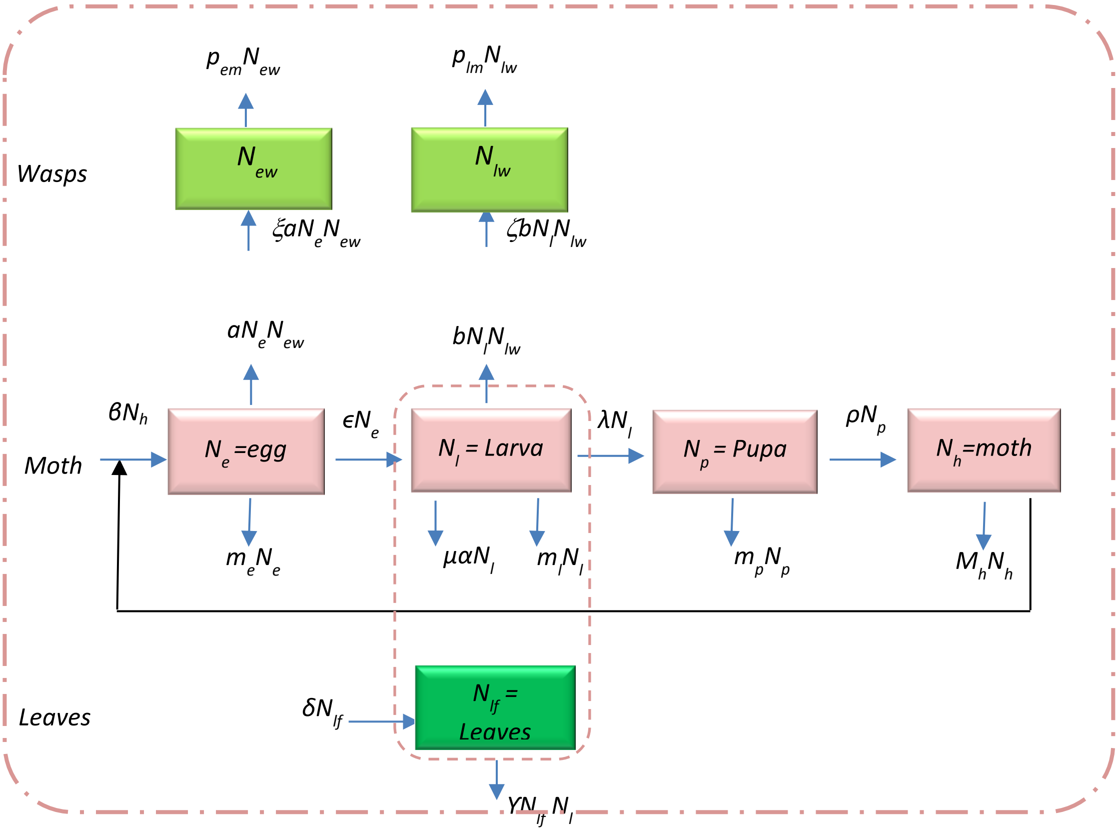


Figure 6. 7 Population dynamics schematic for wasp-pest-crop interaction model describing the detailed activities of how the Trichogramma and Tachinid wasps exercise control over pest (AAW) population in its habitat. (Faithpraise et al., 2014c)

6.5.5 THE INTERACTION BETWEEN THE HOST SCARAB BEETLES AND COMBINED (SCOLIID) AND (TACHINIDAE) LARVAL PARASITOID WASPS

Some pest are so robust that, it may require the combined effect of more than one wasp to gain effective control of the pest (host) in question, which is the case with the scarab beetles, (Illingworth et al., 1920).

The concept provides a general opportunity for the control of all classes and species of Scarabaeid larvae, as it is based on the interaction between the population of all species of adult Scarab beetles and its life cycle stages (egg, larvae and pupae) and the naturally beneficial insects (the *Scoliid* and the *Tachinidae* wasps) Fig. A0.11 –Appendix A1. Fig. 6.8 demonstrates the beetle – wasp interaction model. The blue arrows indicate the normal state flow of the life cycle of a scarab beetles, it demonstrates how the adult beetles lay their eggs, after a time, the eggs transform to larvae, which pupate and the turn into adult beetles. Once the Scoliid or Tachninid wasps lay their eggs in the beetle larvae as indicated by the pink arrow, the reproductive life cycle of the beetles is disrupted as the beetle larvae produce scoliid wasps or tachnind wasps rather than turning into pupae and then into beetles. This is indicated by the green boxes in Fig. 6.8.

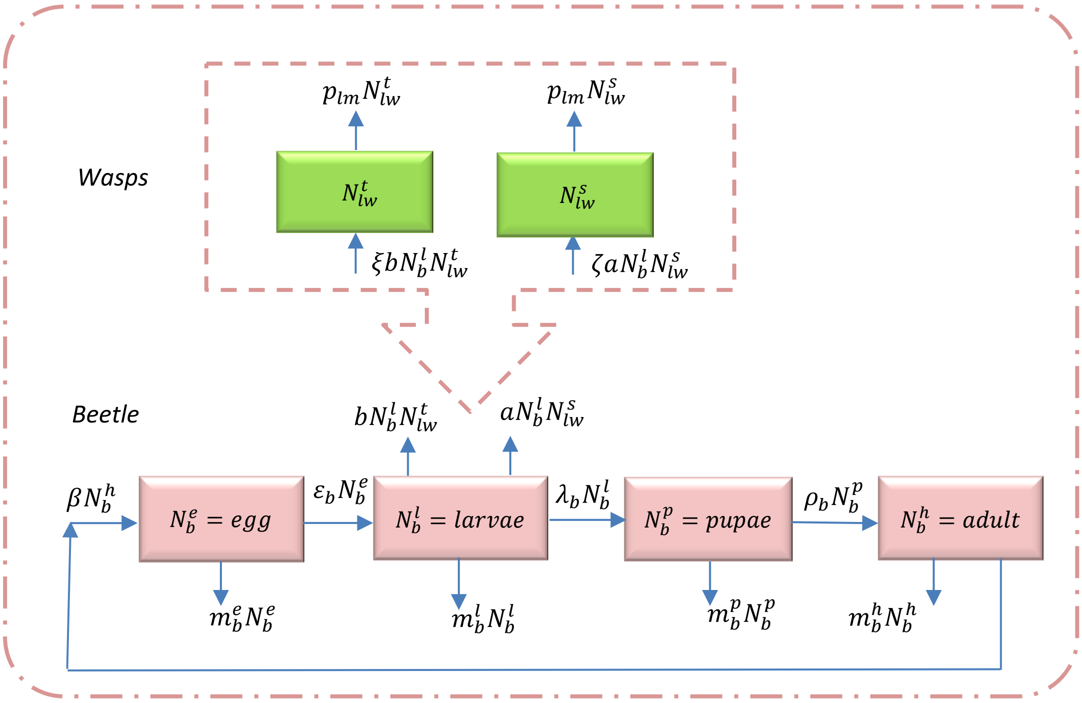


Figure 6. 8 Population dynamics schematic for wasp-beetle interaction model describing the detailed activities of how the wasps exercise control over the beetle population in its habitat, equations 6.32 to 6.37 (Faithpraise et al., 2014b)

6.5.6 THE INTERACTION BETWEEN THE MOSQUITOES AND PREDATORS

A large population density of Anopheles mosquitoes and its life cycle stages were confirmed to be living in the Epono 2 environment and inside the houses located there. When a verbal survey was conducted in the area, the people living in the area confirmed multiple bites from mosquitoes and how they have suffered from several diseases and malaria as a result of the mosquitoes. When further questions were asked about control measures, they expressed concern that the mosquitoes had developed resistance to the insecticide sprays, insecticide-treated nets and that it is very inconvenient to use an insecticide-treated net as they: restrict ventilation, cause insecticide poisoning and are expensive - as confirmed by (Kara et al., 2004).

To provide a lasting solution to the mosquito/malaria problem we propose the use of the natural predator *Odonata* (dragonfly) to control and eradicate the population of mosquitoes.

After sampling a 1km^2 area it was estimated that the density of mosquitoes was above two million, plus similar numbers of its life cycle stages, Table A0.12 –Appendix A1. Four thousand dragonflies and it life cycle stages, Table A0.14 –Appendix A1 are introduced into the environment the effect of them on the mosquito population can be illustrated using the interactive models or equations derived from the predator-host- interaction as shown in Fig. 6.9.

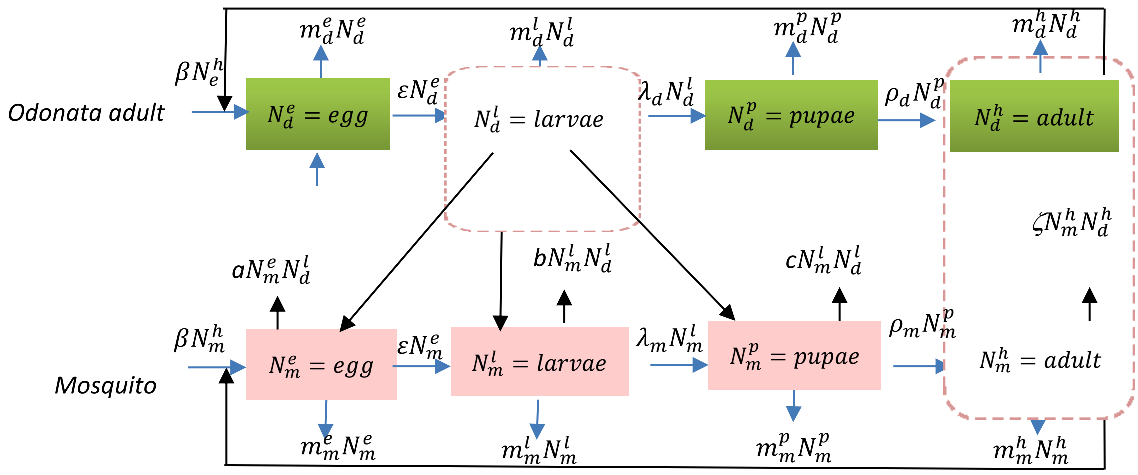


Figure 6. 9 Population dynamics schematic for Odonata-anopheles mosquito interaction model describing the detailed activities of how the predator exercise control over the mosquitoes population in the environment, equations 6.43 to 6.49

When two classes of predators (*Toxorhynchites* larvae, and *Odonata* adult and nymphs) were combine, only a limited number of 200 Odonata were required to produce a tremendous result in reducing the density of the mosquitoes in the environment as illustrated by the model of Fig. 6. 14 below. Fig. 6.14 illustrates the predatory action of

Odonata on the mosquitoes and *Toxorhynchites* and the predatory action of *Toxorhynchites* on the pest mosquito larva. The green arrows indicate the predation of *Odonata* nymphs on pest mosquito and *Toxorhynchites:* eggs, larvae and pupae. The orange arrows indicate the predation of *Odonata* adults on pest mosquito and *Toxorhynchites* adults. The red arrow indicates predation of *Toxorhynchites* on pest mosquito larvae.

Therefore a model of the interaction between the mosquito species and the predators Odonata adult and nymph and *Toxorhynchites* adult and its life cycle stages was created to observe the effect of these combined predators on the mosquito population (Faithpraise et al., 2014d).

6.5.7 THE INTERACTION BETWEEN THE HOST PEACH POTATOES APHIDS AND PREDATORS

The early detection of the symptoms of an aphid pest invasion at all distinct life cycle stages is essential to control and avoid permanent infestation. (Rhainds et al., 2010), (Meihls et al., 2004) and (Mondor et al., 2010) noted the reproductive growth rate of aphids on a leaf or plant under normal and varying conditions. Their investigation and analysis forecast a constantly increasing growth rate of aphids in any infested ecosystem; under favourable conditions aphid reproduction is prolific.

There are several species of aphids and all of the species assume a complicated life cycle as illustrated by (Moran, 1992), (Rutledge et al., 2006), (Rhainds et al., 2008), and (Radcliffe et al., 1993). In order to manage and control an aphid infestation we need to understand its life cycle as illustrated in Fig. 6.10 (Mandrioli, 2012) and Table 6.2;

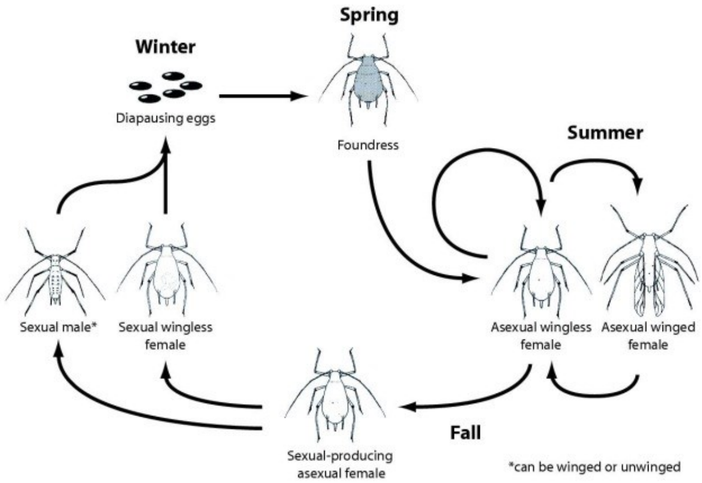


Figure 6. 10 Lifecycle of peach potato aphid (Mandrioli, 2012*)*

Potatoes are a multipurpose vegetable tuber that is eaten all the year round. The target pest is the peach potato aphid ***(****Myzus persicae****).*** The aphid pest was chosen for the case study since it requires early detection of all the stages of its life cycle (Eggs, larvae and adult) and treatment to prevent spreading and uncontrollable infestation.

Myzus persicae is one of the most widespread and well-studied aphids. It is viewed as a major problem for the agricultural sector, because of its virus spreading capabilities amongst crop plants. The pest is extremely polyphagia and has the ability to reproduce both sexually and asexually. The nymph and adult peach aphid cause multiple problems to plant phloem by the use of its sucking styled. This damage includes: blocking up the leaf stomata and reduction of photosynthesis, particularly when dark-coloured fungi (sooty moulds) grow over the foliage, curled or yellowed leaves, stunted growth and the transmission of virus Y to potatoes can occur – (Columbia Electronic Encyclopaedia, 2012).

Field size

The total potato field size is a 100m x 100m square open field located in Nko, a commercial town in Cross River State-Nigeria. The potatoes actually occupy a 90m x 90m square. The beds are cultivated in rows of 90m x 0.3m and the beds are 0.6m apart, seed tubers of potatoes were planted directly into the drilled hole of about 0.075m to 0.15m deep and

0.3m apart. The potato sprouts form within a few weeks and at about eight weeks shoots were 0.08m to 0.09m long and dark coloured as illustrated in Fig. 6.11 (a) and (b). Figure 6.11(c) illustrates infestation damage by aphids . (Faithpraise et al., 2013c)

(a)

(b)

(c)

Figure 6. 11 Potato farm field (early and advance stages)
(Source: www. Pofan.org, 2013)

6.6. MATHEMATICAL MODEL DESIGN

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. Mathematical 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 predatory population on the pest population density.

The research of: (Gamez & Shamandy, 2010), (Rafikov et al., 2008), and (Stankova et al, 2013), (Murdoch, 1990), (Mills & Getz, 1996), (Varga, 2008), (Hassell, 2002), both experimentally and mathematically illustrate the application of host–parasitoid models for biological control. Mills & Getz provide a comprehensive review of host-parasitoid models. (Oluwagbemi et al., 2013), expresses the importance of Mathematical models as a first step to asses control strategies and the efficacy of proposed methods prior to implementation. (Lord, 2007), (Axtell et al., 1996), (Wilensky, 2007) and (McKenzie, 2000) have developed mathematical models to show that it is a crucial element in developing optimised control techniques, especially to understand the Anopheles population and transmission dynamics to strategically control the disease vector.

Therefore according to the different classes of pest and their mode of operation, different models of interaction have been developed to show how the classes of pest can be strategically managed to control their harmful effect.

6.7 CONTROL MODEL DEVELOPMENT FOR PEST AND PARASITOID WASPS

As this research progressed, several models were design and developed as demonstrated below based on the different classes of pest, their infestation habitats and the naturally beneficial enemies of the different species of pest, because most NBI are host specific. Therefore several interactive combinations were explored to understand and check the effectiveness of the various predatory elements for pest control.

6.7.1 CASE 1: HOST DIAMONDBACK MOTHS AND THREE CLASSES OF PARASITOID WASPS

The simulation model of Fig. 6.12 provides an understanding of the interaction between the population of the host diamondback moths (*Plutella xylostella) and* its offspring: eggs, larvae and pupae as indicated in the second row. The transistion stages from the moth eggs to the adult stages and the new birth as a results of parasitoid wasps exploitation is indicated by the horizontal blue arrows. The blue arrows pointing in the downward direction from the second row indicates the natural death rates of the lifecycle stages and starvation. The blue arrows pointing upwards indicate the possible reduction of the pest population from the interaction with the external forces (parasitoid wasps exploitation).

The first row shows the egg parasitoid wasp (*Trichogramma*), the larval parasitoid wasp (*Diadegma semiclausum),* and the pupal parasitoid wasp *(Diadromus collaris).* The upward blue arrows pointing into the first row indicates the emergence of a new wasps from the host (pest) and the upward blue arrows from the first row (wasps) indicates a natural death rate from the wasps. The third row indicate the cabbage growing habitat. The blue arrow pointing downward from the leaf field indicates the possible reduction of the leaf population by the pest larvae as illustrated by the following simultaneous, ordinary differential equations. Equations 6.11 to 6.18, provide a dynamic model of the evolving pest, parasitoids and leaf populations per unit volume as illustrated in Fig. 6.12.

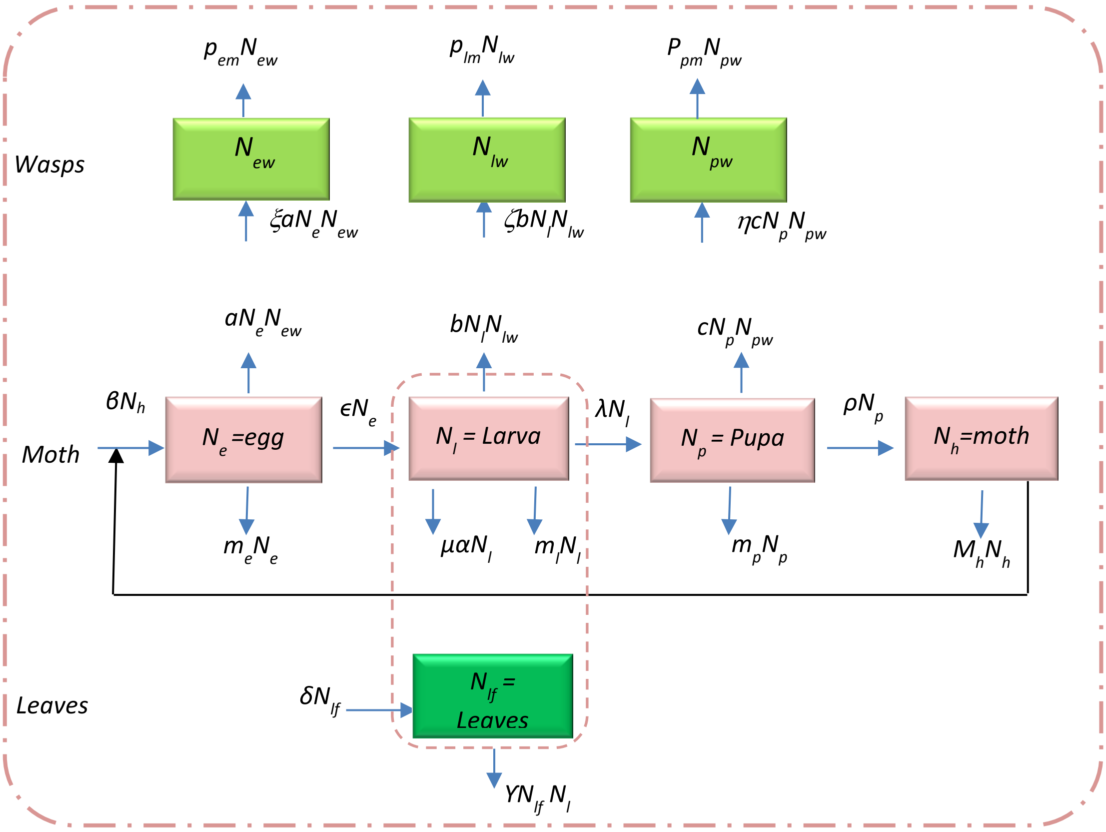


Figure 6. 12 Population dynamics for wasp-pest-crop interaction model describing the detailed activities of how the eggs, larval and pupae wasps exercise control over pest diamondback moth population in its habitat. (Faithpraise et al., 2013b)

$$\frac{dN_e}{dt} = \beta N_h - \varepsilon N_e - aN_eN_{ew} - m_eN_e \qquad \text{Eqn.6. 11}$$

$$\frac{dN_{ew}}{dt} = \xi aN_eN_{ew} - p_{em}N_{ew} \qquad \text{Eqn. 6.12}$$

$$\frac{dN_l}{dt} = \varepsilon N_e - \lambda N_l - bN_l N_{lw} - m_l N_l - \mu \alpha N_l$$ Eqn.6. 13

$$\frac{dN_{lw}}{dt} = \zeta b N_l N_{lw} - p_{lm} N_{lw}$$ Eqn. 6.14

$$\frac{dN_p}{dt} = \lambda N_l - \rho N_p - cN_p N_{pw} - m_p N_p$$ Eqn. 6.15

$$\frac{dN_{pw}}{dt} = \eta c N_p N_{pw} - p_{pm} N_{pw}$$ Eqn. 6.16

$$\frac{dN_h}{dt} = \{\rho N_p - m_h N_h\} \left[N_h \left(\frac{K_h - N_h}{K_h} \right) \right]$$ Eqn. 6.17

$$\frac{dN_{lf}}{dt} = \delta N_{lf} - \gamma N_{lf} N_l$$ Eqn. 6.18

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_{em}, p_{lm}, p_{pm}= 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 = probability that the parasitoid finds and paraitizes 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

Eqn. 6.18 models the leaf population and leaf growth rate, which is determined using Hoffmann's et al, (2002) relative growth rate equations. The proposed model consists of eight simultaneous non-linear, ordinary differential equations (6.11) to (6.18), which are solved using a 4th order Runge –Kutta method as described by (Fehlberg, 1969); (Dormand, 1981); (Butcher, 2007) and (Schreiber, 2007), using the average life span of all the insects and their mortality rates as displayed in Table 6.4.

Table 6. 1 Mortality rates of the parasitoid wasps and Diamondback moths.

Mortalities	Average Life span (x) days	ln (x)	*ψ= b₁*	*(b₀/b₁)*	$\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$	Mortality obtained
p_{em}	6.0	1.7918	1.4411	-1.7259	5.6176	0.26
p_{lm}	13.4	2.5953	0.6675	-2.4529	11.6218	0.055
p_{pm}	14.9	2.7014	0.9148	-2.5976	13.4317	0.068
m_h	8.4	2.1282	1.9249	-2.0786	7.9933	0.25
m_e	4.1	1.4110	1.3916	-1.3427	3.8294	0.37
m_l	6.3	1.8405	0.8707	-1.7314	5.6484	0.15
m_p	7.9	2.0669	2.1836	-2.0234	7.5640	0.30

6.7.2 CASE 2: HOST AFRICAN ARMYWORM AND TWO CLASSES OF PARASITOIDS

Modelling the interaction between the host African armyworm on the Sorghum habitat, the egg parasitoid wasps *(Trichogramma)* and the larval parasitoid (*Tachinidae)* is formulated using the simultaneous, non-linear ordinary differential equations 6.19-6.25, as derived from Fig. 6.7 above:

$$\frac{dN_e}{dt} = \beta N_h - \varepsilon N_e - aN_e N_{ew} - m_e N_e \qquad \text{Eqn. 6.19}$$

$$\frac{dN_{ew}}{dt} = \xi a N_e N_{ew} - p_{em} N_{ew} \qquad \text{Eqn. 6.20}$$

$$\frac{dN_l}{dt} = \varepsilon N_e - \lambda N_l - bN_l N_{lw} - m_l N_l - \mu \alpha N_l \qquad \text{Eqn. 6.21}$$

$$\frac{dN_{lw}}{dt} = \zeta b N_l N_{lw} - p_{lm} N_{lw} \qquad \text{Eqn. 6.22}$$

$$\frac{dN_p}{dt} = \lambda N_l - \rho N_p - m_p N_p \qquad \text{Eqn. 6.23}$$

$$\frac{dN_h}{dt} = \{\rho N_p - m_h N_h\}\left[N_h\left(\frac{K_h - N_h}{K_h}\right)\right] \qquad \text{Eqn. 6.24}$$

$$\frac{dN_{lf}}{dt} = \delta N_{lf} - \gamma N_{lf} N_l \qquad \text{Eqn. 6.25}$$

Where:

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

N_{ew}, N_{lw} = Population density of *Trichogramma* and *Tachinidae* parasitizing: egg and larvae, respectively.

K_h = *African armyworm* moth (AAW) environmental carrying capacity.

m_h, m_e, m_l, m_p = *African armyworm* moth, egg, larvae and pupae mortality rate, respectively.

p_{em}, p_{lm} = *Trichogramma* and *Tachinidae* mortality rate, respectively.

ξ, ζ = efficiency of turning prey into *Trichogramma* and *Tachinidae* offspring: eggs, and larvae, respectively.

a, b = frequency with which *Trichogramma* and *Tachinidae* parasitoids finds and parasitizes a prey: eggs, and larvae, respectively.

β = Number of eggs per day from each S. moth

ε = Fraction of eggs hatching into larvae

λ = Fraction of larvae changing to pupae

ρ = Fraction of pupae turning into *African armyworm* moth

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

Eqn. 6.25 models the leaf population and leaf growth rate, which is determined using the relative growth rate equations, Sorghum growth and development, (Zadoks et al., 2006), (Vanderlip, 1972). These equations are solved as described above using the average life span of all the insects and their mortality rates as shown in Table A0. 18 and Table A0.21.

6.7.3 CASE 3: HOST SPODOPTERA EXAMPTA AND A SINGLE WASP, THE LARVAL PARASITOID WASPS

Model of the interaction of the host *Spodoptera exempta*, and *Cotesia Flavipes (Cameron)* a larval parasitoid wasp and the maize leaf population per square metre is created using equations 6.26 to 6.31 - non-linear simultaneous, ordinary differential equations from the interactive diagram of Fig. 6.5 above. Eqn. 6. 31 models the leaf population and leaf growth rate, which is determined using the maize growth rate and development (Tóth et al., 2002), (Nelissen et al., 2013) and (Hardacre et al., 1986).

$$\frac{dN_e}{dt} = \beta N_h - \varepsilon N_e - m_e N_e \quad \text{Eqn. 6.26}$$

$$\frac{dN_l}{dt} = \varepsilon N_e - \lambda N_l - bN_l N_{lw} - m_l N_l - \mu\alpha N_l \quad \text{Eqn. 6.27}$$

$$\frac{dN_{lw}}{dt} = \zeta b N_l N_{lw} - p_{lm} N_{lw} \quad \text{Eqn. 6.28}$$

$$\frac{dN_p}{dt} = \lambda N_l - \rho N_p - m_p N_p \quad \text{Eqn. 6.29}$$

$$\frac{dN_h}{dt} = \{\rho N_p - m_h N_h\}\left[N_h\left(\frac{K_h - N_h}{K_h}\right)\right] \quad \text{Eqn. 6.30}$$

$$\frac{dN_{lf}}{dt} = \delta N_{lf} - \gamma N_{lf} N_l \quad \text{Eqn. 6.31}$$

Where:

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

N_{lw} = Population density of parasitoid wasps.

K_h = *Spodoptera exempta* carrying capacity of the environment.

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

p_{lm} = larval parasitoid wasps mortality rate.

ζ = efficiency of turning prey into parasitoid wasps offspring.

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

β = Number of eggs per day from each *Spodoptera exempta*

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 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

These equations are solved as described above using the average life span of all the insects and their mortality rates as shown in Table A0.18 –Appendix A1.

6.7.4 CASE 4: HOST SCARAB BEETLES AND TWO LARVAL PARASITOIDS

After the consideration of the biology and the life cycle stages of the pest (scarab beetles) and parasitoid wasps as illustrated in Table A0.11-Appendix A1, a model of interaction was designed to explore the interaction between the pest and the parasitoid (Scoliids and Tachinidae) parasitoids observe the effect of these combined wasps on the scarab beetles population as illustrated in equations 6.32 to 6.37. The equations can be interpreted by looking at Fig. 6.8 above, which illustrates the flow of the interaction between the beetles and the NBI population.

Equations 6.32 to 6.37 provide a dynamic model of the evolving scarab beetle (Taro or Cocoyam corm) life cycle stages, the *Scoliid* wasps and the *Voria* species of the T*achinidae* parasitoid per square metre. The model simulates reproduction, mortality and parasitism.

$$\frac{dN_b^e}{dt} = \beta_b N_b^h - \varepsilon_b N_b^e - m_b^e N_b^e \qquad \text{Eqn. 6.32}$$

$$\frac{dN_b^l}{dt} = \varepsilon_b N_b^e - \lambda_b N_b^l - aN_b^l N_{lw}^s - bN_b^l N_{lw}^t - m_b^l N_b^l$$ Eqn. 6.33

$$\frac{dN_{lw}^s}{dt} = \zeta a\ N_b^l N_{lw}^s - p_{lm} N_{lw}^s$$ Eqn. 6.34

$$\frac{dN_{lw}^t}{dt} = \xi b N_b^l N_{lw}^t - p_{lm} N_{lw}^t$$ Eqn. 6.35

$$\frac{dN_b^p}{dt} = \lambda_b N_b^l - \rho_b N_b^p - m_b^p N_b^p$$ Eqn. 6.36

$$\frac{dN_b^h}{dt} = \{\rho_b N_b^p - m_b^h N_b^h\}\left[N_b^h\left(\frac{K_b^h - N_b^h}{K_b^h}\right)\right]$$ Eqn. 6.37

Where:

$N_b^h, N_b^e, N_b^l, N_b^p$ = Population density of Cocoyam beetles: adult, egg, larvae and pupae.

N_{lw}^s, N_{lw}^t = Population density of Scoliid wasps and Tachinidae parasitoid.

K_b^h = Population carrying capacity of the environment for adult: Taro beetle.

$m_b^h, m_b^e, m_b^l, m_b^p$ = Cocoyam beetles mortality rate: adult, egg, larvae and pupae respectively.

p_{lm}, p_{lm} = scoliid and Tachinidae wasp mortality rate respectively.

ξ = efficiency of turning the pest larva into Tachinidae parasitoid

ζ = efficiency of turning the pest larva into Scoliid parasitoid wasps

a, b = probability that a parasitoid wasps finds and parasitizes a larva prey

β_b = Number of eggs per day from Taro beetle

ε_b = Fraction of eggs hatching into beetle larvae

λ_b = Fraction of beetles' larvae changing to pupae respectively

ρ_b = Fraction of pupae turning into adult Taro beetle

These equations are solved as described above using the average life span of all the insects and their mortality rates as shown in Table A0.21 – Appendix A1.

6.7.5 CASE 5: APHID PREY AND PREDATOR (LADYBUG) SPECIES MODEL

The simulation model provides an understanding of the interaction between the population of *peach potatoes aphid* adults and its life cycle stages (egg and nymph) and the natural beneficial predator (ladybug adult) and its life cycle stages (egg, larvae and pupae) as described by the following set of simultaneous ordinary differential equations 6.38 to 6.42 derived from the aphids-wasps-interaction model of Fig. 6.13.

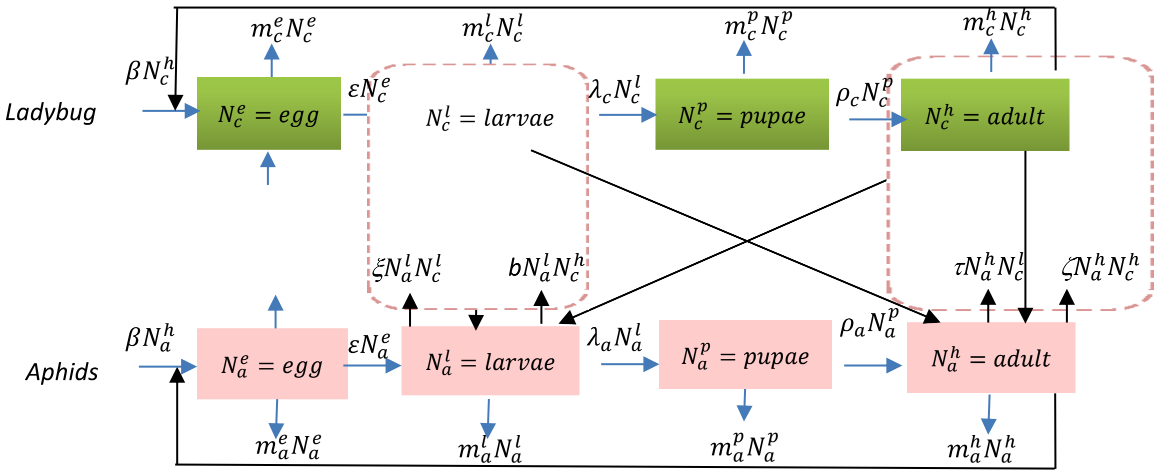


Figure 6. 13 Population dynamics schematic for ladybug-aphids interaction model describing the detailed activities of how the wasps exercise control over the aphids population in its habitat, equations 6.38 to 6.42.

$$\frac{dN_a^e}{dt} = \beta_a f N_a^h - \varepsilon_a N_a^e - m_a^e N_a^e \qquad \text{Eqn. 6.38}$$

$$\frac{dN_a^l}{dt} = \varepsilon_a N_a^e + \sigma_a (1-f) N_a^h - \lambda_a N_a^l - b N_a^l N_c^h - \xi N_a^l N_c^l - m_a^l N_a^l \qquad \text{Eqn. 6.39}$$

$$\frac{dN_a^h}{dt} = \{\lambda_a N_a^l - \zeta N_a^h N_c^h - \tau N_a^h N_c^l - m_a^h N_a^h\} \left[N_a^h \left(\frac{K_a^h - N_a^h}{K_a^h} \right) \right] \qquad \text{Eqn. 6.40}$$

$$\frac{dN_c^e}{dt} = \beta_c N_c^h - \varepsilon_c N_c^e - m_c^e N_c^e$$ Eqn. 6.41

$$\frac{dN_c^l}{dt} = \varepsilon_c N_c^e - \mu_c N_c^l - m_c^l N_c^l$$ Eqn. 6.42

$$\frac{dN_c^p}{dt} = \mu_c N_c^l - \rho_c N_c^p - m_c^p N_c^p$$ Eqn. 6.41

$$\frac{dN_c^h}{dt} = \{\rho_c N_c^p - m_c^h N_c^h\}\left[N_c^h\left(\frac{K_c^h - N_c^h}{K_c^h}\right)\right]$$ Eqn.6.42

Where:

N_a^h, N_a^e, N_a^l = Population density of aphid: adult, egg and larvae.

$N_c^h, N_c^e, N_c^l, N_c^p$ = Population density of ladybug: adult, egg, larvae and pupae.

K_a^h, K_c^h = Population carrying capacity of the environment for adult: aphid, ladybug - respectively.

m_c^h, m_c^e, m_c^l = Aphid mortality rate: adult, egg, larvae - respectively.

$m_c^h, m_c^e, m_c^l, m_c^p$ = ladybug mortality rate: adult, egg, larvae and pupae – respectively

ξ = frequency with which a ladybug larva finds and eats an aphid larva

ζ = frequency with which a ladybug adult finds and eats an adult aphid.

τ = frequency with which a ladybug larva finds and eats an adult aphid.

b = frequency with which a ladybug finds and eats an aphid larva.

f = fraction of aphids laying egg

$1-f$ = fraction of aphids producing larva

β_a, β_c = Number of eggs per day from: aphid adult, ladybug adult

$\varepsilon_a, \varepsilon_c$ = Fraction of eggs hatching into: aphid larvae, ladybug larvae

μ_c = Fraction of ladybug larvae changing into pupa

λ_a = Fraction of aphid larvae changing to adults

ρ_c = Fraction of ladybug pupae turning into ladybugs

σ_a = number of larva births from aphids

These equations are solved as described above using the average life span of all the insects and their mortality rates as shown in Table 6.1 above.

6.7.6 CASE 6: ANOPHELES MOSQUITO PREY AND A SINGLE SPECIES OF PREDATOR (ODONATA)

After sampling a 1km^2 area it was estimated that the density of mosquitoes was above two million, plus similar numbers of its life cycle stages. If some population density of dragonflies and its life cycle stages are introduced into the environment the effect of them on the mosquito population can be modelled by the following non-linear simultaneous ordinary differential equations 6.43 to 6.49 derived from the model of Fig.6.9 above.

$$\frac{dN_m^e}{dt} = \beta_m N_m^h - \varepsilon_m N_m^e - aN_m^e N_d^n - m_m^e N_m^e \qquad \text{Eqn. 6.43}$$

$$\frac{dN_m^l}{dt} = \varepsilon_m N_m^e - \lambda_m N_m^l - bN_m^l N_d^n - m_m^l N_m^l \qquad \text{Eqn. 6.44}$$

$$\frac{dN_m^p}{dt} = \lambda_m N_m^l - \rho_m N_m^p - cN_m^p N_d^n - m_m^p N_m^p \qquad \text{Eqn. 6.45}$$

$$\frac{dN_m^h}{dt} = \{\rho_m N_m^p - \zeta N_m^h N_d^h - m_m^h N_m^h\}\left[N_m^h\left(\frac{K_m^h - N_m^h}{K_m^h}\right)\right] \qquad \text{Eqn. 6.46}$$

$$\frac{dN_d^e}{dt} = \beta_d N_d^h - \varepsilon_d N_d^e - m_d^e N_d^e \qquad \text{Eqn. 6.47}$$

$$\frac{dN_d^n}{dt} = \varepsilon_d N_d^e - \mu_d N_d^n - m_d^n N_d^n - p^n N_d^n \qquad \text{Eqn. 6.48}$$

$$\frac{dN_d^h}{dt} = \{\mu_d N_d^n - m_d^h N_d^h\}\left[N_d^h\left(\frac{K_d^h - N_d^h}{K_d^h}\right)\right] \qquad \text{Eqn. 6.49}$$

Where:

$N_m^h, N_m^e, N_m^l, N_m^p$ = Population density of mosquito: adult, egg, larvae and pupae.

N_d^h, N_d^e, N_d^n = Population density of dragonfly: adult, egg, nymph.

K_m^h, K_d^h = Population carrying capacity of the environment for adult: mosquito and dragonfly - respectively.

$m_m^h, m_m^e, m_m^l, m_m^p$ = Mosquito mortality rate: adult, egg, larvae and pupae - respectively.

m_d^h, m_d^e, m_d^n = Dragonfly mortality rate: adult, egg and nymph - respectively.

ζ = frequency with which a dragon fly adult finds and eats an adult mosquito.

a, b, c = frequency with which a dragonfly nymph finds and eats a mosquito prey: eggs, larvae and pupae - respectively.

p^n = attrition of dragon fly nymphs by natural predators

β_m, β_d = Number of eggs per day from: mosquito, dragon fly, respectively

$\varepsilon_m, \varepsilon_d$ = Fraction of eggs hatching into: mosquito larvae and dragonfly nymph, respectively

μ_d = Fraction of nymphs changing into dragonflies

λ_m = Fraction of larvae changing to mosquito pupae

ρ_m = Fraction of pupae turning into mosquitos

These equations are solved as described above using the average life span of all the insects and their mortality rates as shown in Table A0.19 –Appendix A1.

6.7.6.1 CASE 7: ALL MOSQUITO PREY AND ODONATA AND TOXORHYNCHITES PREDATORS

From the result obtained with the control of a single species of mosquito and a single predator, we thought it would be interesting to explore the effect of deploying a combination of two classes of predators Odonata and Toxorhynchites to control all classes of mosquitos' species.

The following non-linear simultaneous, ordinary differential equations 6.50 to equation 6.60 provide a dynamic model of this interaction as shown in Fig 6.14. All mosquitos' life cycle stages with Odonata and its life cycle stages and Toxorhynchites adult and life cycle stages per square kilometre as shown Table A0.15-Appendix A1 and Fig. 6.14.

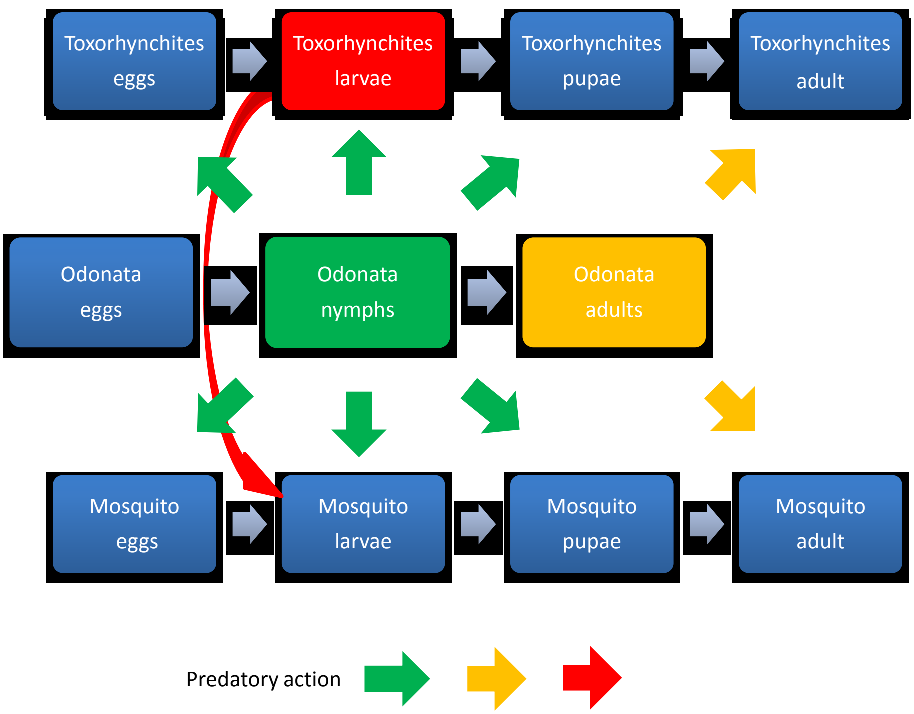


Figure 6. 14 Population dynamics schematic for Odonata - Toxorhynchites –mosquito interaction model describing the detailed activities of how the combined predators exercise control over the mosquitoes population in the environment, equations 6.50 to 6.60 (Faithpraise et al., 2014b)

$$\frac{dN_m^e}{dt} = \beta_m N_m^h - \varepsilon_m N_m^e - aN_m^e N_d^n - m_m^e N_m^e$$ Eqn. 6.50

$$\frac{dN_m^l}{dt} = \varepsilon_m N_m^e - \lambda_m N_m^l - bN_m^l N_d^n - \xi N_m^l N_e^l - m_m^l N_m^l$$ Eqn. 6.51

$$\frac{dN_m^p}{dt} = \lambda_m N_m^l - \rho_m N_m^p - cN_m^p N_d^n - m_m^p N_m^p$$ Eqn. 6.52

$$\frac{dN_m^h}{dt} = \{\rho_m N_m^p - \zeta N_m^h N_d^h - m_m^h N_m^h\}\left[N_m^h\left(\frac{K_m^h - N_m^h}{K_m^h}\right)\right]$$ Eqn. 6.53

$$\frac{dN_e^e}{dt} = \beta_e N_e^h - \varepsilon_e N_e^e - eN_e^e N_d^n - m_e^e N_e^e$$ Eqn. 6.54

$$\frac{dN_e^l}{dt} = \varepsilon_e N_e^e - \lambda_e N_e^l - fN_e^l N_d^n - m_e^l N_e^l$$ Eqn. 6.55

$$\frac{dN_e^p}{dt} = \lambda_e N_e^l - \rho_e N_e^p - gN_e^p N_d^n - m_e^p N_e^p$$ Eqn. 6.56

$$\frac{dN_e^h}{dt} = \{\rho_e N_e^p - \tau N_e^h N_d^h - m_e^h N_e^h\}\left[N_e^h\left(\frac{K_e^h - N_e^h}{K_e^h}\right)\right]$$ Eqn. 6.57

$$\frac{dN_d^e}{dt} = \beta_d N_d^h - \varepsilon_d N_d^e - m_d^e N_d^e$$ Eqn. 6.58

$$\frac{dN_d^n}{dt} = \varepsilon_d N_d^e - \mu_d N_d^n - m_d^n N_d^n - p_d N_d^n$$ Eqn. 6.59

$$\frac{dN_d^h}{dt} = \{\mu_d N_d^p - m_d^h N_d^h\}\left[N_d^h\left(\frac{K_d^h - N_d^h}{K_d^h}\right)\right]$$ Eqn. 6.60

Where:

$N_m^h, N_m^e, N_m^l, N_m^p$ = Population density of mosquito: adult, egg, larvae and pupae.

$N_e^h, N_e^e, N_e^l, N_e^p$ = Population density of Toxorhynchites: adult, egg, larvae and pupae.

N_d^h, N_d^e, N_d^n = Population density of Odonata: adult, egg, nymph.

K_m^h, K_e^h, K_d^h = Population carrying capacity of the environment for adult: mosquito, Toxorhynchites , Odonata - respectively.

$m_m^h, m_m^e, m_m^l, m_m^p$ = Mosquito mortality rate: adult, egg, larvae and pupae - respectively.

$m_e^h, m_e^e, m_e^l, m_e^p$ = Toxorhynchites mortality rate: adult, egg, larvae and pupae - respectively.

m_d^h, m_d^e, m_d^n = Odonata mortality rate: adult, egg and nymph - respectively.

ξ = frequency with which an Toxorhynchites larva finds and eats a mosquito larva

ζ = frequency with which a dragon fly adult finds and eats an adult mosquito.

τ = frequency with which an Odonata adult finds and eats an adult Toxorhynchites .

a,b,c = frequency with which an Odonata nymph finds and eats a mosquito prey: eggs, larvae and pupae - respectively.

e,f,g = frequency with which a Odonata nymph finds and eats an Toxorhynchites prey: eggs, larvae and pupae - respectively.

$\beta_m, \beta_e, \beta_d$ = Number of eggs per day from: mosquito, Toxorhynchites , Odonata

$\varepsilon_m, \varepsilon_e, \varepsilon_d$ = Fraction of eggs hatching into: mosquito larvae, Toxorhynchites larvae, Odonata nymph

μ_d = Fraction of nymphs changing into Odonata

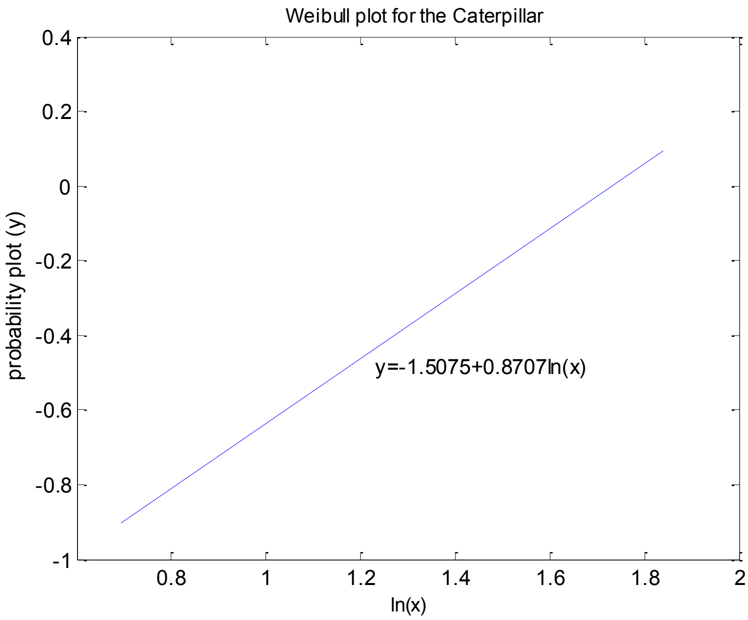
λ_m, λ_e = Fraction of larvae changing to pupae: mosquito, Toxorhynchites - respectively

ρ_m, ρ_e = Fraction of pupae turning into: mosquitos and Toxorhynchites

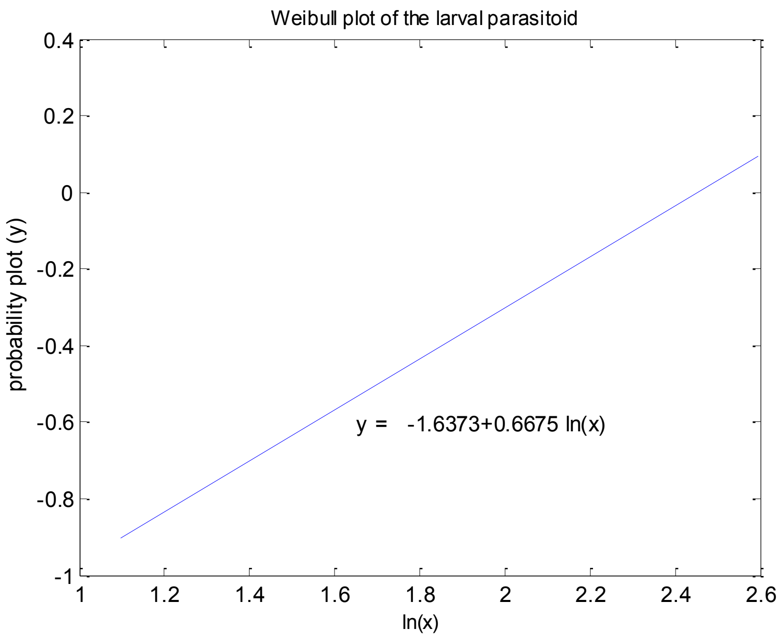
These equations are solved as described above using the average life span of all the insects and their mortality rates as shown in Table A0.19 and Table A0.20.

6.8 ANALYSIS OF THE RESULTS OF THE MORTALITY RATES

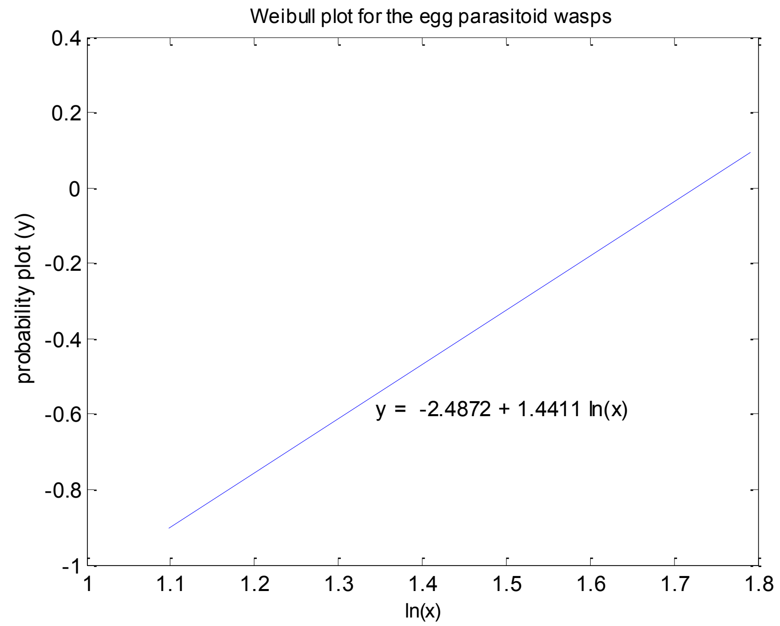
The Weibull plots used in combination with the equations 6.5 to 6.10 to obtained the results of the mortalities of Tables 6.4 is shown below


Weibull plot for the Caterpillar
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
probability plot (y)
0.8
1
1.2
1.4
1.6
1.8
2
ln(x)
y=-1.5075+0.8707ln(x)

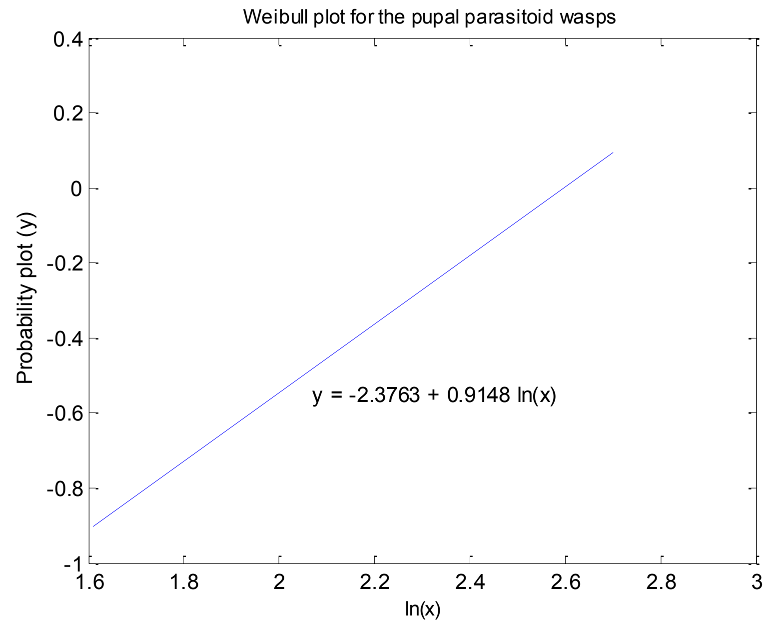
(a)


Weibull plot of the larval parasitoid
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
probability plot (y)
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
ln(x)
y = -1.6373+0.6675 ln(x)

(b)



(C)



(d)

Figure 6. 15 Weibull plots of the Diamondback moth caterpillar and the parasitoid wasps

The Weibull plots of Fig. 6.15 and the rest of the Fig. A4.1 to Fig. A4.4 (a) to (d) - Appendix A3, shows that the fit of the points to the least squares line is perfect. Table 6.1, Table 6.4 and Tables A0.18 to Table A0. 21 - Appendix A4, column 1-4 shows the variable names of all the pests and NBIs, the average lifespan and lifespan of all the naturally beneficial insects and pests used, the natural log of the pest and NBI lifespan, the slope of the least squares line of all the pests and NBIs. The intercept of the least squares line for all the pests and NBIs is determind from the eqn. 6.8 as shown in the Weibull program design of Appendix A5,. Tables A0.18 to Table A0. 21- Appendix A4, column 6-7 shows how the characteristic life expectancy and the mortality rates of the pests and NBIs are obtained from the model.

6.9 CONCLUSION

By combining simultaneous nonlinear differential equations, the Weibull probability distribution function and a negative binomial distribution, numerical models of the interaction between all classes of pest and all species of NBI stages were obtained. Via systematic application of the numerical model it has been demonstrated that it is possible to optimize biological pest control strategies to control the activities of the different pests. This pest control planning tool provides agriculturists with a means to calculate the number of NBIs to deploy in any pest infested habitation in order to suppress the pest population within a determinable time frame. This approach offers a replacement for pesticides to enable the quality of life for man to be improved.

Finally, the Optimization Statistical Algorithm for Pest Control offers the opportunity for pest control with minimum cost without the application of chemical pesticides. It can also serve as a pest forecasting tool, even to the point of predicting pest outbreaks, which is vital to prepare growers for potential pest problems before serious losses occur.

CHAPER -7-
DESIGN & DEVELOPMENT METHODOLOGY OF THE PEST CONTROL SYSTEM

CHAPTER -7-DESIGN AND DEVELOPMENT METHODOLOGY OF THE PEST CONTROL SYSTEM

7.1 AUTOMATIC SUSTAINABLE CONTROL SYSTEM DESIGN

The integration of all the individual subsystems designed and developed in the previous sections to form a single entity or device for the agricultural sector nationwide is achieved, as shown in Fig. 7.1.

The automatic sustainable pest control system is made up of five subsystems:

i. Pest UAV Surveillance System (PUS);
ii. Automatic plant Pest Detection and Recognition algorithms (APDRS);
iii. Optimization Statistical Pest Control model (OSPC);
iv. Naturally Beneficial Insect e-database (NBI);
v. Remote control system and a static system (a farm habitat or crop field) as shown in the block diagram of Fig.7.2.

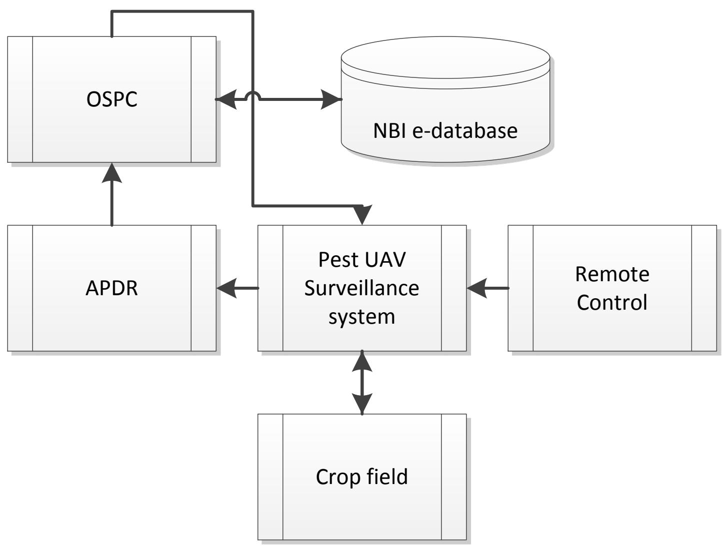


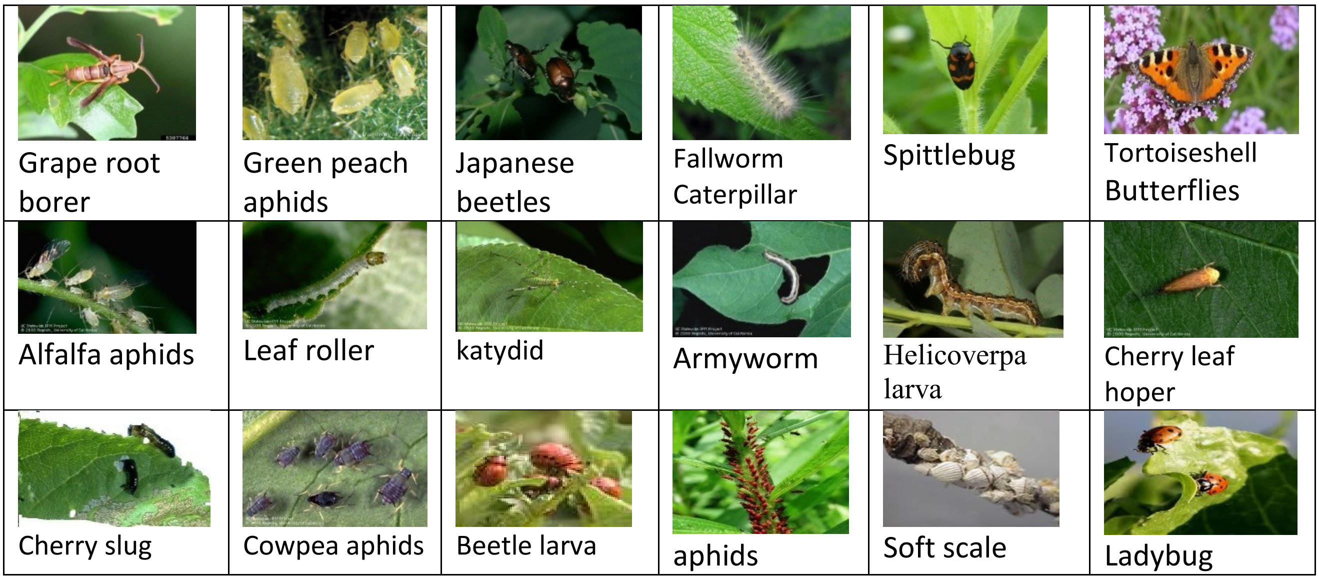
Figure 7. 1 Automatic sustainable pest control system

7.2 APDRS DESIGN AND METHODOLOGY

In this chapter we shall attempt to solve the full pest problem by combining two existing techniques, which are capable of achieving invariance to several of the possible variations of the target object.

The automatic plant pest detection and recognition algorithm presented in this thesis uses k-mean clustering (see section 3.2) and the Correspondence filter (see section 3.3.1). As a test bed we investigate a collection of plant pests, which were obtained from different online resources, among which are: (ALABAMA Nursery and Landscape), (Iannotti, 2012) and (Hamilton, 2012), (Yarham, 2013), (Cossey, 2007). The algorithms have been tested on more than ten crop or plant pests as shown in Fig.7.2

Owing to the risks crop pests impose on livestock and mammals, in a bid to control pest invasion and reduce the risks from chemical pesticide, pest detection and recognition algorithms were proposed by (Faithpraise et al., 2013a). The algorithms were divided into two operational phases, the detection phase and the recognition phase because of the complex nature of the object pest. The proposed pest detection and recognition algorithms are explained in the flow chart of Fig. 7.3.



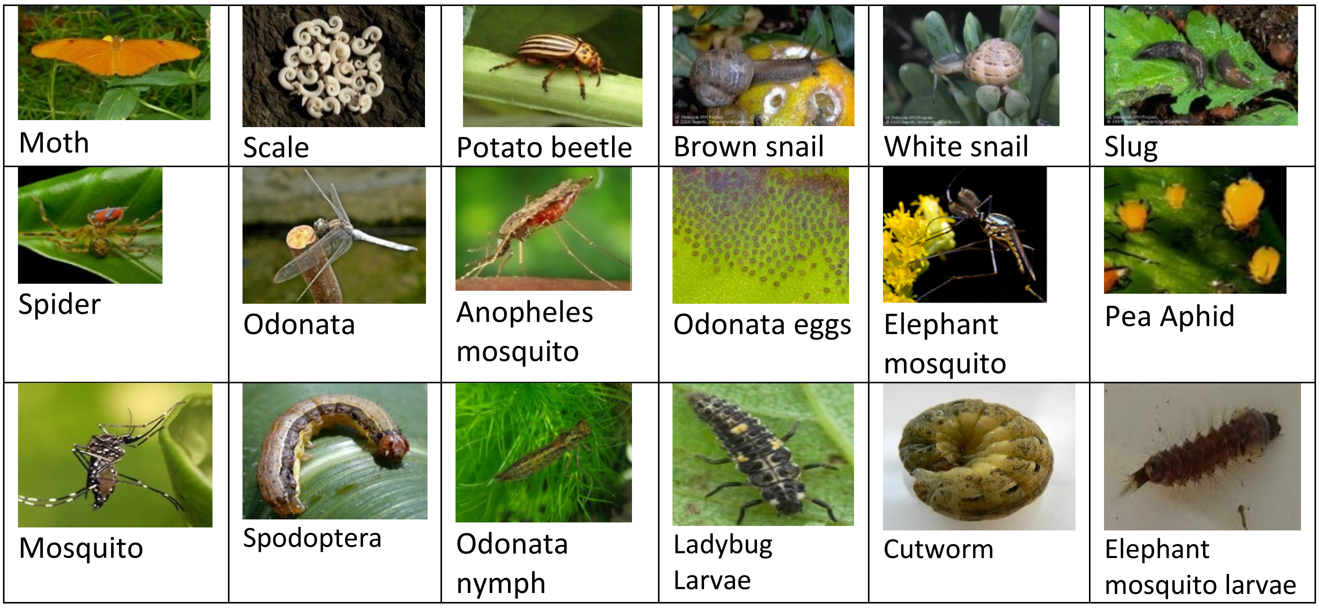


Figure 7. 2 Crop Pests & NBI in their habitats

7.2.1 DETECTION SYSTEM

The APDR algorithm starts with the Pest Surveillance system acquiring the digital images from the environment and loading them as the filter construction images; following acquisition the colour transformation structure for the RGB plant pest images was created. A device-independent, L*a*b* (abbreviation for the CIE 1976 (*L**, *a**, *b**) (or CIELAB) which consists of luminosity L*, chromaticity layer a* and chromaticity layer b*, which houses all the colour (red-green and blue-yellow axis) information, colour space transformation structure was applied; the k-means clustering technique was then used to segment the plant pest images. Now the object(s) or pest segmentation process begins by identifying the principally green colour pixels based on using a varying threshold, mainly all the red, green and blue colour components of the pixel are assigned a zero value so that all the pixel intensities that are less than the threshold value will be deleted. This technique is applied in as much as we assume that, these pixels are not useful for the pest identification. All the pixels on the boundaries of the object cluster and all the colour pigments, which are designated zero, were deleted totally and the segmented pest result is shown in chapter 8, Fig. 8.1. The same steps were repeated for each pest image in the data set.

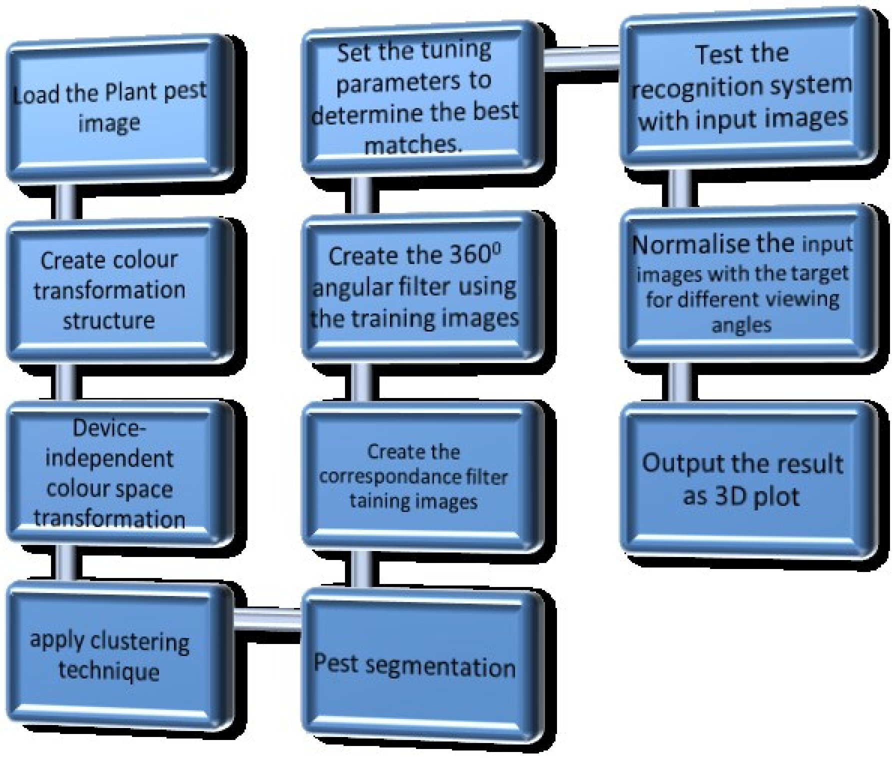


Figure 7. 3 Proposed plant pest detection and recognition process flow chart

The problem of identifying crop pest species despite distortion in position, orientation and scale when occluded or hidden in its cluttered habitat (cluttered background refers to plants or leaf) is a demanding problem that requires an immediate solution to offer the right control measure. Detecting the pest images from the clustered environment as shown in Fig. 8.1, of chapter 8, is the first step to establish the presence of insect objects on the crop. To confirm the presence of pest species, the position and the population density on the habitat, a recognition system is required.

7.2.2 RECOGNITION SYSTEM

The second stage of the APDR algorithm began by angle multiplexing the pest detected from the detection algorithm into the correspondence filter at 5^0 increments. The recognition system is expected to correctly detect the pest images despite variation in its position or orientation. To create invariance to orientation changes of the pest, the correspondence filter was created using a training image set consisting of the expected range of rotations taken at small intervals of viewing angle as shown in chapter 8, Fig. 8.2. The correspondence filter uses a small size moving window system to scan the input image in one pixel increments in order to test every location of the input image for the presence of a target. We discovered that there was some tolerance to the position of the filter centre relative to a target centre. The moving window was then increased to two pixels and there was an insignificant reduction in the detection of the target object.

The correspondence filter has been tested precisely for its detection and recognition accuracy especially for its distortion invariance ability. The sub-database is made up of 10 training images rotated in plane by 5^{o} increments between each training image of the pest. To optimise the recognition performance of the correspondence filter, suitable values of the tuning parameters alpha, beta and gamma had to be selected. The values of these parameters were picked by observing the impact of different values for a number of trials until the most appropriate values that yield the best recognition ability was established. For these correspondence filters the tuning parameters chosen were α= 0.0000009; β= 0.45 and γ= 0.1. The α value was set so low to produce sharp peaks while still being tolerant to noise in the habitat. β was set at a large value to produce sharp peaks with good distortion tolerance. γ value was made low to maximise the discrimination ability of the filter while still producing good distortion tolerance.

7.3 OPTIMIZATION STATISTICAL PEST CONTROL ALGORITHM

The design step of the OSPC system exploits several NBI/pest interactions as illustrated in the previous section and in Fig. 7.2.

Based on the analysis of the reproductive life cycle of all the crop pests and the population dynamics of Fig. 6.2, in chapter 6, we developed the model shown by the various equations listed in chapter 6, section 6.6.1 to 6.6.7, which were then used, to quantify how the naturally beneficial predators should be deployed into any pest infested environment.

7.3.1 THE PEST CONTROL ALGORITHMS DESIGN STEP.

The pest control experimental results were obtained following the application of the following steps.

- Understand the biology of the pest and the corresponding NBI relative to the environment.
- Study the life cycle stages and life expectancy and gestation period of both pest and NBI
- Use the Weibull probability distribution function to predict the mortality rates of all classes of pest and NBI.
- Use the negative binomial distribution function to predict the probability and the frequency an NBI can locate and capture its prey or host respectively.
- Set an initial starting population for all the pests and NBI and simulate the interaction between them using the differential equations
- Set an environmental carrying capacity for the adult pests

7.4. NATURAL BENEFICIAL INSECTS E-DATABASE (NBI)

As illustrated in the previous section, the NBI e-database is partitioned into segments according to the various classes or species of wasps and predators. The wasp and predator images are stored in a database as shown in section 5.

7.5 PEST UAV SURVEILLANCE SYSTEM DESIGN METHODOLOGY

The pest surveillance system used in this research is the Storm Drone 6 GPS system designed and built by Drone 6, for all the detailed design and device characteristics, please refer to the Drone 6 Manual (www.helipal.com).

7.5.1 PEST UAV SYSTEM PAYLOAD (PUSP)

Payload is the carrying capacity of an aircraft. It is usually measured in terms of weight (kg). The PUS payload includes the power system, GoPro Hero 3 camera system and the NBI carriage box as shown in [Appendix (B) to (B2)].

7.5.1.1 PUSP VEHICLE'S PAYLOAD CAPACITY

To calculate the PUSP vehicle's payload capacity we need to know the Gross vehicle weight rating i.e. maximum allowable weight of an entire vehicle (GVWR) and the weight of the unloaded vehicle. Therefore

The GVWR of Drone 6 GPS is 1900g ~ 1.9kg and if the unloaded weight is 500g (0.5kg). The PUSP payload capacity = 1900-500 = 1400g~ 1.4kg.

7.5.1.2 PEST UAV CARRIAGE BOX DESIGN (PUCB)

The UAV NBI delivery system boxes are designed taking account of the weight of the NBI as illustrated in Appendix (B). For the detailed calculation of the 7 flight trips required by the surveillance system (whose payload capacity is 1.4kg) to deploy 8.9kg of the NBI (ladybug), see Appendix B. Appendix (B1) shows the detailed calculation on how, each of the 52 small boxes will house a total of 2,434 NBI (both larvae and adult ladybugs) for every flight trip, and Appendix (B2) shows the detail design of the volume of the carriage box with the dimensions 44mm*44mm*84mm for the small boxes as shown in Fig. 7.4, and 204mm*348mm*252mm for the main carriage box as shown in Fig. 7.5.

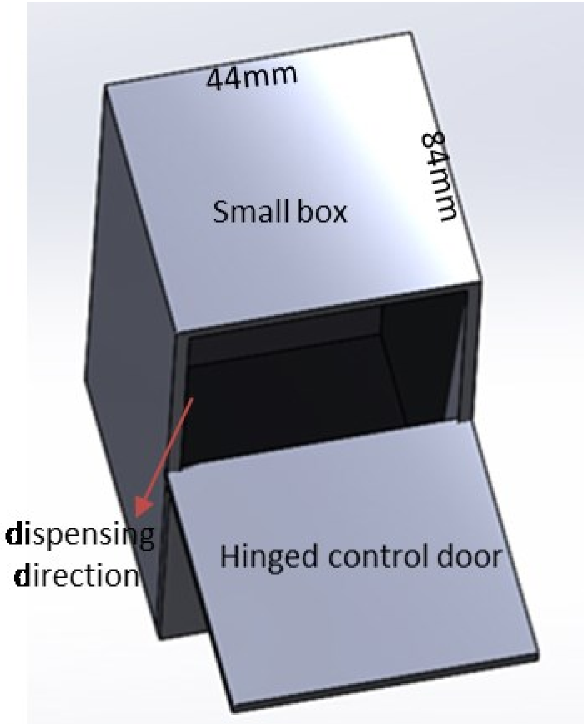


Figure 7. 4 The dimension of small NBI carrier box.

The dimension of the carriage main box is 204mm*348mm*252mm. The design was accomplished using Solidworks version 2013 development environment. For further illustration of the PUCB main design and construction, see Fig. 7.5.

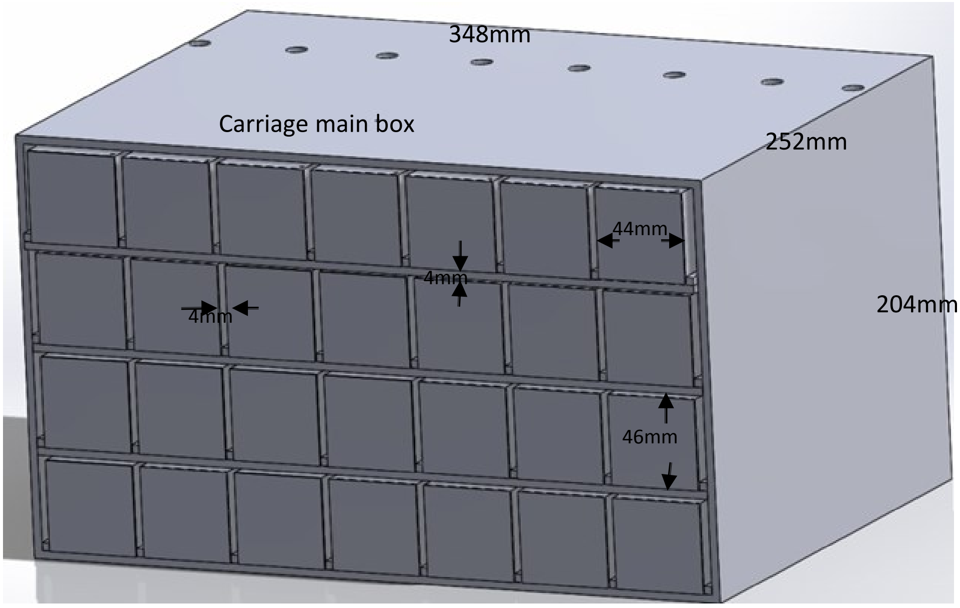


Figure 7. 5 NBI Carriage Main Box Dimension

7.6 CONCLUSION

Chapter seven outlines the materials and methodology for the various designs of all the sub-systems that make up the pest control system. The steps and the algorithm flowchart to implement the model and simulation result. Most importantly the detailed calculation of the payload design with the corresponding volume and weight of both the boxes to carry the NBI. The detailed design and dimensions of the carriage main box and the small boxes to be used in the deployment of the NB insects.

CHAPTER -8-

AUTOMATIC PEST CONTROL SYSTEM RESULTS ANALYSIS

CHAPTER -8- AUTOMATIC PEST CONTROL SYSTEM RESULTS ANALYSIS

8.1 IMAGE CLUSTERING & DETECTION

The detection stage begins by using the k-means clustering technique to segment the crop pest images. As described earlier in the previous thesis. The object(s) or pest segmentation process begins by identifying the principally green colour pixels based on using a varying threshold estimate, which assign a zero value to mainly all the red, green and blue colour components of the pixel so that all the pixel intensities that are less than the threshold value will be discarded. This technique is applied in as much as we presume that, these pixels are not useful for the pest identification. All the pixels on the boundaries of the object cluster and all the colour pigments, which are designated zero's, were deleted totally and the segmented pest and detected object result is shown in Fig. 8.1 for all the data set of Fig. 7. 2., of chapter 7.

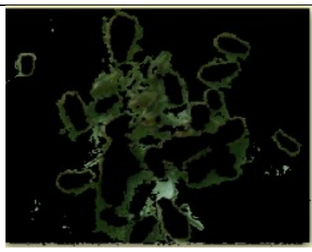
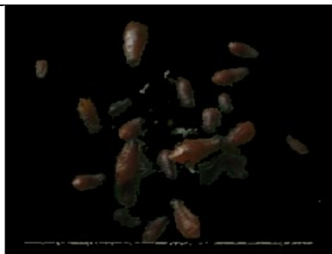
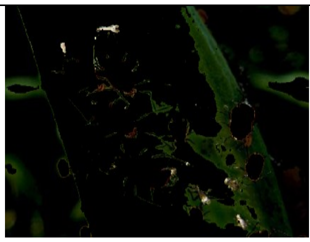
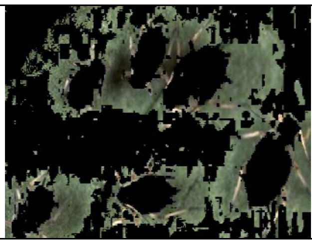
Original crop image *Column 1*	Segmented image *Column 2*	Detected image *Column 3*
		
		
		

Figure 8. 1 **Pest images detected from the detection system**

The result of Fig. 8.1 column (1) display the original crop images sent to the detection system from the pest surveillance system. Fig. 8.1 column (2) displays the segmented images according to clusters for detection. Fig. 8.1 column (3) displays the detected objects (pest images) found on the crop.

8.1.1. DETECTION SYSTEM RELIABILITY

The detection system is very reliable due to its ability to detect all forms of insects both pest and NBI and their number, no matter what the size, scale, position and orientation. The detection system is capable of revealing all the hidden objects found on the crop that may not be visible to the naked eye.

8.2 RECOGNITION VIA THE CORRESPONDENCE FILTER

The correspondence filter has been tested precisely for its detection and recognition accuracy especially for its distortion invariance ability. A subset of the training image data base is shown in Fig. 8.2. The sub-database is made up of 10 training images rotated in plane by five degree increments between each training image of the: grape root borer (line1), cowpea aphids (line 2), Japanese beetle (line 3), mosquito (line 4) and peach aphids (line 5). To optimise the recognition performance of the correspondence filter, suitable values of the tuning parameters alpha, beta and gamma had to be selected. The values of these parameters were picked by observing the impact of different values for a number of trials until the most appropriate value that yielded the best recognition ability was established. For these correspondence filters the tuning parameters chosen were α= 0.000009; β= 0.45 and Y= 0.1. The training images used are rotated in a step of 5^0 increments from 0^0 to 45^0 as illustrated in Fig. 8.2, (line 1, 2, 3, 4 and 5). Each of the training images were used to create the correspondence filter and the results of correlating the input images with the correspondence filter are shown in Fig. 8.3 (a) to (f)

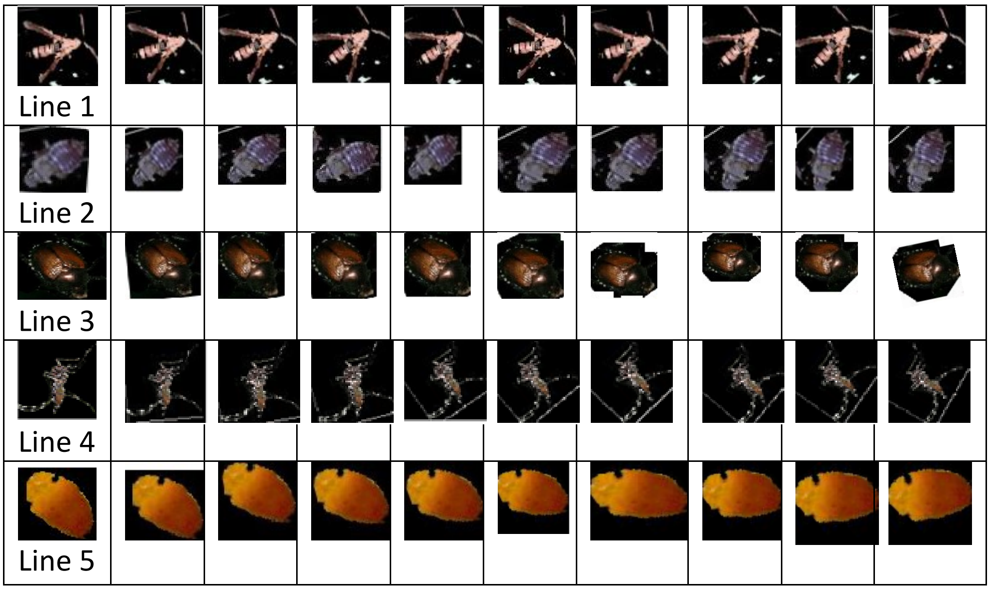
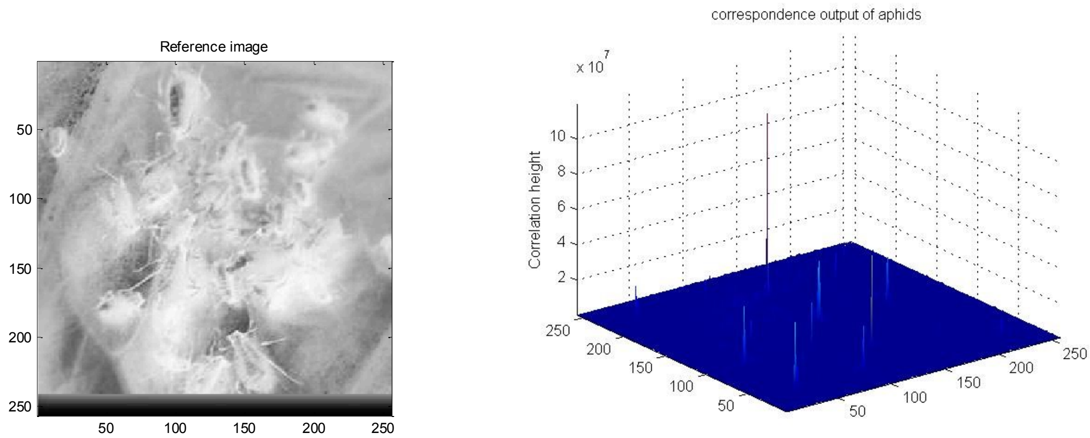
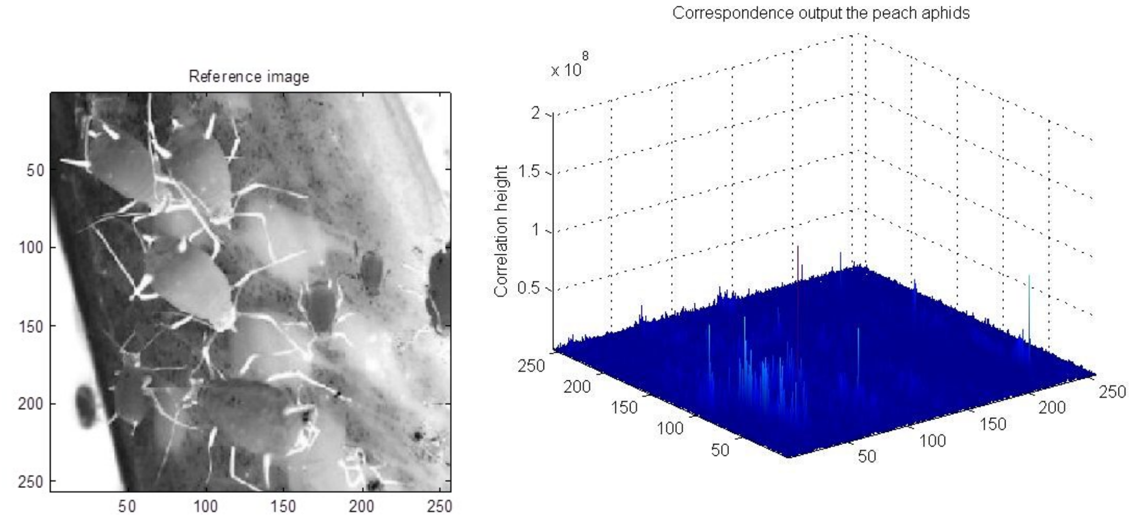


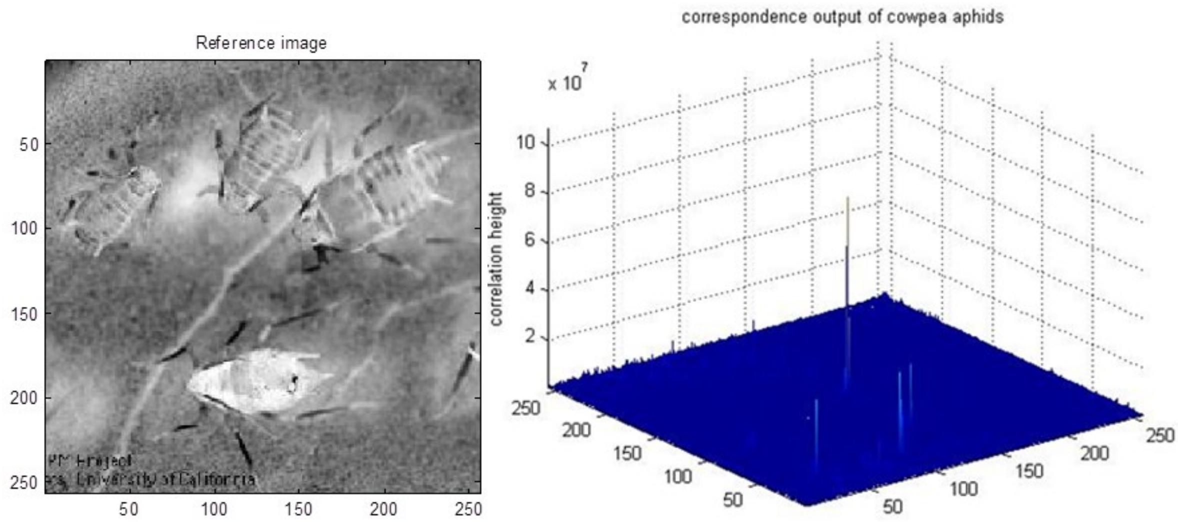
Figure 8. 2 Samples of the training image data base



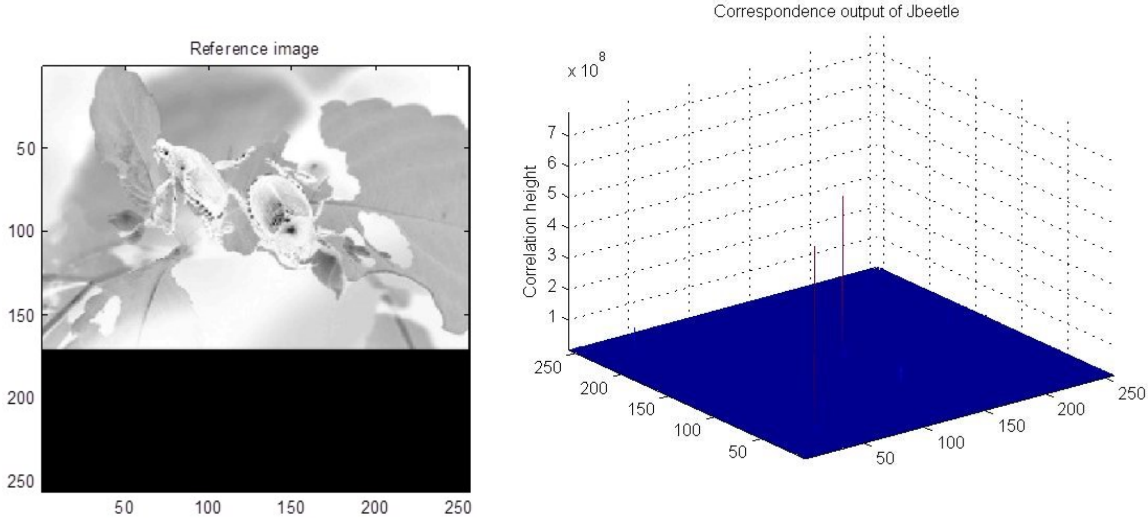
(a)


Reference image
Correspondence output the peach aphids
x 10^8
Correlation height
2
1.5
1
0.5
50
100
150
200
250

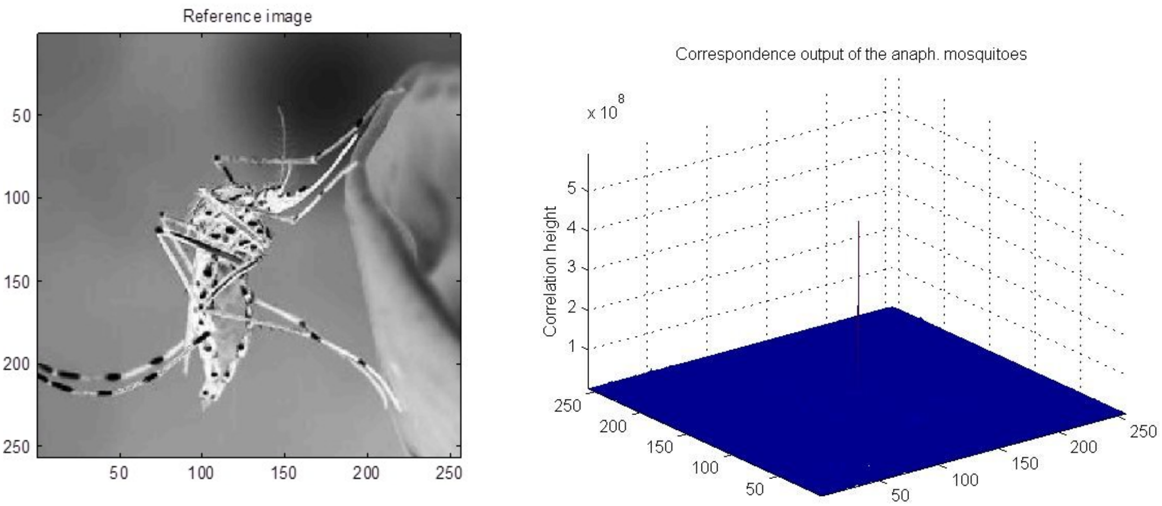
(b)


Reference image
correspondence output of cowpea aphids
x 10^7
correlation height
10
8
6
4
2
50
100
150
200
250
University of California

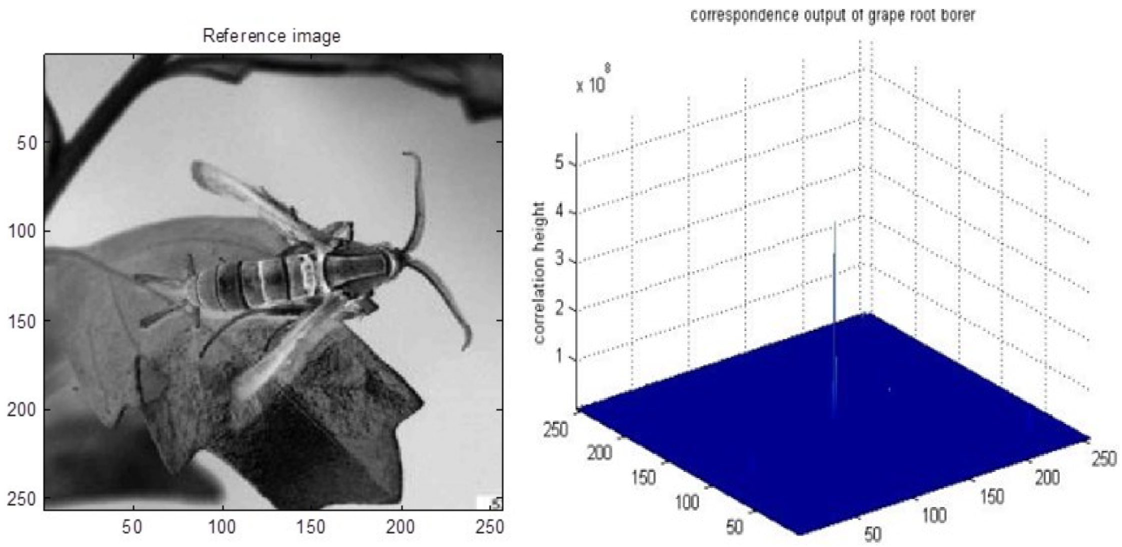
(c)


Reference image
Correspondence output of Jbeetle
x 10^8
Correlation height

(d)


Reference image
Correspondence output of the anaph. mosquitoes
x 10^8
Correlation height

(e)



(f)

Figure 8. 3 Output from the correspondence filter (a) to (f)

The plot of Fig. 8.3 shows the output from the correspondence filter of some of the detected pest images sent from the detection system to the recognition system.

The correspondence filter is able to recognise the different pest images found in the various crops forwarded to the recognition system in spite of the pest size, position and angular orientation. Fig. 8.3 (a) to (f) shows the correlation plane outputs of the filter when correlated with [0^o, 5^o, 10^o, 15^o, 20^o, 25^o, 30^o, 35^o, 40^o, 45^o] images respectively. The x-y coordinate plane of the correlation output is represented by the x and y axis and the correlation intensity is represented by the z axis. The filter performed well producing a sharp peak with little or no out-of-class peaks depending on the angular orientation. The correlation plane shows the position of the strongest peaks during scanning of the image with a target object filter. It was observed that the filter performance varies according to the species of pest and the orientation angles but definitely it outputs a peak to confirm the presence of a pest image.

8.3 CORRESPONDENCE FILTER RELIABILITY

The reliability of the correspondence filter is shown by the ability of the filter to detect and identify the number and position of bugs in the input images. For instance the input image of the species of aphids of Fig. 8.3 (a) and (b) shows the presence of numerous number of pest images on both the crops and the 3D plot. The plot further confirmed the recognition and the position of the number of bugs via the number of spikes in the correlation plane. The cowpea aphids of Fig. 8.3(c) show the presence of four bugs on both the crop and the 3D plot. The plot also confirmed the recognition and position of the number of bugs via the number of spikes. Fig. 8.3 (d) displayed both two Japanese beetles on the crop and two spikes on the 3D plot, Fig. 8.3 (e) and Fig. 8.3 (f) shows only one spike to confirm the presence of only one bug in the input images of the mosquito and the grape root borer.

The peak of the matrix occurs where the pest images are best correlated yielding a maximum correlation height, equivalent to +1.0 and above. The results reported show accurate matching between the input images processed using the k-mean clustering algorithm and the correspondence filter training images. The results confirmed the presence of homogenous and similar objects, which proves that the pest detection and recognition algorithm is working effectively. The reliability of the algorithm is shown to be excellent as the filter can respond to in-plane rotation of the pests from 0^0 to 360^0.

8.3.1 INVARIANCE AND DISTORTION RANGE OF THE FILTER

To confirm the invariance and distortion range of the correspondence filter, all the pest images, as listed, above were correlated at different angular positions and the response observed is as shown in Fig. 8.4.

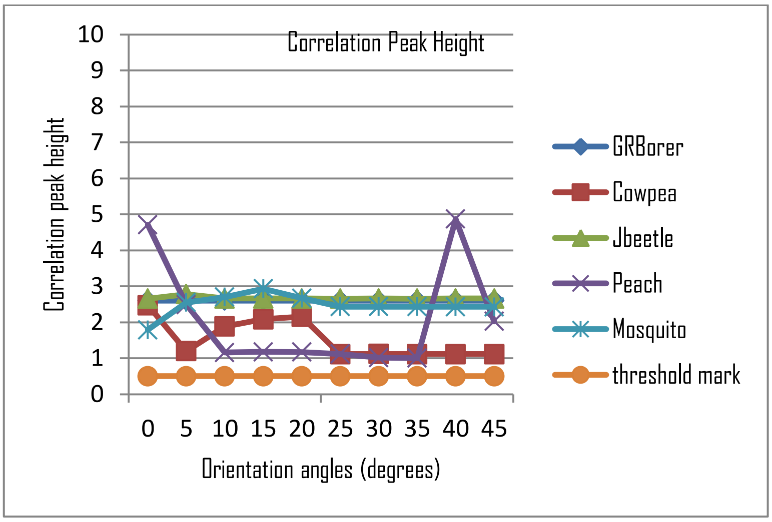


Figure 8. 4 Orientation rotation angles

The plot of Fig. 8.4 shows the correlation peak height of the training set over the orientation range of [0^o to 45^o] at 5^o increments for the filter. The test set consists of the pest images over the same range. The correlation peak height of all the training images varies slightly but still stays well above the detection threshold mark, which proves that the filter is totally rotationally invariant around the entire angular range.

Looking at the plot of Fig. 8.3, all the pest images plotted were confirmed present despite their angular position or distortion. The result illustrates the capability and the invariant nature of the correspondence filter to respond to all the distorted images of the pest at different positions, from 0^0 to 360^0, the filter's response for 45^0 of rotation shows an upward trend with the bug rotation.

The reliability of the APDR algorithm is based on the ability of the algorithm to distinguish and sort between several species of pest images, predators and parasitoid wasps at different scales, sizes, shape and orientations. At this point the recognition of the exact specie and population of each pest is established from the output spikes displayed in the correlation plane.

8.4. OPTIMIZATION STATISTICAL PEST CONTROL (OSPC) SIMULATION RESULTS

The simulation result of the pest control system is shown in different phases starting from the Weibull probability distribution function (chapter 6 section 6.3) that makes possible the determination of the mortality rates of all the pest and the naturally beneficial insects as shown in Table A0.18 to Table A0. 21- Appendix A4.

The data retrieved from the Weibull plot of Fig. A4.1, to Fig. A4.4 - Appendix A3, obtained from the program code [see Appendix A5] in combination with the pest life span data of Table A0.7 to Table A0. 15- Appendix A1, is use to establish the insects mortality rate. From the mortalities established in Table A0.18 to Table A0. 21- Appendix A4, the following simulation possibilities results were obtained

8.4.1 EXPLORING THE CONTROL POSSIBILITIES

This section explores the control possibilities by the deployment of different combinations of the different stages and species of parasitoid wasps and predators in any pest infested habitation. This section gives an understanding of the most economical approach to pest management in any infested habitat by using NBIs to control the infestation to an economically viable level. The application of chemical pesticides is highly discouraged as this will kill the NBI.

8.4.2 SIMULATION TEST RESULTS OF THE DIAMONDBACK MOTH WITH PARASITOID WASPS

The first scenario test result considers a situation where there is a pest free environment. A cabbage growing field was used as an example in this experiment. 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 result is plotted in Fig. 8.5, this shows the normal uninterrupted growth rate of the crop over an interval of 90 days, the leaf population increased from 130 to 324 per cubic metre.

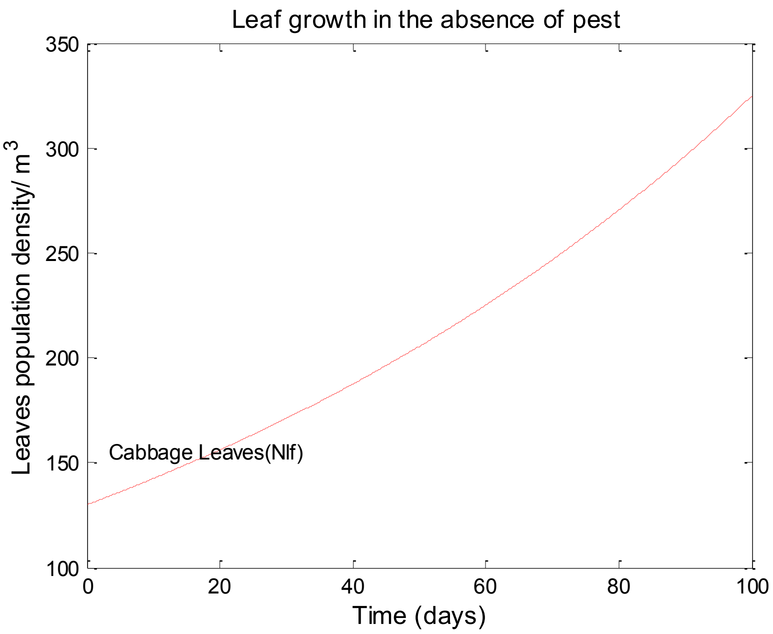


Figure 8. 5 **Pest free crop habitation**

In Fig. 8.6 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 1154 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 collapse of the leaf to 19 leaves and dependant larva population to 226 larvae causes the pupae population to fall to steady metastable values of 164 pupae.

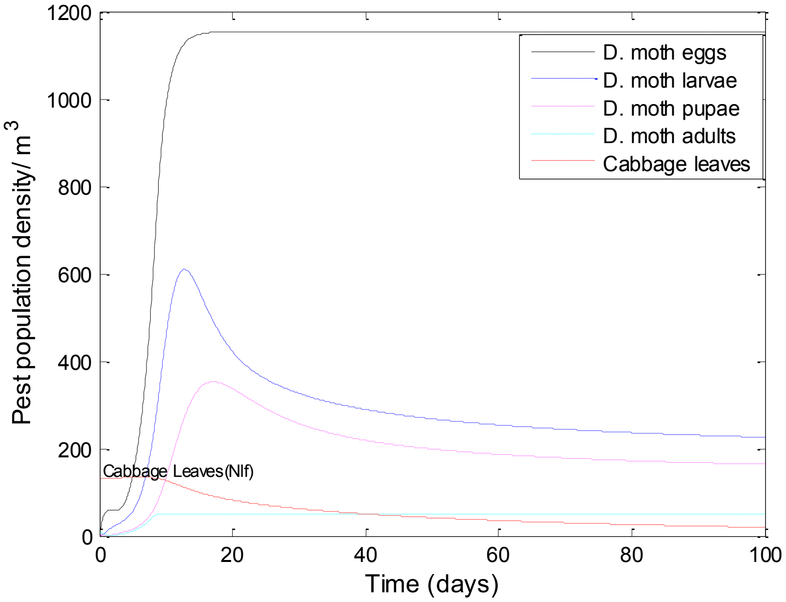


Figure 8. 6 Effect of moth visitation on the crop habitat

In Fig. 8.7, the initial population densities are: 10 moths, 150 eggs, 100 larvae, 85 pupae, 130 leaves. As before we assume that each moth lays 15 eggs per day. The populations of the parasitoid wasps (N_{ew} = N_{lw} = N_{pw} =0) are set to zero. The results in Fig. 8.7, illustrate the negative effect of moth larvae, as the leaf population continues to drop from day 4 across the 100 day period to < 18. The moth population saturates after about 3 days due to the limited carrying capacity of the environment, this is reflected in the egg population, which also saturates at 1154 in 15 days.. The results of Fig. 8.7 also show a drop in the population density of the larvae at about 9 days as a result of the fall in leaf population. This response is similar to Fig. 8.6 but things are just happening more quickly due to the initial populations of: eggs, larvae and pupae. The rest of the results reported hereafter use the same initial population densities.

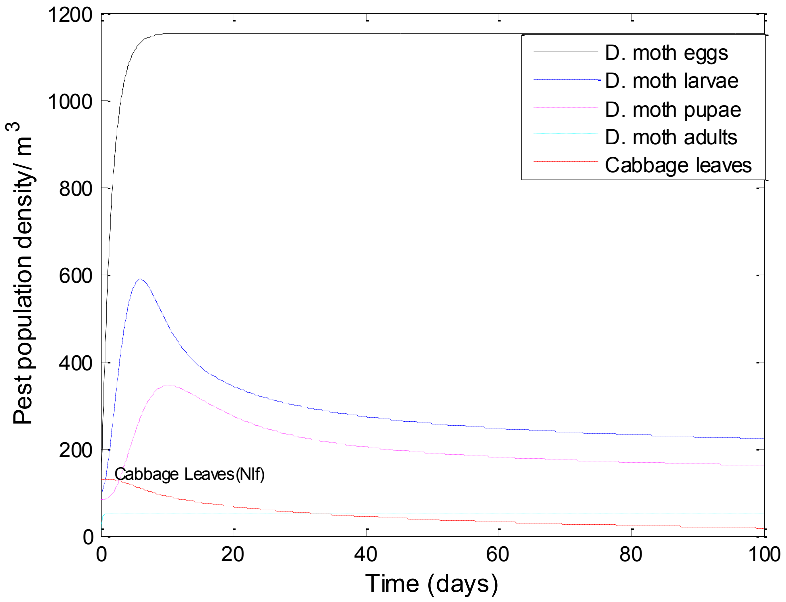


Figure 8. 7 Pest destruction of cabbage growth

8.4.3. 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 below.

8.4.3.1 SCENARIO 1 – DEPLOYMENT OF A SINGLE (EGG) SPECIES OF PARASITOID WASP

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. The first step was to deploy different single species of parasitoid wasp to determine their effect on the density of pests; the results are shown in Fig. 8.8, & Fig. 8.9. In Fig. 8.8, thirty pupal parasitoids (N_{pw}) were deployed and in Fig. 8.9, thirty egg parasitoids (N_{ew}) were deployed. This is to evaluate the effectiveness of the egg and pupal wasp species for pest control. The results of Fig. 8.8, illustrate the inability of the pupal parasitoids alone, to exercise effective control of the pest infestation, as shown in Fig. 8.8, there is an overall decrease in leaf population to < 125 in 100 days. Due to the suppression of the pupae in Fig. 8.8 the moth population density never reaches the environmental carrying capacity and this suppresses the egg population density to a peak of 955 much less than 1154 eggs and a peak of 500 larva much less than 609 in Fig. 8.7 ; the pupal parasitoid wasps were able to control the density of the moth pupae to a value of 4 pupae, 28 larvae and 68 eggs.

In Fig. 8.9, the leaves are observed to be destroyed from day 3 through the 60 days of the observation. The egg parasitoid displays its control ability as it suppressed the moth egg population density, which peaks at 941, then drops to 493 in 60 days; the leaf growth decline across the 60 days to 63, due to the destructive nature of the moth larvae. The moth reaches the environmental carrying capacity of 50 within the first few days. Fig. 8.9 illustrates the inability of the egg wasps alone to control pest infestation. In all cases, as the host population decreases the parasitoid wasp population starts to decrease leading to some recovery in the host population Fig. 8.8, the model demonstrates the classic prey/predator oscillation in population density but overall the pest population is decreasing with time.

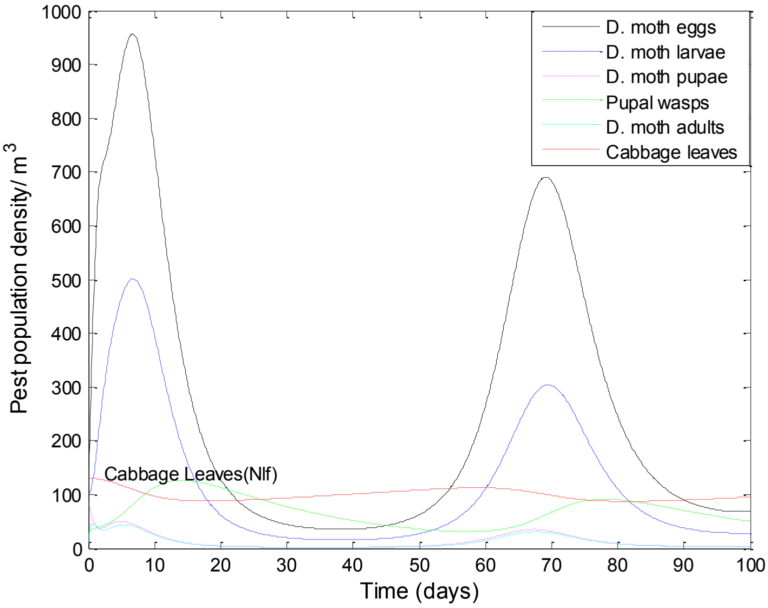


Figure 8. 8 Effectiveness of Pupal parasitoid wasp in reducing pest population density

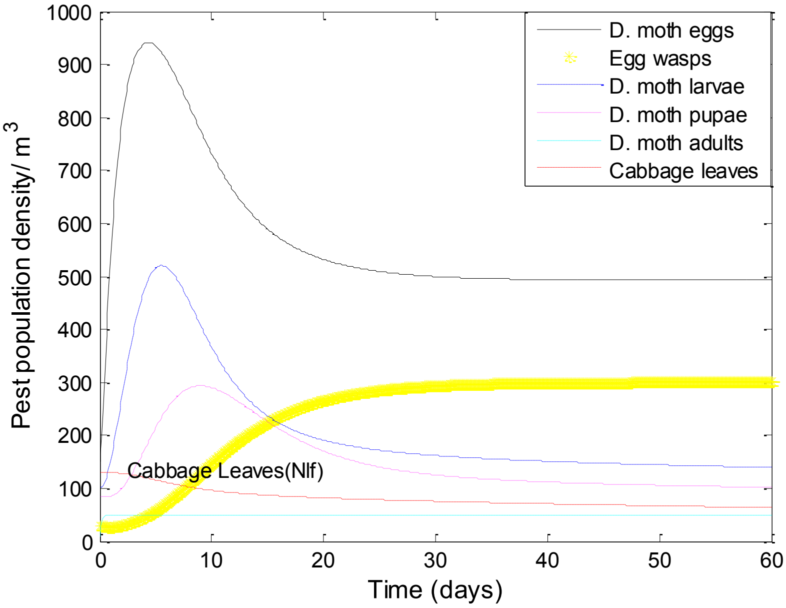


Figure 8. 9 **Effectiveness of Egg parasitoid wasp in reducing pest population density**

8.4.3.2 SCENARIO 2 – 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 combination were deployed simultaneously; the outcome is as illustrated in Fig. 8.10, & Fig. 8.11. In all cases the moth population density is well below the environmental carrying capacity.

In Fig. 8.10, 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 less than 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. 8.11, thirty larval and thirty pupal parasitoid wasps were deployed into the habitat. The result shows the maximum pest population grows to: 663 eggs, 174 larvae, 75 pupae and 28 moths. Due to the control effected by 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 Fig. 8.10 and Fig. 8.11, show reasonable control of the pest density when two wasp species are deployed simultaneously, rather than just deploying a single class of wasp. Better control is achieved when the larval parasitoid wasps are combined with either the egg or pupal parasitoid, as there is an increase in leaf growth as illustrated in Fig. 8.11. in Fig 8.11 from about the 7th day, the pest population was subdued and leaf growth rises up due to the combined efforts of the larval/pupal parasitoid wasps; this gives a better performance than deploying the egg /pupal parasitoid wasp combination, as illustrated by Fig. 8.10. 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 deployment.

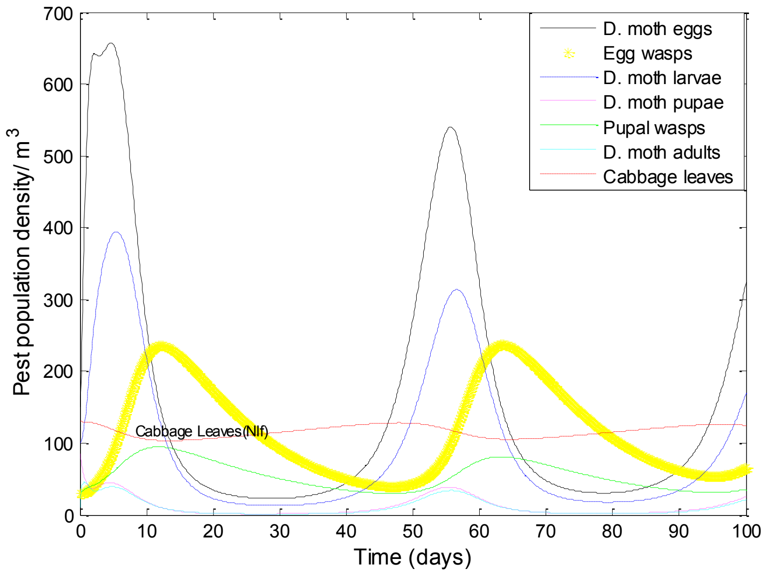


Figure 8. 10 Effectiveness of Egg and Pupal parasitoid wasps in reducing pest population density

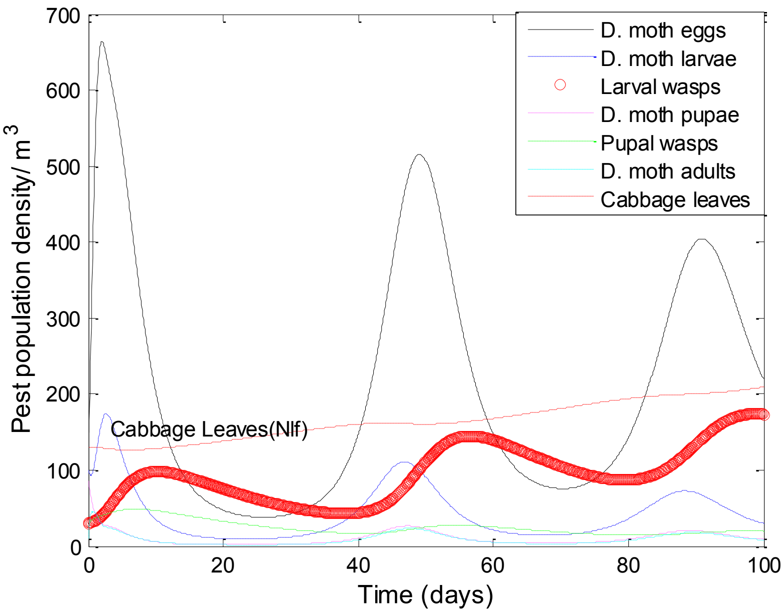


Figure 8. 11 Effectiveness of Pupal and Larval parasitoid wasps in reducing pest population density

8.4.3.3 SCENARIO 3 – THE DEPLOYMENT OF 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. 8.12 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 egg, larvae, pupa and moth were reduced to 57, 17, 6 and 3 respectively; which are economically viable values, with the populations moving towards equilibrium.

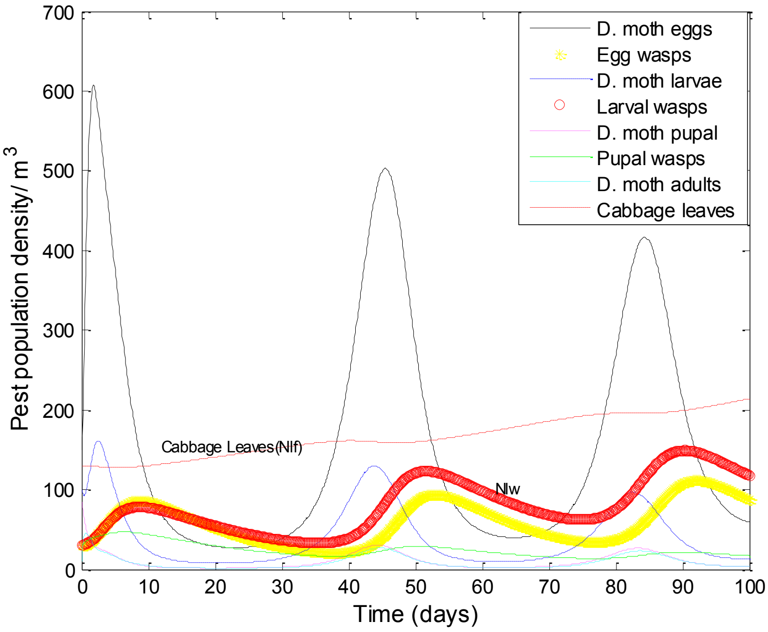


Figure 8. 12 Effectiveness of all three parasitoid wasps in reducing pest population density.

8.5 RESULT ANALYSIS

8.5.1. DIAMONDBACK MOTH AND PARASITOID WASPS

In Fig. 8.5, 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 from130 leaves/m^3 to > 325 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. 8.6, 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. 8.7, the larvae population drops more rapidly due to the initial pest population, this results in a greater leaf destruction rate and a shortage of food for the larvae. The moth and egg population density are limited by the environmental carrying capacity.

The pupal parasitoid wasps deliver reasonably effective biological pest control when deployed alone, Fig. 8.8, and when combined with the larval parasitoid as illustrated by, Fig.

8.11. 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. 8.6, and Fig. 8.7, shows 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 results of Fig. 8.8, and Fig. 8.9, show pest density suppression by the pupal and egg parasitoid wasps alone; although there was suppression in Fig. 8.8 & Fig.8.9, there was a large increase in the population density of the moth eggs peaking at 953 and dropping to 69 in Fig. 8.8 and peaking at 941 eggs and dropping to 492 eggs after 100 days; whilst in Fig. 8.12, the moth egg, larvae, and pupae density peaks at 601 eggs, 160 larvae and 65 pupae before dropping to 57 eggs, 13 larvae and 4 pupae. 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, see Fig. 8.12.

8.6 THE RESULT OF THE MODEL OF INTERACTION BETWEEN THE SCARAB BEETLES AND TWO LARVAL PARASITOID WASPS

The model of interaction between the Scarab beetles and the parasitoid wasps considers an established infestation of Cocoyam or Taro beetles with numerous populations of the adult, eggs, larvae and pupae. For this simulation model 10 Cocoyam adult beetles were used with an initial population of 60 eggs, 40 larvae and 20 pupae per square metre of cocoyam cultivated field, the population density of the beetles' increases as illustrated in Fig. 8.13, with great damage to the cocoyam field. The environmental carrying capacity was set to 25 beetles per square metre.

To control the damage to the field 6 *Scoliid* and 6 *Tachinid* wasps were introduced into the infested habitat. Fig. 8.14 illustrate the result for a 90 day period.

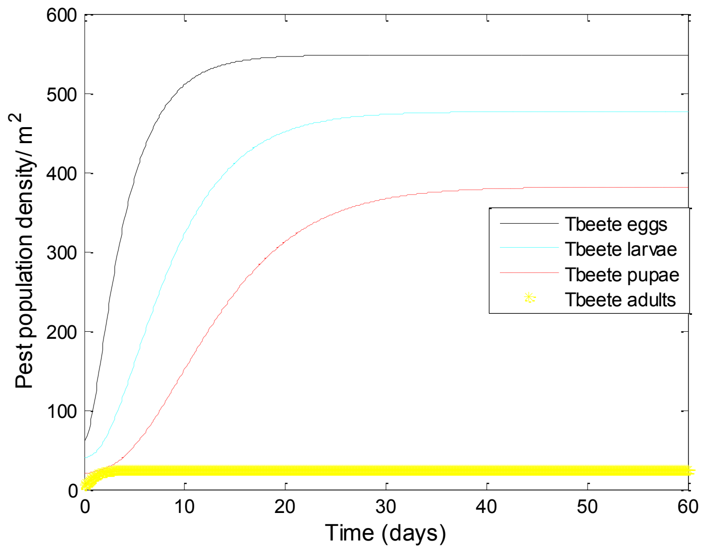


Figure 8. 13 Scarab beetles rate of increase in the absence of any control measure

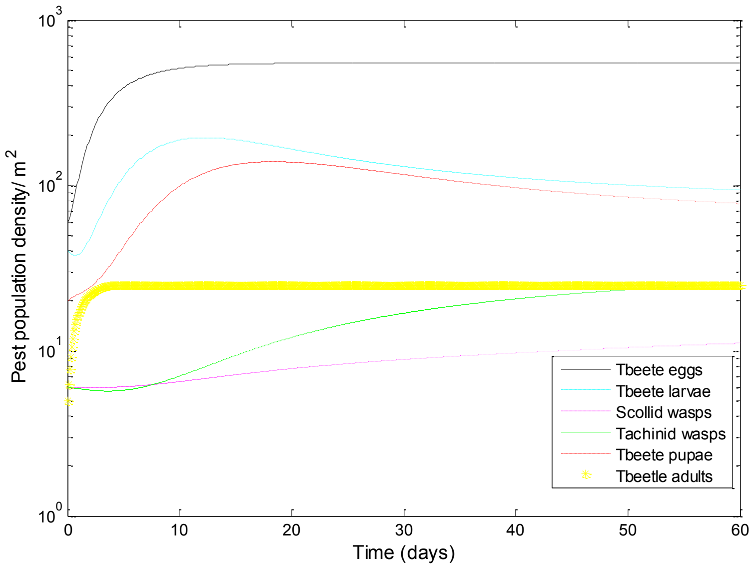


Figure 8. 14 The effect of beneficial insects on the control of scarab beetles establishment

The result of Fig. 8.13 shows that it is possible to have Scarab beetle outbreaks when an ecosystem is left unattended, as observed by the reproduction rate of the Scarab beetles on the cocoyam corm field within an interval of 60 days. The population increased from an initial starting population of 60, 40, 20 and 10 for the egg, larvae, pupae and adults to a peak of 549 eggs, 477 larvae and 382 pupae and the adult population reached the environmental carrying capacity, rising from the initial 5 to 25 adult's beetles in six days.

The result of Fig. 8.14 shows a measure of control is exhibited when the *Scoliid* and *Tachinid* wasps were introduced into the habitat, the population of the beetles larvae and pupae where under firm control. There was an increase from the initial population densities of 40 and 20 for the larvae and pupae to peak at 195 larvae and 139 pupae during the first 13 days and 19 days. The wasps suppressed these populations to 84 larvae and 68 pupae over a 90 day interval. However, the adult and eggs populations were not suppressed as the population had reached the maximum limit of 25 in 6 days, also because the wasps introduced here can only attack the 2nd or 3rd instar larvae stages. Any larvae that escapes parasitism will transform to pupae and then into adults that continue reproduction.

8.6.1 ANALYSIS OF SYSTEM

From our model, we are able to identify that Scoliidae and Tachinidae wasps can only attack the larvae stage of scarab beetles, therefore any larvae that escape attack will definitely undergo transformation to the adult stage, thereby continuously increasing the number of the adult beetles, whose population will only be reduced by natural mortality.

The adult will continue reproducing and will only die at the due time because there is no control measure to terminate the adult beetles. As long as the adult female beetles live, daily reproduction is certain.

The model demonstrates control of the beetles' larvae and pupae population to an acceptable level, given time. The use of pesticides has the tendency to cause pest outbreaks because, insecticides do not only kill the pest but will completely eliminate the naturally beneficial parasitoid wasps.

We therefore recommend the deployment of *Scoliidae* and *Tachinidae parasitoids* in combination with the introduction of a biocontrol agent either a virus or a fungus, which can attack the adult beetles to force its population down.

Care should be taken when choosing a virus or fungi, in order not to create an ecological disaster by eliminating both the adult beetles with a concomitant effect on the naturally beneficial insects.

8.7 THE RESULT OF THE MODEL OF INTERACTION BETWEEN THE SPODOTERA EXAMPTA AND A SINGLE LARVAL PARASITOID WASP

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, Amarillo.*osti.gov, 2014)*. 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, 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. 8.15. 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. 8.15, to Fig. 8.20.

8.7.1 RESULTS AND OBSERVATIONS - PERFORMANCE OF COTESIA FLAVIPES (CAMERON)

8.7.1.1 A CONSTANT MAIZE LEAF GROWTH

Fig. 8.15 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. 8.15 shows the normal uninterrupted growth rate of the crop over an interval of 100 days, the leaves increased from 68 to 281.

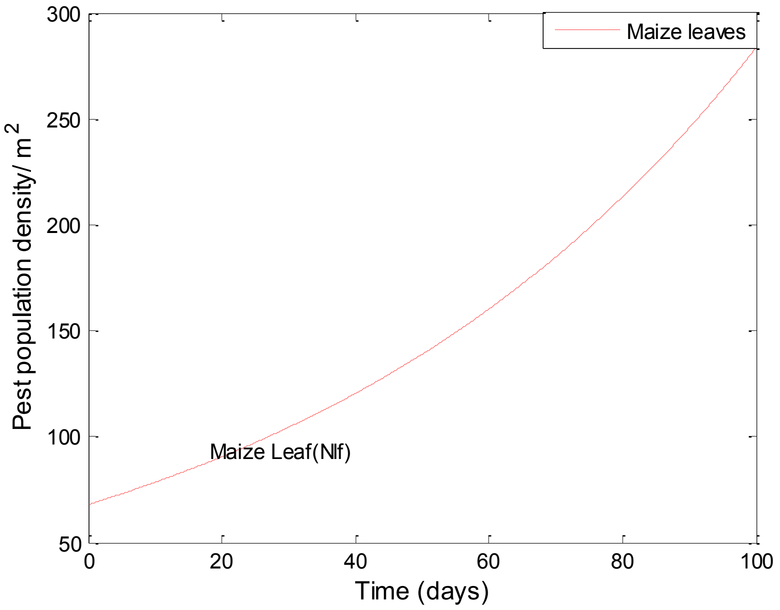


Figure 8. 15 Leaf growth in the absence of pests

8.7.1.2 SPODOPTERA EXEMPTA (SE) VISITATION

In Fig. 8.16, 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 after 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.

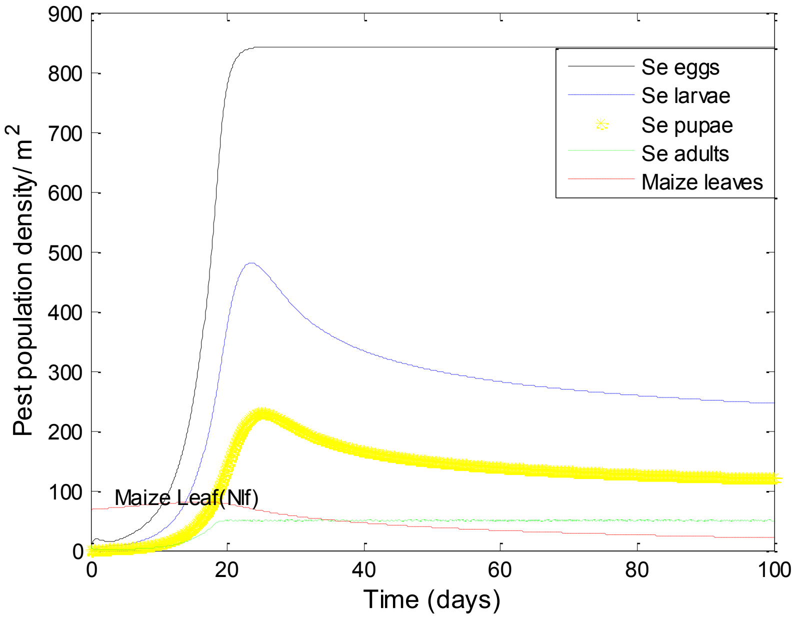


Figure 8. 16 **The effect of Spodoptera Exempta (Se) visiting the maize field habitat**

8.7.1.3 INTRODUCTION OF A CONTROL MEASURE

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. 8.17. In Fig. 8.17, the leaf population drops 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 moths egg density is still high at 179.

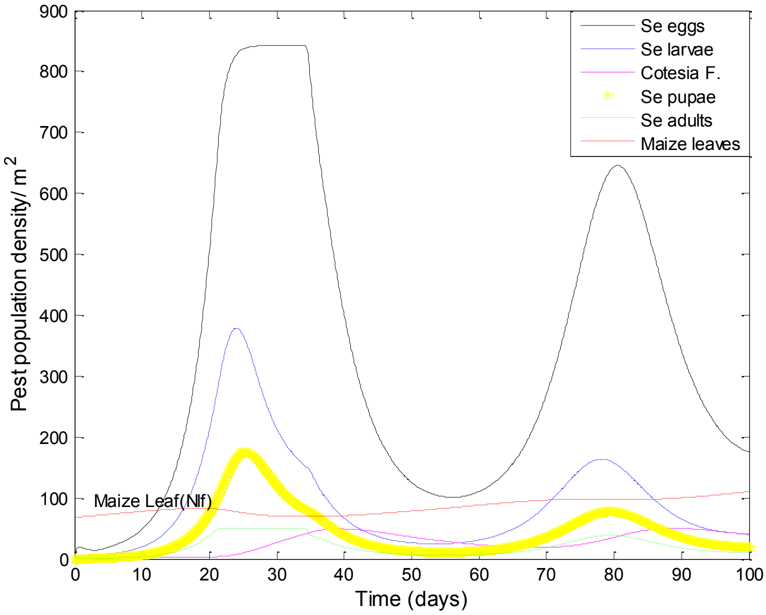


Figure 8. 17 **Effect of deploying five *Cotesia Flavipes (Cameron)* larval wasps**

Step 2: due to the losses observed in the leaf population of Fig. 8.17, 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. 8.18. In the result of Fig. 8.18, 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. 8.18, 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 wasp's 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.

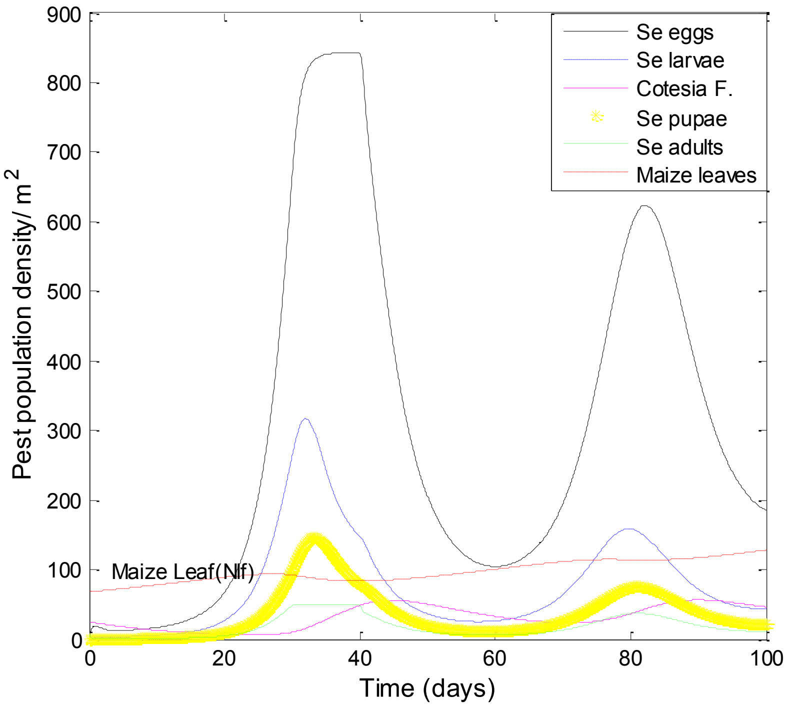


Figure 8. 18 Effect of deploying twenty five *Cotesia Flavipes (Cameron)* larval wasps

8.7.1.4 MODEL RELIABILITY

From the result of Fig. 8.16, there was a severe leaf loss 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. In the first 18 days there was an initial leaf growth to 81 from the initial leaf starting value of 68. Continuous leaf destruction was noted when the larvae population grew to a peak of 481 in 24 days.

From the result of Fig. 8.17, it was observed that, the presence of Cotesia wasps introduced early into the habitat has a 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. 8.17, and Fig. 8.18 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 no hosts for the wasps. This highlights the importance of not totally destroying the Se population, the wasps need them.

From the result of Fig. 8.18, 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. 8.18 when 25 *Cotesia Flavipes (Cameron)* wasps were introduced, 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 raise the leave growth to 129 after 100 days, with a significant drop in the population of the larvae to 44.

8.7.1.5 ESTABLISHED INFESTATION

In a scenario where an infestation is already established as illustrated in Fig. 8.19, 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. 8.19 that the initial 5 *Cotesia Flavipes (Cameron)* population started to rise contrary to our previous observations in Fig. 8.17, and Fig. 8.18, 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 pest population to a symbiotic level. The most favourable result was observed when twenty five *Cotesia Flavipes (Cameron)* wasps were introduce as indicated in Fig. 8.20.

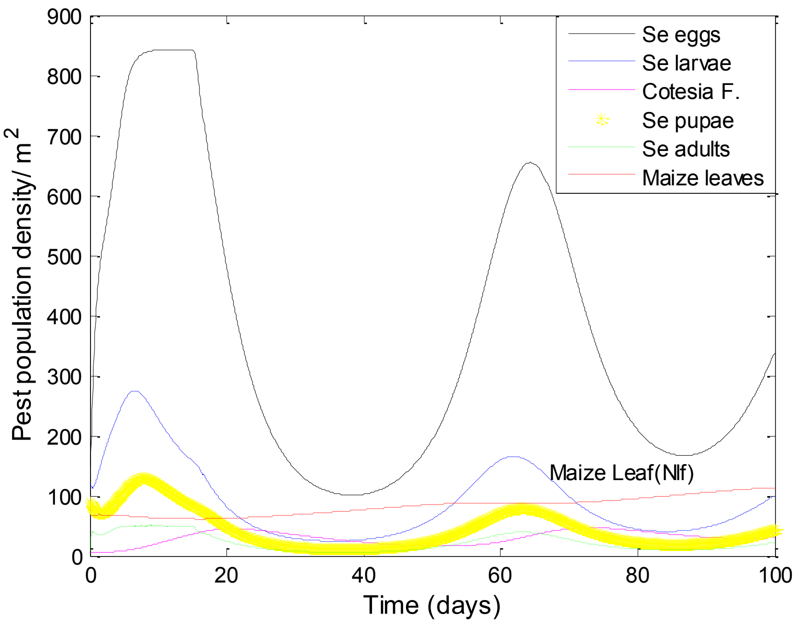


Figure 8. 19 Effect of five Cotesia Flavipes (Cameron) wasps on an established infestation

In a scenario where an infestation is already established as illustrated in Fig. 8.20, 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 population 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.

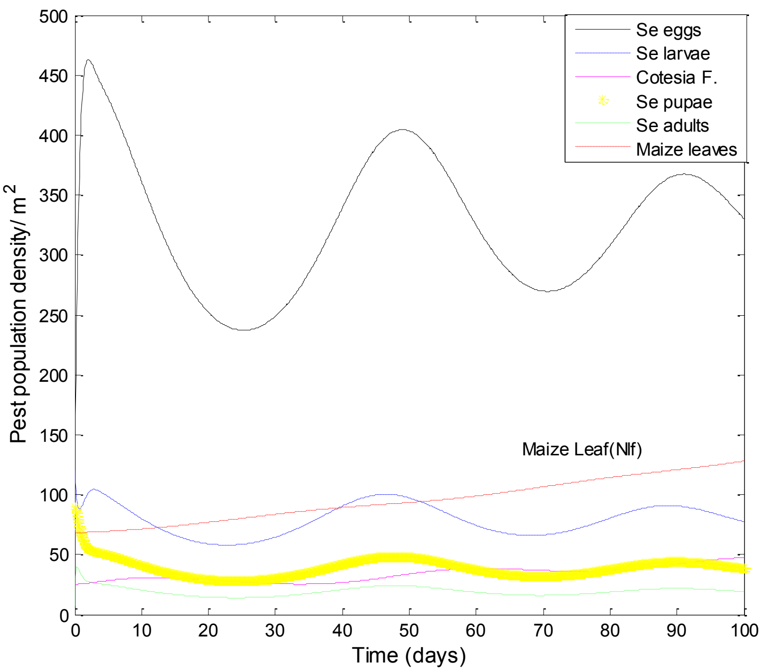


Figure 8. 20 Effect of twenty five Cotesia Flavipes (Cameron) wasps on an established infestation

8.7.2 RESULTS ANALYSIS OF A SINGLE LARVAL WASPS (COTESIA FLAVIPES (CAMERON))

In Fig. 8.15, 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 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. 8.16, 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. 8.17, 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. 8.19, also illustrates the destructive nature of caterpillars in an established infestation, initially there was a small decrease in the leaf population. Fig. 8.18, and Fig. 8.19 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 Fig. 8.18, and Fig. 8.20. 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 Fig. 8.17 & Fig. 8.18, 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, it also estimates the time required 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. 8.18, and Fig. 8.20. 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**,** (Faithpraise et al., 2014e)**.**

This pest control approach will result in the production of high quality crops with good yield. Furthermore, there will be a great reduction in health hazards and difficulties triggered from contact with the caterpillar.

8.8 THE RESULT OF THE CONTROL OF AFRICAN ARMYWORM WITH EGG AND LARVAL PARASITOIDS

Our aim is to find lasting preventive control measures to the problems of pest outbreak, which has caused so much harm to nations and the agricultural sector and also to understand how effective the combined efforts of both the *Trichogramma* and *Tachinidae* NBI can be when deployed for pest management and control.

In this illustrative simulation we consider a square metre area of Sorghum growing habitat with 5 -7 plants per square metre each with 8 – 22 leaves per plant, (Tamworth, 2011). We assume an initial equilibrium population density of 7 adult female African armyworm moths, which each lay an average of 150 eggs per day. In the first instance the model is run with only an assumption about the number of invading armyworm moths, with zero initial number of pest: eggs, larvae or pupae. We then explore how to control pest infestations using parasitoid wasps that can be delivered via a UAV (Faithpraise et al, 2013c).

8.8.1 MODELLING CASES

8.8.1.1 CASE 1. SORGHUM LEAF GROWTH

Sorghum field without any African armyworms is as shown in Fig. 6. 4(a). The simulated result of sorghum leaf growth in the absence of pests is given in Fig. 8.21. The result shows the normal uninterrupted growth rate of the crop over an interval of 90 days as the leaves increased from 110 to 229 per square metre. The result of Fig. 8.21, illustrates the constant growth of the sorghum field in favourable conditions and in the absence of any pest infestation.

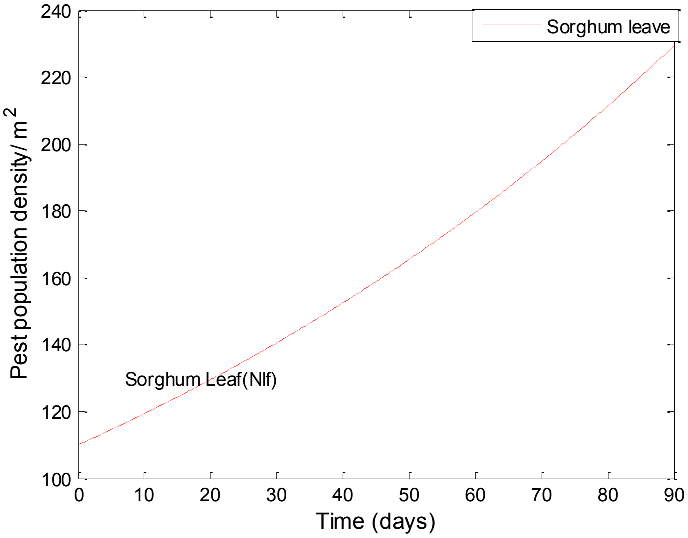


Figure 8. 21 Leaf growth In the absence of pest

8.8.1.2 CASE 2. AFRICAN ARMYWORM MOTH VISITATION

In order to monitor the activities of the crop pests in the newly grown field, a plant pest surveillance system will be deployed, this is described in, (Faithpraise et al, 2013e). This system is able to keep records of all activities of pest invaders and take snap shot images of the pest. Once the images are taken, the files are uploaded into the plant pest detection and recognition system, design by (Faithpraise et al., 2013a) to assess if there are areas of the field that constitute a threat. The moment the surveillance system confirms the presence of armyworm moths as illustrated in Fig. 6.4(b) action can be taken.

On average each of the moths can lay eggs in batches of 150, which hatch into larva (caterpillar) within two to five days, this is the damaging stage of the moth. Within an interval of seven days, the field will be mutilated as shown in Fig. 6.4(c). The simulation result for the African armyworm moth visitation is shown in Fig. 8.22.

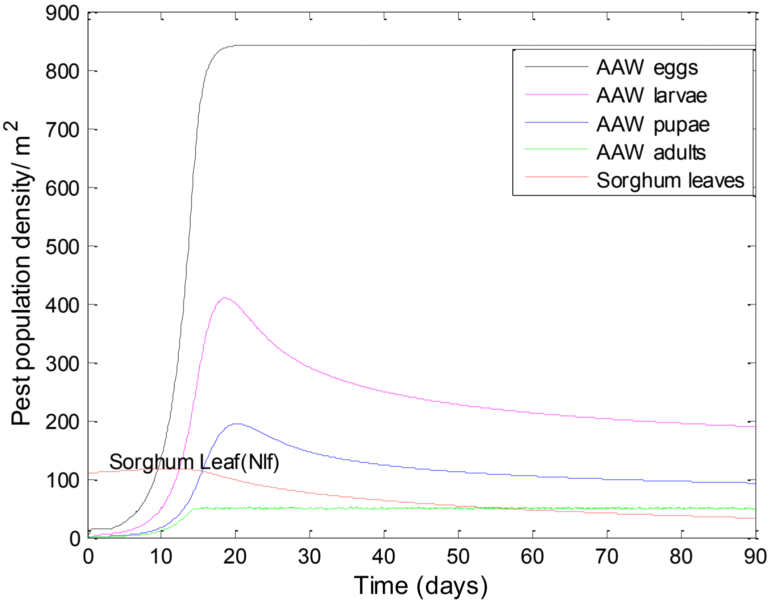
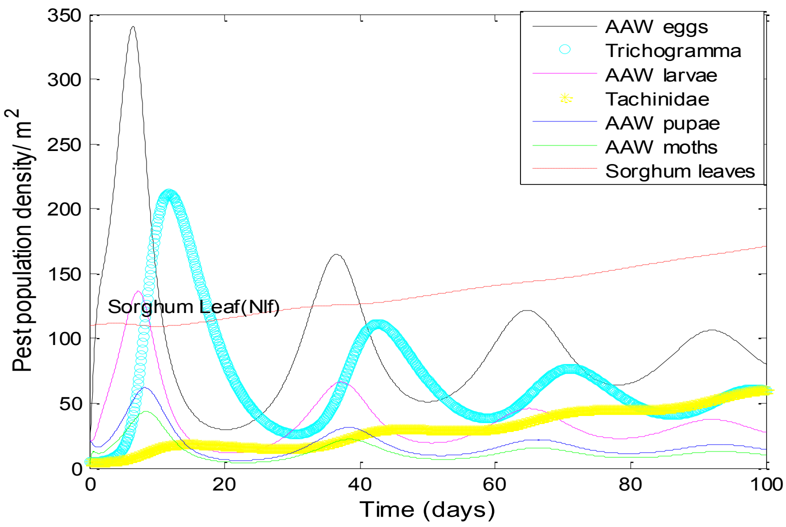


Figure 8. 22 Pest activities in the absence of control measure

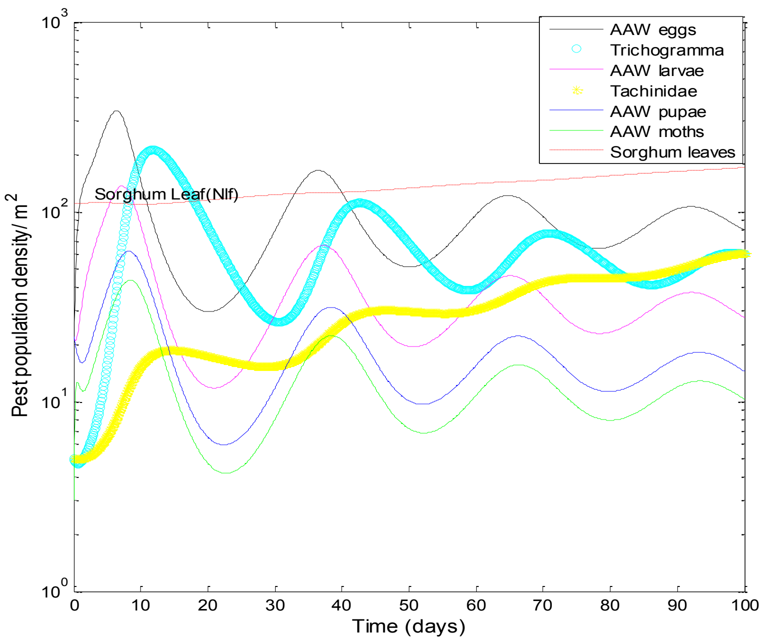
From the result of Fig. 8.22, it was observed that in the absence of any control measures, the armyworm moth reproduced prolifically and reached its environmental carrying capacity of 50 within 14 days; the egg production peaks at 843 eggs in 21 days, and the larvae density peaks at 402 larvae in 19 days while the pupae peaks at 192 in 20 days. This increase in the pest population had an adverse effect on the growth of the sorghum leaves as the leaf growth declined from an initial increase to 117 in 11 days, to 33 leaves after 90 days. This result illustrates the voracious nature of the larvae (caterpillar).

8.8.1.3 CASE 3. PARASITOID PREVENTIVE CONTROL WITH A SMALL INITIAL PEST LIFE CYCLE POPULATION

A simulation experiment was set up with the introduction of five (*Trichogramma)* and five (*Tachinidae*) parasitoid , still with the initial population of five African armyworm moths The initial population of AAW eggs, larvae and pupae, was given a nominally small value of twenty-two for each life cycle stage, this is required to allow the wasp population to survive, with zero population of pest eggs and larva the NBI population will fall, case 4 demonstrates this. The result of the simulation experiment is shown in Fig. 8.23 (a) & (b)



(a)



(b)

Figure 8. 23 Effect of deploying five of both the egg and larvae parasitoids , with the initial pest lifecycle stage populations: eggs, larvae and pupae set to 22 each; (a) normal plot (ai) semi-log plot

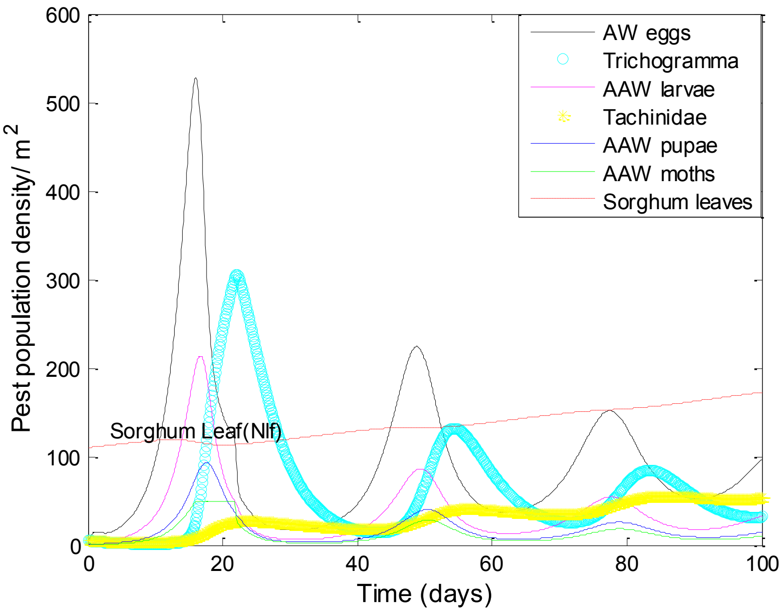
The result of Fig. 8.23(a) shows constant leaf growth to 113 for the first 8 days, after which it declined constantly to 110 leaves for 7 days as the pest population peaks at 339 eggs, 136 larvae, 61 pupae and 44 moths in less than 14 days.

The effective control exerted by both parasitoid wasps was observed by the decline of the pest population to 79 eggs, 27 larvae, 14 pupae and 10 moths with a corresponding constant leaf growth to 171 across the 100 day period.

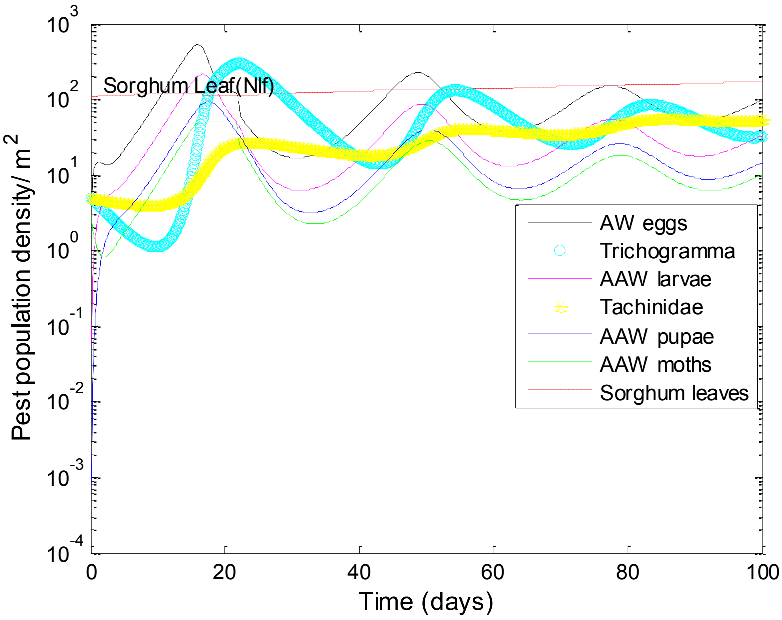
From the result of Fig. 8.23(a), the introduction of the five egg and larva parasitoids has a great effect in preventing pest outbreak as successful control was observed within 30 days, furthermore the pest population was maintained to a low level for the 100 day trial period. The semi-log plot in Fig. 8.23(b) shows that the starting population of pest eggs and larva is sufficient to maintain initial growth of the *Trichogramma* and *Tachinidae* populations.

8.8.1.4 CASE 4. PARASITOID PREVENTIVE CONTROL WITH ZERO INITIAL PEST LIFE CYCLE POPULATION

A simulation experiment was set up with the introduction of 5 *Trichogramma* and 5 *Tachinidae* parasitoids with an initial population of 5 African armyworm moths. The initial populations of AAW eggs, larvae and pupae were all set to zero, the result of the simulation experiment is shown in Fig. 8. 24(a) & (b).



(b)



(b)

Figure 8. 24 Effect of deploying five of both the egg and larvae parasitoids, with five pest adult moths and zero initial pest lifecycle population (eggs, larvae and pupae = 0); (a) normal plot (b) semi-log plot

The result of Fig. 8.24(a) shows constant leave growth to 118 for the first twelve days, after which it declined constantly to 112 leaves for 14 days as the pest population peaks at 483 eggs, 195 larvae, 85 pupae and 50 moths in less than 18 days.

The effective control exerted by both parasitoids was observed by the collapse of the pest population to 113 eggs, 39 larvae, and 17 pupae with a corresponding constant leaf growth to 172 across the 100 day period. The parasitoids population cause the armyworm moth population to drop from the peak of its carrying capacity 50 in 20 days to 12 Moths in 100 days.

From the result of Fig. 8.24, the introduction of the five egg and larva parasitoids has a great effect in preventing the pest outbreak as successful control was observed within 30 days, this action also maintains the pest population to a low level across the 100 days trial period. The only remaining challenge was in the population density of the pest eggs that was observed to be above 100.

Table 8. 1. Comparison of the control ability of the wasps, Case 3 - Fig. 8.23 and Case 4 – Fig. 8.24

Case 3 - Fig. 5	Case 4 - Fig. 6
Initial pest population (eggs, larvae, pupae = 10) and moth = 5	Initial pest population (eggs, larvae, pupae =0) and moth =5
Leaf destruction duration = 7 days	Leaf destruction duration = 14 days
Moths control = could not reach the carrying capacity, peak at 44 before suppression	Moths control = could reach the carrying capacity of 50 before suppression
Egg population was suppressed to 79	Egg population was suppressed to 113

Comparing the result of Fig. 8.23, and Fig. 8.24, confirmed that parasitoid wasps cannot exist and be active without the presence of the pest. The semi-log plot of Fig. 8.23(bi) illustrates how the wasp population declines in the initial stages due to the lack of pest eggs and larvae. As observed in Table 8.1, the pest continued to destroy the leaves for 14 days in Case 4 -Fig. 8.24, compared to 7 days for Case 3 - Fig. 8.23, despite the same number of wasps being deployed.

Due to the initial pest life cycle populations the suppression rate of the moths, eggs and larvae in Case 3-Fig. 8.23, was more effective than in Case 4 - Fig. 2.24, . It can be seen from Fig. 8.24 that the moth population reaches the environmental carrying capacity of 50 and the egg population was above 100, whilst in Case 3- Fig. 8.23, the moth population was suppressed below its environmental carrying capacity and the egg population was suppressed below 100.

It is therefore important to consider timing in pest control, it is better to release the wasps into the environment once a small population of all pest life cycle stages has established itself.

Another simulation experiment was set up with the introduction of 8 *Trichogramma* and 8 *Tachinidae*, parasitoid wasps with an initial population of 5 African armyworm moths, with the same initial population of 22 AAW eggs, larvae and pupae, the result of the simulation experiment is shown in Fig. 8.25.

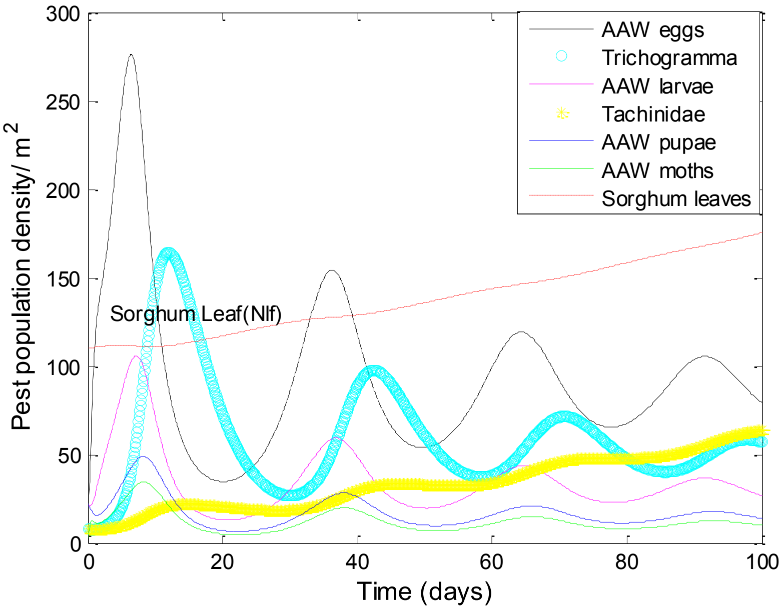


Figure 8. 25 The effect of deploying eight egg and larval parasitoid wasps

The result of Fig. 8.25 shows constant leaf growth from an initial population of 110 to 176 across the 100 day period. More effective pest control is observed with an increased number of wasps deployed as observed by the maximum population size of the pest, which peaks at 274 eggs, 105 larvae and 48 pupae and 34 moths.

The results of Fig. 8.25 provides a satisfactory answer to our goal, as maximum control of the pest population was achieved, the moth population was unable to reach its environmental carrying capacity and dropped to 9 Moths, 78 eggs, 26 larvae and 13 pupae with a resultant increase in the leaves to 176.

Greater success in the control and management of crop pest activities was observed with the deployment of both the egg and larval parasitoid wasps compared to when only the larval parasitoid wasps were deployed. For details of the performance of deploying only the larval parasitoids, see: (Faithpraise et al., 2014e)

The result further confirmed the effectiveness of the combined effect of the egg and larval parasitoids on pest management and preventive control. Once the NBI are deployed in the right quantity into any armyworm infested habitat, the pest outbreak will be controlled as illustrated in (Faithpraise et al., 2013b)

8.8.1.5 CASE 5. PARASITOID PREVENTIVE CONTROL WHERE THERE IS AN ESTABLISHED PEST OUTBREAK

A simulation experiment was set up with the introduction of 25 (*Trichogramma)* and 25 (*Tachinidae*), parasitoid wasps with the initial population of 5 African armyworm moths, 150 eggs, 120 larvae and 90 pupae per square meter and 110 sorghum leaves , the result of the simulation experiment is shown in Fig. 8.26

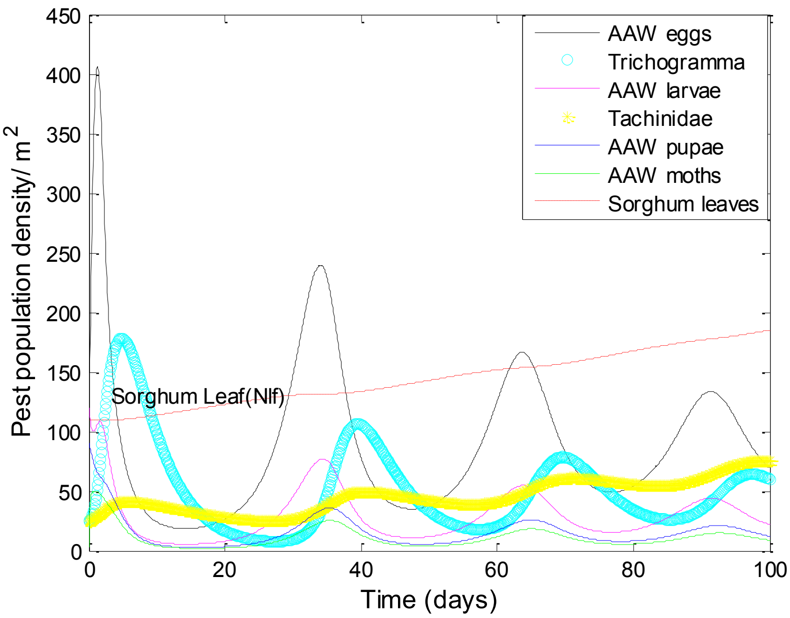


Figure 8. 26 **Introduction of 25 Trichogramma egg & 25 Tachinidae larval parasitoids into an established infestation**

8.8.2 RESULTS ANALYSIS OF EGGS & LARVAL WASPS ON AAW

Several simulation experiments were performed to determine the right quantity of wasps to deploy that could guarantee optimal control of the pest outbreak, the best results are shown in Fig. 8.26.

The result of Fig. 8.26, shows maximum control of all the life cycle stages of the African armyworm (AAW), as the population of the pest was suppressed to peak at 406 eggs, 110 eggs, and 88 pupae. The control strength of the combined wasp deployment suppressed the moth's population from the height of its environmental carrying capacity of 50 to 8 moths, 69 eggs, 22 larvae and 12 pupae with a corresponding leaf growth gain to 185, despite there being loses in the first 5 days below the initial starting value of 110.

The result of Fig. 8.24 demonstrate wasted investment, when wasps are deployed into a habitat before there are sufficient pest eggs and larvae; the result is that the wasp population declines as the wasps requires there to be some eggs and larvae for them to thrive

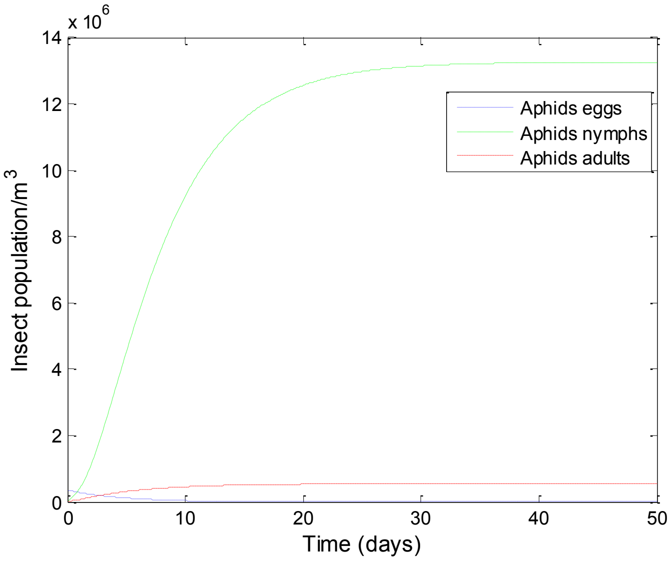
The result of Fig. 8.25, compared to Fig. 8.23, shows that it is very important to deploy the right quantities of beneficial insects and at the right time to obtain good control of pest infestation without wasting resources. The importance of the egg parasitoid cannot be over emphasised as it shows great control of the egg population when combined with the larval parasitoid.

The result of Fig. 8.26 shows that even in an established infestation, the combination of the egg and larval parasitoids are able to mitigate the activities of the pest and exercise control if the right quantities are deployed in Fig. 8.26, demonstrates maximum control within ten days, with slight destruction of the sorghum field.

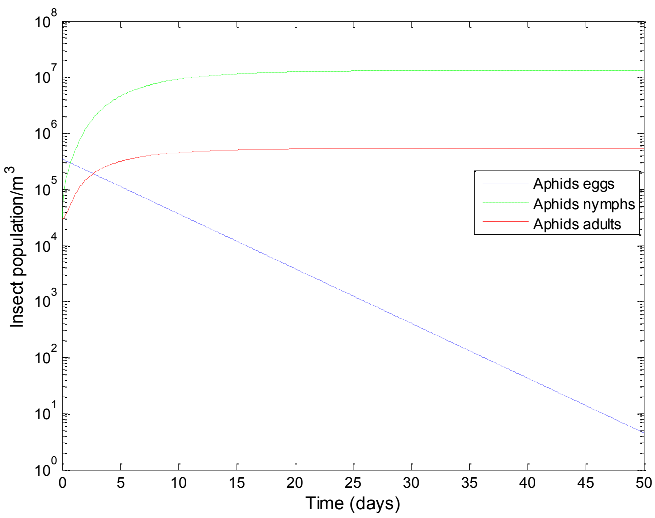
8.9 SIMULATION TEST RESULTS FOR THE APHIDS AND LADYBUG PREDATORS

A statistical model of the interaction between the peach aphids and their offspring and ladybug predators and its offspring was based on the results of the life span of the pest and predators reported in Table 6.1 to Table 6.3-chapter six.

Our aim is to optimise control measures to prevent the damaging effect of the aphid pests on crop habitats. In this illustrative simulation, a cubic metre volume of potato growing habitat is considered with an initial population density of approximately 350,000 aphid diapausing eggs laid in the winter, which do not hatch until the spring season: we assume an initial population of 30,000 adult aphids and 30,000 nymphs. Though there were zero number of eggs laid in the spring season according to eqn. (6.38), aphids are able to multiply viviparously as illustrated by eqn. (6.39) and eqn. (6.40). Fig. 8.27 illustrates the very rapid growth of the aphid population in the absence of predators. The growth rate of the aphid density over a short period of time resulted in severe damage to the potato farm. To prevent total destruction of the potato farm as illustrated in the previous section; predators (ladybug adult and larva) are introduced into the potato growing habitat. The results of the simulation explored a number of predator deployment combinations. For the illustration, we assume an initial predator population of 50 ladybugs: egg, larvae, pupae and adult; the best simulated outcome is presented in Fig. 8.28 to Fig.8.32.



(a)



(b)

Figure 8. 27 Aphid growth rate in the absence of naturally beneficial insects (a) normal and (b) semi log plots

From the simulation result, the right quantity of predators that will comfortably control and bring the population of aphids under control within 50 days was obtained and the results illustrated in Fig. 8.28, to Fig. 8.32. It was observed from Fig. 8.27 (a) and (b) that, the population density of aphids adults and nymphs multiplied to greater than 5.4 $*10^5$ adults and $13*10^7$ nymphs within 50 days in the absence of any control measure.

Once a predator (ladybug and offspring stages) is introduced into the damaged habitat, the population of the pest (aphids) started declining with time to < 50 for both adult and nymph aphids within 50 days, which is an economically acceptable pest population density value, as noted by (Rhainds et al., 2008).

In a bid to established the optimum quantities of NBI to deploy in the aphid damaged habitats, and the most economical and cost effective method of clearing the habitat, the following simulation test results were obtained with varying combinations of predator: egg, larva, pupa and adult populations.

8.9.1 MODELLING TRIAL CASES

8.9.1.1 CASE 1- DEPLOYING SAME QUANTITY OF ADULT AND NYMPH

Using the same initial population density of 30000 aphids adults , eggs, and nymphs on the damage habitats. Fifty adults and larvae and five eggs and pupae [adult=50, larvae=50, egg & pupae =5] ladybugs were introduced into the damage habitat as illustrated in the simulation results of Fig. 8.28.

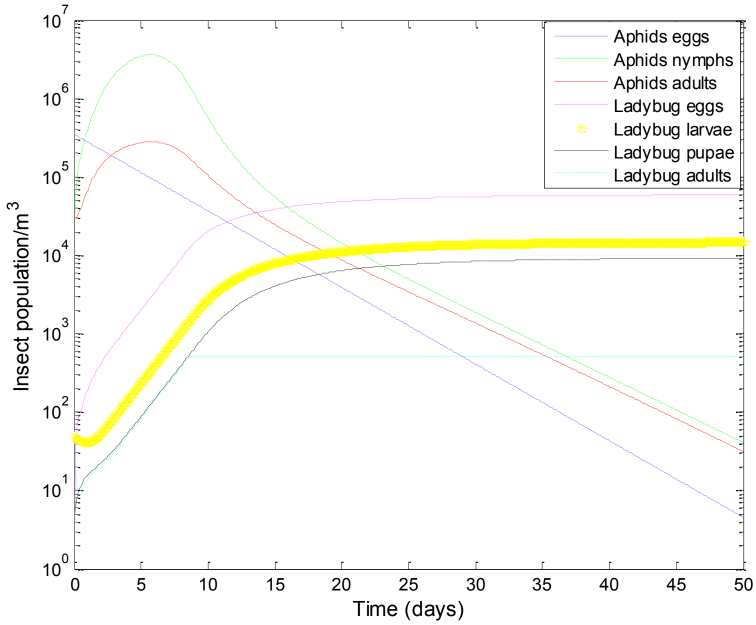


Figure 8. 28 Effectiveness of the deployment of same quantity of adult and Larval ladybug and a lower quantity of eggs & pupae ladybugs

The result of Fig. 8.28, shows the aphids (adult and nymphs) population to peak at $2.79*10^5$ adults and $3.6*10^6$ nymphs before the population was reduced to 31 adults and 40 nymphs within the 50 day trial periods with the combine effort of the predators

8.9.1.2 CASE 2-DEPLOYMENT OF MORE ADULT APHIDS

Using the same initial population density of 30,000 aphids adults , eggs, and nymphs on the damage habitats. Eighty adults & Fifty larvae and five eggs and pupae [adult=80, larvae=50, egg & pupae =5] ladybugs were introduced into the damaged habitat as illustrated in the result of the simulation shown in Fig. 8.29.

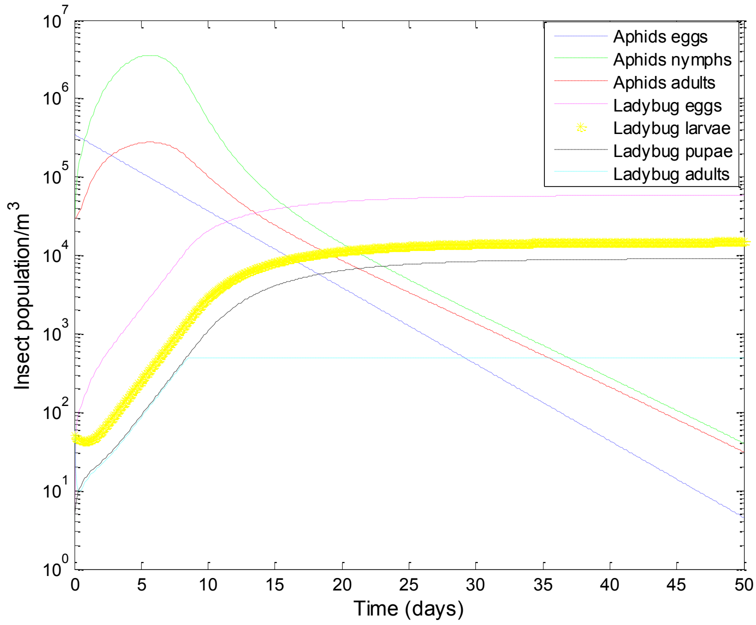


Figure 8. 29 Effectiveness of the deployment of a greater quantity of adult ladybug and a lower quantity of larvae, eggs & pupae ladybugs

The result of Fig. 8.29, shows that even with the increase in the initial quantities of the adult ladybug deployed, there was a great rise in the initial aphids population which peaks at $2.77*10^5$ adults and $3.5*10^6$ nymphs before the population declined with time to 31 adults and 40 nymphs due to the control effort of the predators within the 50 days trial period.

8.9.1.3 CASE 3- DEPLOYMENT OF INCREASED QUANTITY OF THE PREDATOR LARVAE, EGG AND PUPAE STAGES

Using the same initial population density of 30,000 aphids adults , eggs, and nymphs on the damage habitats. Fifty adults & Eighty larvae and twentyfive eggs and pupae [adult=50, larvae=80, egg & pupae =25] ladybug offsprings were introduced into the damage habitat as illustrated in the result of the simulation shown in Fig. 8.30.

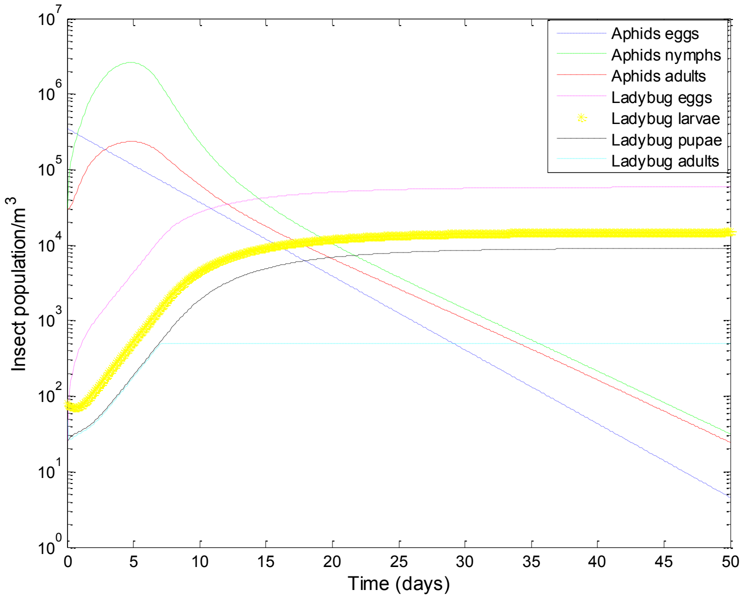


Figure 8. 30 Effective control of deploying more larvae than adult ladybugs

The result of Fig. 8.30, shows great suppression on the aphids as its initial population rise could only peak at $2.35*10^5$ adults and $2.61*10^6$ nymphs within the first 5 days, before the predators: Fifty adults , Eighty larvae and Twentyfive eggs and pupae [adult=50, larvae=80, egg & pupae =25] ladybugs could force the population to decline with time to 24 adults, and 31 nymphs, within 50 days.

8.9.1.4 CASE 4-REDUCTION ON ADULTS APHIDS

From the results of Fig, 8.30, we try to optimise further by reducing the number of adult ladybug to 20 and increased the quantities of its offsprings to 30 eggs & pupae, and 80 larvae [adult=20, larvae=80, egg & pupae =30] ladybugs as shown in the results of Fig. 8.31

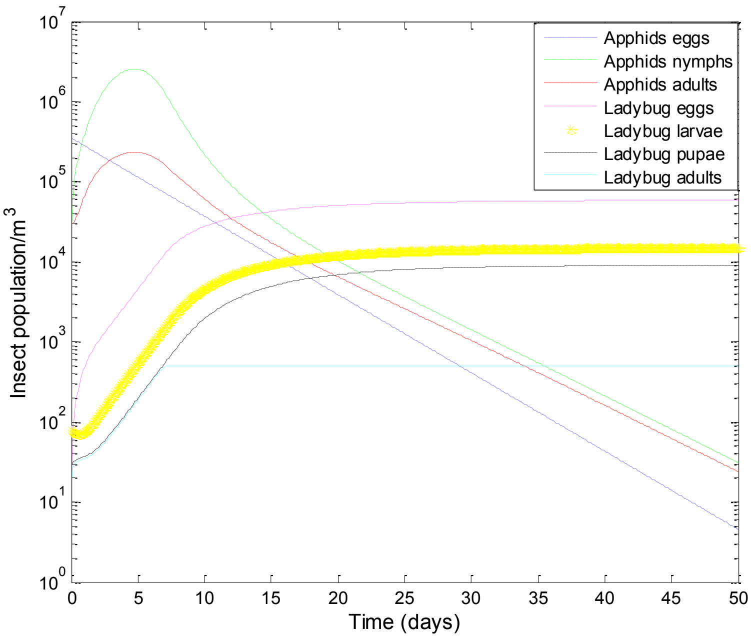


Figure 8. 31 Effective control with more larvae ladybug and increased eggs and pupae

The result of Fig. 8.31, shows amazing control of the predators [adult=20, larvae=80, egg & pupae =30] on the aphids population as it suppresses the initial population of the aphids to only peak at $2.32*10^5$ adults and $2.541*10^6$ nymphs within the first 5 days, and with time dropped the population to 23 adults, and 31 nymphs, within the 50 day interval.

8.9.1.5 CASE 5-DEPLOYING THE SAME QUANTITY FOR ADULT AND ALL LIFE CYCLE STAGES

Using the same initial population density of 30,000 aphids adults, eggs, and nymphs on the damage habitats. Fifty (50) quantity of adults, eggs, larvae and pupae ladybug predators were introduced into the damage habitat as illustrated in the result of the simulation shown in Fig. 8.34.

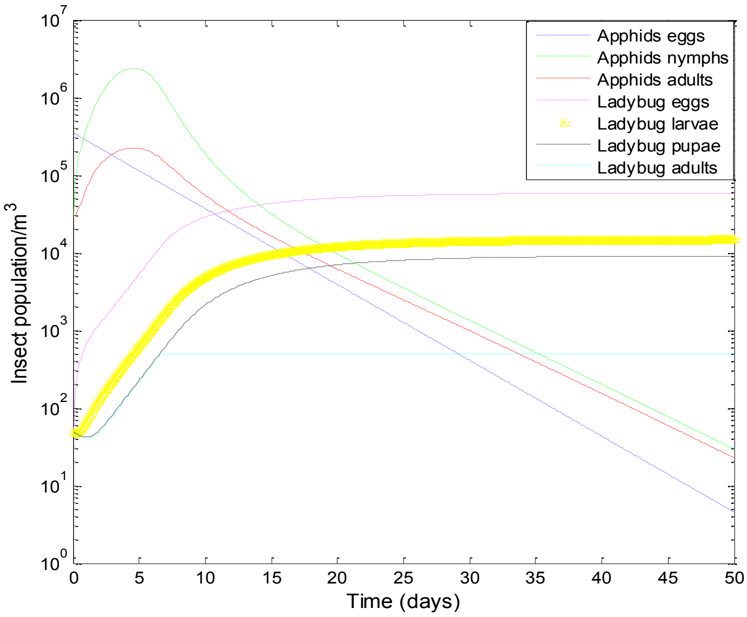


Figure 8. 32 The effect of all the predator (ladybug) life cycle stages on the control of aphids -semi log plots

The result of Fig. 8.32, shows very good control of the predators [adult=50, larvae=50, egg & pupae =50] on the aphid population as it suppresses the initial population of the aphids to only peak at $2.23*10^5$ adults and $2.371*10^6$ nymphs within the first 5 days, and with time dropped the population to 22 adults, and 29 nymphs, within the 50 day interval

8.9.2 RESULTS ANALYSIS OF THE LADYBUG PREDATORS ON THE APHIDS

From the results of Fig. 8.30, to Fig. 8.32, we notice good control of the aphid population, compared to the results of Fig. 8.30, to 8.31. Though all the results shows good suppression of the aphid population, there is still disparity depending on the quantity of the combination deployed. peaks at $2.77*10^5$ adults and $3.5*10^6$

For instance in Fig. 8.28, the aphids (adult and nymphs) initial population peaks at $2.79*10^5$ adults and $3.6*10^6$ nymphs, before the population was suppressed to 31 adults and 40 nymphs, when 50 adults, 50 larvae, 5 eggs and 5 pupae were introduced. And in Fig. 8.29, the aphids (adult and nymphs) initial population peaks at $2.77*10^5$ adults and $3.5*10^6$ nymphs, when 80 adults, 50 larvae, 5 eggs and 5 pupae were introduced.

While in Fig. 8.30, to Fig. 8.31, the aphids (adult and nymphs) initial population peaks at $2.32*10^5$ adults and $2.541*10^6$ nymphs, before the population was suppressed to 23 for the adult, and 31 for the nymph, when 80 ladybug larvae were deployed with 50 adults, 25 eggs and 25 pupae within the 50 day period.

The results of Fig. 8.31 with: 20 adult, 80 larvae, 30 eggs and pupae and Fig. 8.32 with 50 eggs, larvae, pupae and adults illustrates very good and best control ability of the predator and its life cycle stages.

Our investigation gives more credit to the ladybug larvae as the controlling engine with consideration to cost of habitat management as it is more expensive to purchase ladybug adults than the cost of deploying more ladybug larvae, eggs and pupae. A unit size of 250 adults cost $ 16.50 and 3000 larvae cost $ 58.00 (buglady, 2014), alternatively a unit size of 25 adult ladybug cost £ 18.99 and unit size of 100 ladybug larvae cost £ 23.95 (Crocus, 2014).

It very important to state that, notwithstanding the activeness of the larvae in aphid control, it is not possible to function without the adult, eggs and pupae as they play significant roles of transformation from one stage to the next in habitat management or pest control.

The results of Fig. 8.28 to Fig. 8.32, confirmed the possibility of managing aphid population density in an established colony without the application of chemical pesticides, which adversly affects human life and health. It is clearly possible to control the aphid population by the deployment of the right proportion of predators within a stipulated period of time.

Finally this model has established the most economical way of maintaining and controlling an aphids infested habitat by simply introducing greater quantities of the life cycle stages of ladybug and smaller quantities of the adult ladybug.

8.10. SIMULATION TEST RESULTS OF ANOPHELES MOSQUITO WITH THE PREDATORS (DRAGONFLY)

After the confirmation of the presence of anopheles mosquito as illustrated in the previous chapter 6 section 6.4.6, our goal is to find a permanent and lasting solution for the total eradication or management of Anopheles mosquitoes, which has transmitted life threating diseases to mankind in many regions of the world. In this simulation experiment the population of Anopheles mosquitoes (adult, egg, larvae and pupae) was modelled with each female mosquito laying an average of 85 eggs per day as illustrated in Table A0.12-Appendix A1. In the absence of any control measure or NBI, the result of Fig. 8.33 was obtained for a period of 30 days.

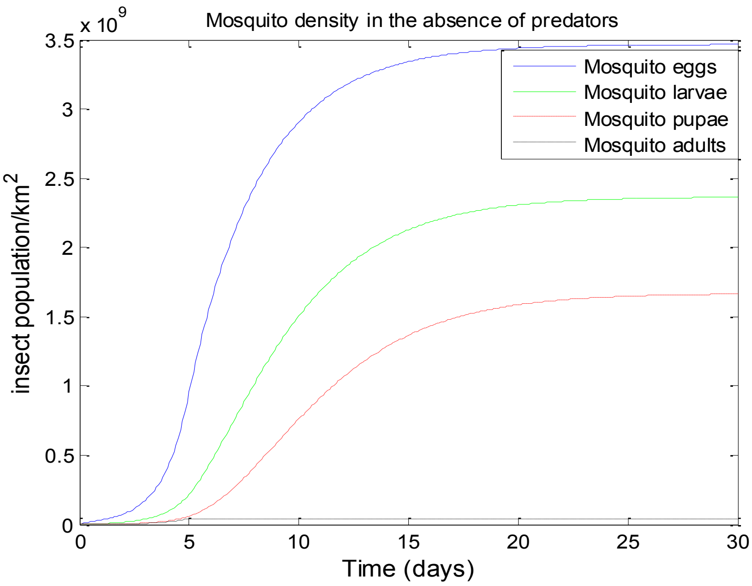


Figure 8. 33 Mosquito density in the absence of any control measures

The result of Fig. 8.33, shows a tremendous increase in the population densities of the mosquitoes to a value of 3.4×10^9 for the egg, 2.3×10^9 for larvae and 1.6×10^9 for pupae, and 4×10^7 for the adult. The adult mosquito reached its environmental carrying capacity within six days, since there are no control measures to check its growth rate. The multiplication rate of the population of mosquito has raised great concerns over the years as the only available solution so far has been insecticide–spray, for which the mosquito has developed resistance.

8.10.1 CONTROL POSSIBILITIES OF ANOPHELES MOSQUITOES

The first 30 days shows that the mosquito population growth peaks at a height greater than 3.4 x 10^9 per km^2. To exercise effective control of the pest, several simulation test experiments were conducted, as shown in Fig. 8.34 to Fig. 8.35.

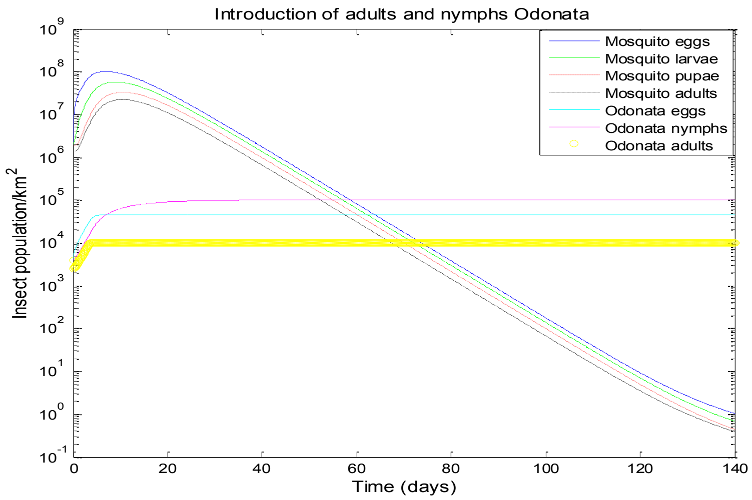


Figure 8. 34 Deployment of *Odonata* species against the mosquito population

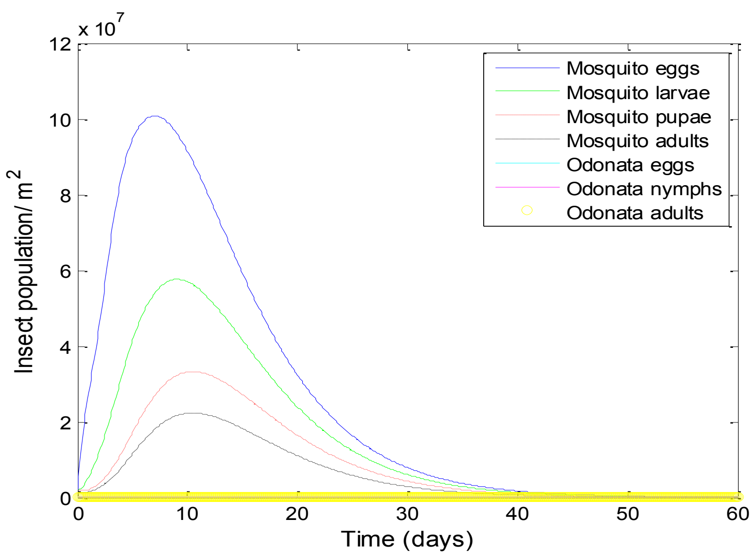


Figure 8. 35 Deployment of *Odonata* species against the mosquito population

The result of Fig. 8.34, illustrates the semi-log view of the plot of Fig. 8.35, which shows the control capability that the *Odonata* adults and nymphs have over the mosquito population in less than 120 days. The first 30 days shows that the mosquito population growth peaks at a height greater than 1.5 x 10^7 per km^2. As the population of the *Odonato* species increases from the initial population of 4000 (egg, nymph adult) dragonflies, it was possible to cause the population of the mosquito species to fall to 37 for the egg, 26 for the larvae, 17 for the pupae and 12 for the adult in 120 days. Due to its longevity, the *Odonata* nymph grows to a population of 9.5×10^4, it has the greatest effect in culling the mosquito by eating its eggs larva and pupa, its population is limited by the environmental carrying capacity for the adult dragonfly. The *Odonata* adult population grows to 10^4, and has a big impact in culling adult mosquitoes. The *Odonata* egg population grows to 4.5×10^4. After 140 days, the dragonflies were able to reduce the population of the mosquito (adults, eggs, larvae, and pupae) to < 5.

Fig. 8.34 shows complete stability in the population of the mosquito pest as their population drops to almost zero, indicating almost complete eradication of the species in the environment as the population of dragonflies and nymphs becomes stable. (Faithpraise et al., 2014a)

8.10.2 RESULTS ANALYSIS OF THE CONTROL OF ANOPHELES MOSQUITOES

This result is in line with the findings of (Hallem et al., 2004), which states that female mosquitoes will always hunt to get a blood meal in order to reproduce. The female mosquito is attracted to its host due to its carbon-dioxide emissions, Octenol and other compounds that make up body odour.

The result of Fig. 8.33 shows that as long as the mosquito has a blood meal, it will keep on reproducing, thereby increasing its population density and only being limited by the environmental carrying capacity.

The results of Fig. 8.34 show that, the effect of predators on the pest population takes time. When predators are deployed, it is not possible to obtain a pest free environment in one day; we need to exercise patience as it will take a number of days to obtain favourable and lasting results. Insecticide sprays can be used to kill *Anopheles* mosquitoes rapidly in a local area, for instance a person's house, but this is only a short term solution as the mosquitos will soon reinvade the house. Whilst the dragonfly adult eats great quantities of mosquitoes it is the dragonfly nymph that is most effective in limiting the population of the mosquitoes, and it is the nymph that is most vulnerable to pollution and pesticides. Therefore, it is possible to obtain a pest free environment when the population of beneficial insects becomes stable.

8. 11 THE RESULTS OF THE CONTROL OF ALL CLASSES OF MOSQUITOES USING COMBINED PREDATORS

Having observed the positive effect of introducing a single predator species: Odonata, on reducing the population density of anopheles mosquitoes. A model of the interaction between the pest mosquito's species and the predators *Odonata* adult and nymph and *Toxorhynchites* adult and its life cycle stages was created in order to observe the effect of these combined predators on the mosquito population

8.11.1 SCENARIO1. MOSQUITO GROWTH IN FAVOURABLE CONDITION

With no initial infestation, the area is invaded by over two million adult mosquitoes, each laying an average of 85 to 175 eggs per day. The results obtained in Fig. 8.36 illustrate the reproductive capability of a typical pest mosquito, which has had its blood meal. Since there were no control measures in place to manage the mosquito growth rate, within the space of 20 days the mosquito population density reaches its carrying capacity of 4.0 $*10^7$.

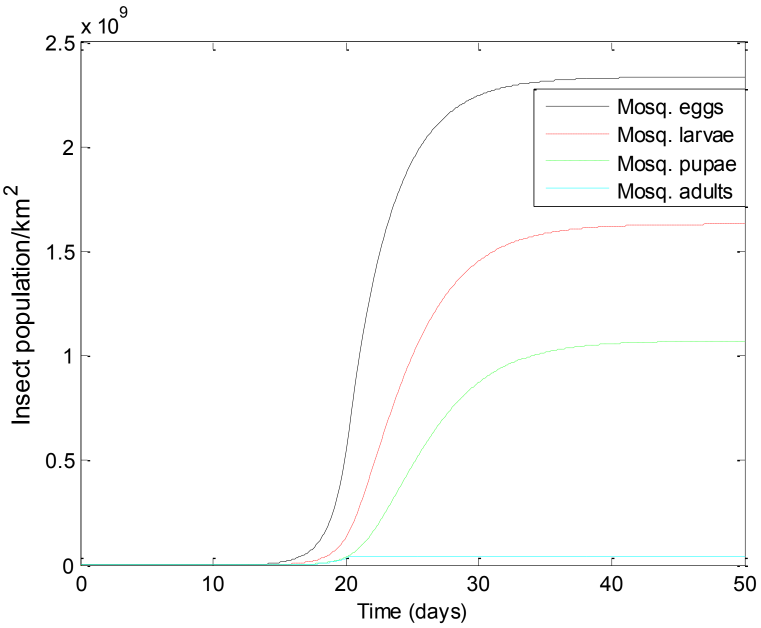


Figure 8. 36 Population of adult mosquitoes in favorable conditions, starting with zero population of: eggs, larva & pupa.

8.11.1.1 SCENARIO 2. MOSQUITOES BREEDING ZONES

This illustrates how an already established infestation level develops, as would be the case in the conditions around the residential areas of the Atimbo community, illustrated by Fig. 8.37. We estimate the mosquito (adult, eggs, larvae and pupae) population densities to be at least above 2,000,000 females per km^2, with each female mosquito laying an average of

175 eggs per day. In the absence of any control measure, the simulated results are shown in Fig. 8.38

(a)

(b)

(c)

Figure 8. 37 Mosquito breeding zones – Atimbo, Calabar – (a) to (c)

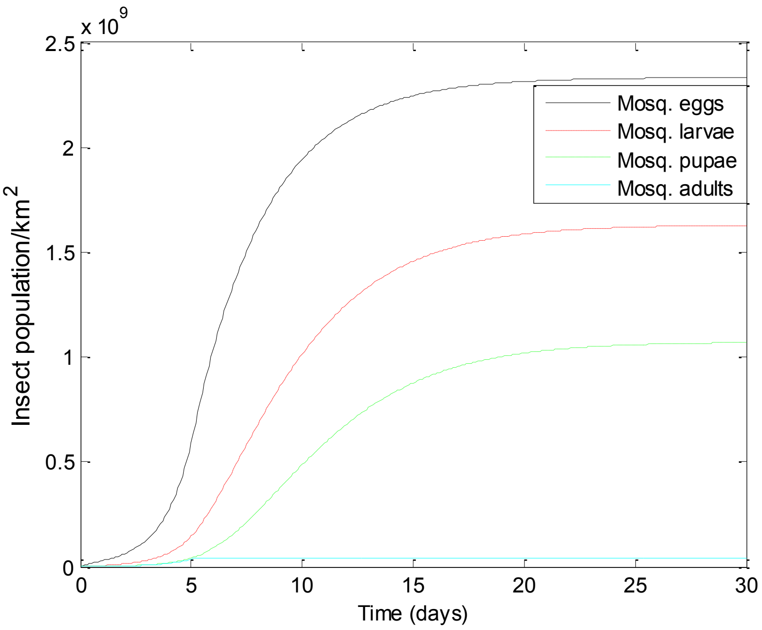
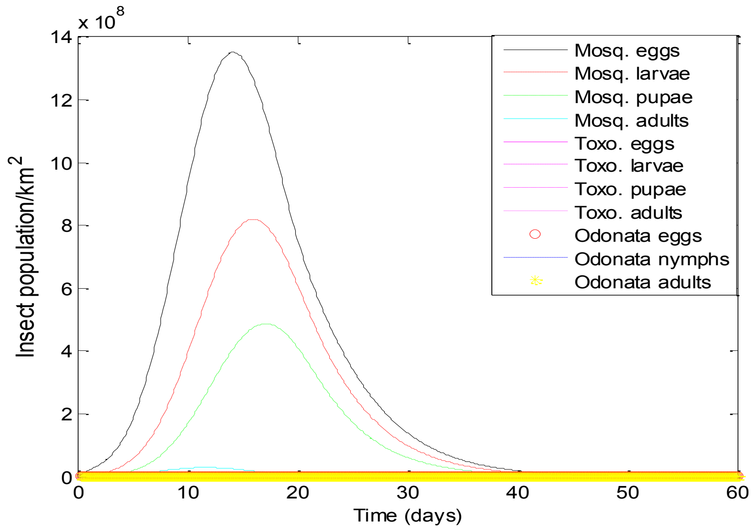


Figure 8. 38 Mosquito population in the absence of any control measures or predators.

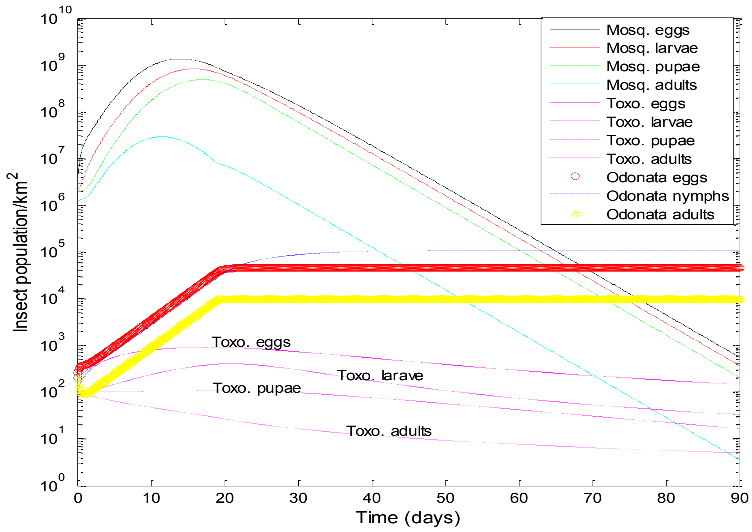
The result of Fig. 8.38 shows a great increase in the population of the mosquito: eggs, larvae, pupae - from 2,200,000 to $2.33*10^9$ eggs; $1.63*10^9$ larvae, $1.07*10^9$ pupae and the adult population reaches the carrying capacity of $4.0 *10^7$ in the environment within 6 days. It is hardly surprising that the health of people living in this dwelling area is very poor.

Scenario 3.

The model was set up with different populations of *Odonata* and *Toxorhynchite.* The results reported in Fig. 8.38 are for a starting population of 200 *Odonata* adult and its life cycle stages and 100 adult *Toxorhynchites* and its life cycle stages.



(a)



(b)

Figure 8. 39 Effect of the introduction of *Toxorhynchites:* adult, eggs, larvae & pupae and *Odonata:* adult, eggs & nymph - (a) normal plot, (b) semi-log plot

In Fig. 8.39, with the introduction of 200 *Odonata* adult and all its life cycle forms and 100 *Toxorhynchites* adults and its life cycle stages the mosquito population density was controlled; the population was observed to drop from a peak of $1.35*10^9$ to 560 eggs, $8.14*10^8$ to 372 larvae, $4.87*10^8$ to 207 pupae and $2.90*10^7$ to 4 adults in 90 days.

There is predation of *Toxorhynchites* adults and its life cycle stages by *Odonata*, which is evident from the results of Fig. 8.39(b), this is incorporated into equations 6.54 to equation 6.57. 100 *Toxorhynchites* adult and life cycle stages (egg, larvae and pupae) were introduced into the mosquitoe infested habitats, the maximum population observed for the *Toxorhynchites* eggs, larvae and pupae were 905 eggs, 404 larvae and 109 pupae for the first 30 days. Out of the total population of 100 *Toxorhynchites* deployed, the population at 90 days is 148 eggs, 33 larvae, 17 pupae and 5 adults. These findings are consistent with the experimental work of (Polis, 1981), (Mehlis et al., 2010), and (Volker et al., 2008), that reports that predation occurs between predators.

8.11.2 DISCUSSION OF RESULTS OF THE CONTROL EFFECT OF TWO SPECIES OF PREDATORS ON THE MOSQUITO POPULATION

The results of Fig. 8.38, show that mosquito have the ability to multiple uncontrolably expecially if a blood meal is obtained as discussed earlier in the works of (Faithpraise et al., 2014a). When any pest mosquito specie is sighted action should be taken.

The result of Fig. 8.39(a), & Fig. 8.39(b), illustrate a successful reduction of the population of mosquitoes as the predators established their population in the environment. The result demonstrates the possibility of obtaining a healthier environment with the deployment of *Odonata* and *Toxorhynchites* species into mosquito infested environments, Fig. 8.39(b), is plotted on a semilog scale in order to see the predator population, which is relatively small when compared to the pest mosquito population.

The combination of predators controls the mosquito population and demontrates the great potential of this strategy to significantly reduce the mosquito life cycle stages in a reasonable number of days. This duplex approach requires fewer *Odonator* preditors to be deployed, reducing the resources required to achieve an impressive result. (Faithpraise et al., 2014d)

8.12 CONCLUSION

In this research, we apply k-means clustering and correspondence filtering for Identification of the plant pests, respectively. Detection, recognition and control of the pest infestation are one of the goals of this research. Thus, the algorithms were evaluated to check their performance on several plant pests as illustrated in Fig. 8.1. The experimental results obtained demonstrate that the proposed method is a useful technique, which can sustain detection and recognition and the control of plant pests in their various shapes, sizes, positions, and orientations using computationally efficient algorithms.

The Pest control model gives us a guide as to what we should be expecting and the steps to be taken in combating the pest (aphids, moths, beetles and mosquitoes) problem in any environment. It also helps in minimising ecological damage by estimating the correct quantity of predators to deploy and the right proportions of each lifecycle stage at any given time especially when combining different classes of species. Most importantly we estimate the most economic cost effective approach (a decision tool to save cost).

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 demonstrated in the model. This pest control planning tool provides agriculturists with the means to calculate the number of NBIs to deploy in any pest infested environment 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 a pest infestation, this study illustrates that it is advantageous to deploy NBIs that attack the larval stages of pests, significant benefits are gained by deploying an NBI that attacks at least one or other pest lifecycle stages, with maximal control being obtained by deployment of NBIs against all three lifecycle stages of a pest.

The experimental results indicate that the proposed approach of deploying different species of larval parasitoid wasps is a valuable approach, which can significantly support accurate plant pest detection, prevention and control system with a little computational effort. We therefore recommend preventive control methods to farmers and growers worldwide, rather than waiting for the forecast of an armyworm moth invasion of the field, which causes major harm before resorting to the fire brigade approach to control its effect. Preventive control will encourage increased crop yield, quality and quantity of food production and healthy living avoiding illnesses caused by the application of chemical pesticides or an encounter with caterpillars.

For the Scarab beetle problem we recommend the deployment of scoliid and tachinidae wasps in combination with the introduction of a biocontrol agent either a virus or a fungus which can attack the adult beetles to reduce its population to a minimum level.

Sustainable Control of the *Anopheles* Mosquito Population Model (SAMCM) demonstrates an effective methodology to cure the long term problem of mosquitoes that have overwhelmed several solutions for many years. This model demonstrates how to permanently reduce to the lowest value the parasitic diseases such as malaria caused by various varieties of *plasmodium*, carried by mosquitoes of the genus *Anopheles* through the continuous application of the *Odonato* predators.

The simulation results encourage the restoration of natural habitats by every home, to enable a clean and healthy environment that will attract naturally beneficial organisms to keep the population of all kinds of pest under control. These results absolutely discourage the application of pesticides with either minor or major effect, both short term and long term. It is very important to understand that larvicides will kill dragonfly nymphs, which is very counterproductive; this study demonstrates that *Odonato* nymphs can make the greatest contribution in controlling the mosquito population by natural means.

To solve the mosquito problems, we need to encourage the global breeding of dragonflies in our environment and for success we need a cleaner insecticide free environment.

It is observed that as long as an environment is left uncared for, it will definitely become a breeding ground providing for many mosquito hatcheries. When an environment is occupied by millions of mosquitoes, no preventive measures can cure or manage the mosquito pest. Therefore it is recommended that in addition to managing the environment and preventing it from becoming a breeding zone, a permanent control measure with a combination of predators should be employed.

Breeding, then deploying beneficial insect predators like the *Odonata* and *Toxorhynchites* will transform a hostile environment into a zone habitable by humans, as these predators have a great ability to control mosquitoes at low cost and in a short amount of time. We also advise the restoration of natural habitats that will attract the visits of important naturally beneficial insects.

Finally patience must be exercised to breed beneficial insects as it takes several days before significant results will be noticed and to achieve a mosquito free environment. Any form of insecticides must be avoided in order to preserve the life span of the predators. The goal should be a world free of: disease vector mosquito species and chemical pesticides

The results obtained in this research work endorse the feasibility and capability of the Automatic Robotic Drone Management System (ARDMS) for use in controlling the invasion of harmful pests into all kinds of agricultural environment. This system can be used to maintain surveillance of the activities of the pest as well as monitor the population of both beneficial and harmful pests allowing control interventions. This system is able to reduce the stress on typical farmers as the major work of inspection, surveillance and NBI deposition is performed automatically by the robotic system. This system also promotes increased food security, increasing the quality and quantity of food produced as chemical pesticides and insecticides no longer need to be applied in the agricultural habitat. This system is efficient, cost effective and safe.

CHAPTER -9- DISCUSSION, CONCLUSION AND FUTURE WORK

CHAPTER -9- DISCUSSION & CONCLUSION

9.1 DISCUSSION & CONCLUSION

A novel system is proposed and modelled to find a lasting solution to the life threatening causal agent of many life threatening diseases like: yellow fever, Dengus fever, Chikungunya fever, Japanese encephalitis, Meningitis, Urticaria, West Nile virus, Dirofilaria Immitis, Malaria and pests that limit food supplies. Three major approaches where considered to solve the problems of pest invasion, pest resistance and resilience and bring to an end the application of chemical pesticides and sprays, thereby improving the security of life and food as well as promoting a healthy environment devoid of pollution.

The three main approaches adopted include: the detection and recognition of several pest species; understanding the biology of each pest and the corresponding natural enemy; and adoption of a control measure by the application of a surveillance robotic system.

To detect a pest image, image processing algorithms based on segmentation are recommended, since segmentation as a method of data consolidation is a very useful tool in image and object recognition. This research focuses on a clustering type of image segmentation, as it classifies pixels with similar texture and/or colour, this is a traditional method of implementing clustering. If each object in an image has a homogeneous and constant colour property and the pixels of the image are mapped using a certain colour space, it is expected that clusters of the same colours will represent the object in the image. This provides clustering-based segmentation using the feature-space and the colour-space which are useful in the detection of plant pests since insect pest have unique features that differentiate them from the surrounding environment (plants or leaves).

Plant pest datasets are so large that direct manipulation is not feasible, therefore clustering is required first to reduce the size of the dataset without losing the essential features of the image. The result of image segmentation is a set of partitions that collectively cover the entire image.

To recognize a detected pest image, the main type of approach offered by the linear combinatorial filter or synthetic discriminant function (SDF) was adopted. This type of filter has several design options like the minimum average correlation energy (MACE) filter, the minimum variance synthetic discriminant function (MVSDF), the optimum trade-off maximum average correlation height (OT-MACH) filter and the Correspondence filter, which are implemented based on the SDF principles.

The second part of the research is based on control of the existing plant pests in their habitats. This is achieved by a novel system design based on modelling with non-stiff simultaneous, non-linear ordinary differential equations.

In this short section, all the results of our studies analytically presented in chapters: 2,3,4,5,6,7 and 8 are summarized with much emphasis on the achievements as well as the proposed recommendation for the future research arising from the current work.

Chapter 2 is dedicated to the study of the effects of pesticides on the economy and health of any nation; it uses Nigeria as a case study. It was discovered that, the major problems confronting mankind are caused by man as a result of the introduction of chemical pesticides into plant habitats to manage pest infestation. Because man considers pesticides to be a quick and easy method for controlling weeds and insect pests, little consideration has been given to the short and long term effects of pesticides and herbicides on human health, beneficial insects and the economy.

This chapter has enumerated the effects of contamination from pesticides used on major food crops and offered a solution to saving mankind from the risk of exposure. Victims of chemical pesticides cut across all walks of life, nations worldwide and populace of all ages including unborn infants through the volatilization (is the process whereby a dissolved sample is vaporised) of some chemical pesticides as explained in this work.

Chapter 3 explores the some of the most notorious, harmful and economically damaging pests in the agricultural environment and concentrates on the best method to detect the pest image within a cluttered scene no matter what its size and orientation.

The pest detection problem was solved by using a form of image clustering call the k-means clustering algorithm. This algorithm clustered the crop pest dataset by assigning each point to a cluster, which is characterised by a single reference point which is usually an average of the point in the cluster, which is realized by replacing the coordinates of each point in a cluster with the coordinates of that cluster's reference point, then iterative-partitioning was applied by a set of k reference points whose initial values were chosen as 3. The goal is to find a reasonable consolidation of the N data points into k clusters. To achieve our target the position of the reference points and the assignment of the data points to clusters are then adjusted during successive iterations. The purpose of the iteration is to move the partition closer to this configuration and thus to approach a local minimum, thereby extracting the useful features or target.

After extracting the target, the next step is to recognize the object (crop pests) species. Since crop pests are deformable and change shape at will, a formidable filter is required to achieve rotation-invariant recognition and detection of such groups of pest. The problem of recognition was solved by the application of a correspondence filter, which is based on the principles of the MACH and OT_MACH filter. To analyse the performance of the algorithm and the correspondence filter, algorithms were coded using MATLAB.

The tests of the plant pest detection and recognition algorithm, using MATLAB performed well, however it has a delay time of about 10 minutes to process data from the detection phase to the recognition phase. This problem can be partially solved by using two specialized digital signal –processing chips to pre-process the image multiplexing phase. This proposed approach is possible in future, when manufacturers will make hardware technologies (motherboard, CPU, GPU and memory) that will be dedicated to solving pest recognition problems.

In chapter 4, a review of the design of an unmanned aerial vehicle (UAV) for pest surveillance was completed and justifications given for the recommended UAV. A novel carriage box system to convey the naturally beneficial insect was modelled as part of the payload to be carried by an existing UAV system. This carriage box was designed with carbon composite fibre to carry 52 smaller boxes that will be refilled with naturally beneficial insects in the stock up zone or station using automated loading of NBIs. The activation for opening and closing of the sides and down opening doors will be achieved using solenoids and micro-computer control.

In Chapter 5, we focused on pest population density control. Various strategies were adopted to control the pest population. This is done by the development of an e-database for some major classes of pest and their corresponding naturally beneficial enemies. The behaviour of the pests were surveyed and the operational strategies for using the beneficial insect employed to manage their population was illustrated. This gaves confidence that a pesticide free environment can be achieved if the population densities of beneficial insects is maintained at the correct levels and not damaged by insecticides.

In chapter 6, we derived a novel system of algorithms for pest control. The detailed methodology for the successful design and simulation of the control system illustrating how the NBI are capable of reducing the long existing problems of pests. This control system was achieved by using different sets of non-stiff, simultaneous non-linear ordinary differential equations (ODE). The biology of the pest and the control agents was studied as well as the various life cycle stages. The Weibull probability distribution function was employed to determine the mortality rates and the negative binomial distribution function was used to model predator/ prey capture rates.

The success of the control system focuses on the interaction of some well-known pests (that are a threat to mankind as a result of their activities and the transmission of life theatening sicknesses and diseases) with their corresponding naturally beneficial enemies (NBIs).

The numbers of beneficial insects to deploy and the length of time to achieve a pest free environment was evaluated with these models.

In chapter 7, we concentrated on the various materials and methodology that was used to achieve the goal of this research question; creation of an automatic sustainable pest control system. The integration of the different subsystems to form an entity, most notably a novel method of statistically calculating the number of the naturally beneficial insects to be deployed in any given size of field or habitat, the number of days required for the pest suppression or control to be achieved and an NBI delivery system

Chapter 8, shows the simulation results of the entire pest control system. The system illustrates the detection results from the k-mean clustering algorithm. This algorithm uses a two-phase iteration procedure to reduce the sum of distances (squared Euclidean distances) between nearest neighbour and at the same time re-assign points to the nearest cluster centroid. The recalculation of the cluster centroids phase rarely does not converge to a local minimal. This is observed when a dataset is partitioned, any single point moved to a different cluster increases the total sum of the distances. The batch phase is fast, but can estimate a solution as a starting point for the second phase.

The second phase will usually converge to a local minimum, although there may be a few local minima with a low total sum of distances. Finding a global minimum requires an exhaustive choice of starting points, but using several replicates with random starting points typically results in a global minimum solution. The iterative partitioning of the points in the m-by-n data matrix x into k clusters minimizes the sum over all clusters, of the within-cluster sums of point-to-cluster-centroid distances. Rows of x correspond to points, columns correspond to variables. It then returns an m-by-1 vector, which contains the cluster indices of each point regardless of its orientation.

The goal is to detect pests on plants. This is achieved by segmenting the colours in an automated fashion by the use of the $L^*a^*b^*$ colour space, since the colour information exists in the 'a^*b^*' space, therefore the objects are pixels with 'a^*' and 'b^*' values. Then the clusters were set to an initial value (three) to avoid local minima and the "pixlabels" function then separates objects in the pest/plant image by colour, which resulted in three segmented clustered images. The pest image can be separated from the leaf by the use of the 'L^*' layer of the $L^*a^*b^*$ colour space because the 'L^*' layer contains the brightness values of the colour. So when the dataset is clustered, the L* layer will usually extract the brightness value of the pixels in the cluster and threshold it by the use of "im2bw" function. K-means returns a different index value every time the program is executed as the centre value contains the mean ‘a^*’ and ‘b^*’ value for each cluster. The pest is detected as the pest cluster holds the smallest centre value by experiment. After the detection stage, the confirmation and identification of the species of pest is achieved by invoking the correspondence filter.

The correspondence filters have been evaluated to optimise the performance of the peak sharpness and detectability, distortion range, discrimination ability and clutter tolerance. All the images presented in the simulation results were tested for in plane rotation and the shift-invariance ability of the filter.

Peak sharpness and detectability:- all the pest images detected respond with a number of sharp peaks that correspond to the number of pest images, no matter what the size or scale of the pest is.

Distortion range: several possible angular views of the pest images from 0^o to 360^o were tested on all the images. The filter shows good response to distortion, which means that no matter what the position of the different pest species, they can be recognised.

Discrimination ability: the filter was able to discriminate between species of pest, as the number of spikes correspond to the number and location of pest images found on each crop irrespective of the size, position, scale and orientation.

Clutter tolerance: even in the mix of plants, leaves, and background, the filter is capable of extracting the pest image from its surroundings irrespective of its size and orientation. The filter has detected and classified correctly the true class objects, whilst suppressing the background clutter - though there may be a few false alarms or under-representation of the number of objects recognised, it is still an acceptable solution because we are only interested in the confirmation of a particular species of pest to kick-start treatment.

The main objective of this research is how to achieve control of a pest invasion without the use of chemical pesticides. Therefore the detection and recognition stages of this system are very important because, to achieve better control - causal agent identification is vital , which is achieved in the two stages as a prerequisite to a better deployment of the exact species and quantity of naturally beneficial insect to control the population density of the pest in the field.

Therefore the pest control algorithm was used to model populations of some classes of notorious pest like the anopheles mosquito, the caterpillar, the beetles and aphids and their corresponding naturally beneficial insects (parasitoid wasps and predators); results were produced showing the total number of beneficial insects to deploy as well as indicating the length of time to gain control and management of the pest population.

It is very important to deploy the estimated number of NBI to control the pest population to an economically acceptable threshold level to avoid complete elimination of the pest species as their existence contributes economic importance to the trophic level or Pyramid of Energy (PE) "(*the trophic level is the location an organism or creature inhabits in a food chain - what it eats, and what eats it. The classification of the organisms is based on their feeding behaviour whereby the green plants called the producers occupied the first and lowest level. The herbivores, which consumed the plants or plant products occupied the second-level , or plant eaters (pest and the third level organisms consumed the plant eaters – predators or wasps belong to this categories and so on)" (www.original.britannica.com)*.

It is important to state that the existence of the parasitoid wasps depends solely on the pest as its host, to multiply its population and subdue the pest population into a symbiotic existence.

Therefore this research recommends that the control of the pest population should be to a minimum economic threshold level and not result in total elimination or eradication.

Pesticide usage of any kind must be completely avoided in order to allow the growth of NBIs to manage the pest population. A pesticide free environment will support a sustainable life, healthy living and lower infant mortality.

Clean and natural habitats should be encouraged, nations should engage in breeding programs of naturally beneficial insects like the Odonata and the elephant mosquitoes

(*Toxorhynchites*) and a restoration of healthy environments that will attract the visits of important naturally beneficial insects.

Finally patience must be exercised to breed beneficial insects as it takes several days before significant results will be noticed

Manufacturers of integrated circuits electronics (IC) in the near future should develop components and mother boards specifically for the detection and recognition of plant pest images.

Summarily, the author of this thesis does not claim to have completely solved the pest problems as several issues remain still to be considered in further studies. However, this research has successfully laid the foundation of pest control using vision and image processing systems and modelling of the interaction NBIs with pest populations. We expect this work to be an example for the development of pest control systems in the near future.

9.2 RECOMMENDATION FOR FUTURE RESEARCH

The models of interaction between different species can be significantly extended, it has been demonstrated that multiple predator species can have a greater effect in controlling pest populations than a single preditor or parasitoid. There is great scope for exploring the optimisation of the deployment of multiple predator species and for establishing which are the best combinations to minimise economic costs. We have recommended that governments or companies start insect breeding programs in order to combat agricultural pests. There is a lot of work to be done in establishing the best methods to produce these predators or parasitoids at a reasonable cost. In the case of Ladybugs it is economically beneficial to deploy more ladybug larva than ladybug adults; further optimisation studies are required to understand the best strategies. Whilst it has been shown that scrabab beetle instars can be controlled by using parasitoids, the longevity of the beetles makes it difficult to bring the adult population under control. The model needs to be extended to explore the effect of fungus or viruses that can kill the beetles directly. Several interaction models have been presented to show the power of modelling in trying to understand how to control pest problems; this research has demonstrated how to create the models and offers the opportunity to greatly increase the scope of the models. Nevertheless, too much complexity may obscure strategic planning to combat insect pests.

The use of image processing with UAV's provides huge scope for extending this research, optimisation of sampling schemes to identify and quantify the scale of an infestation requires further research. The image processing algorithms developed herein have proven to be effective for the purposes of this research but there is great scope for exploring the plethora of other algorithms that may improve results.

The use of the technologies presented herein provides significant opportunities for business development, so it would be interesting to formulate a multi-disciplinary research program that assessed the economic opportunities that are emerging and understand how to move this forward to create jobs and wealth.

There are significant opportunities to quantify the improvements in the environment and the impact on health of not using pesiticides; studies of this kind will require great interdisciplinary effort but would be invaluable if they could be completed; studies need to be conducted for several years.

Farmers all over the world are looking at integrated methods for pest control, including the use of biologically prepared solutions which are deemed by the Pest Management Regulatory Agency (PMRA) to have lower environmental risks for human and animal health risks.

From the foundations built by this research work, we are looking at achieving many technical reforms with the assistance of the agricultural sector, food processing industries, computer manufacturing industries, biochemical producing industries, microbiological industries, environmental protection sectors and the education sector.

All these afore mentioned sectors need to support the ideas developed in this research work in order to realise the goal of pest management and control in combating pest threats without the use of chemical toxins.

We will create awareness of the implications of using chemical pesticides for the entire environment and to all mankind through publicity, seminars and awareness programs.

We shall implement the restoration program of developing natural habitats to every household in Africa as a means of breeding naturally beneficial insects like the elephant mosquitoes and the dragonfly for the successful clearing of the environments and homes of the disease vector mosquito.

We shall partner with the Manufacturers of integrated electronics (IC) in the near future to develop components and mother boards specifically to optimise hardware for the fast operation of the plant pest detection and recognition algorithm for pest detection.

We shall partner with the chemical industries at all levels to stop the production of chemical pesticides for crop pest control, we will try to persuade them to start breeding NBIs as their new product range.

We shall educate growers in the food and agricultural sectors of the risks and negative use of pesticides on crops, the dangers of their application and the alternative control methods for pest management.

Educationally, we shall introduce environmental cleaning modules to the future pupils, underlining the reasons and the best methods to employ especially those in the rural communities to keep the environment clear of pest breeding zones.

We shall encourage the development and construction of the designed pest surveillance system to create efficient and timely monitoring of the environment as well as the crop habitat.

APPENDICES

APPENDIX

A0.1 CLASSES OF CROP PESTS

TABLE A0. 1 Aphids species

Scientific names	Common names	*Scientific names*	Common names
Dysaphis apiifolia	rusty banded aphid	*Aphis spiraecola*	spirea aphid
Acyrthosiphon pisum	pea aphid	*Aulacorthum circumflexum*	crescentmarked lily aphid
Aphis citricola	an aphid	*Brachycolus heraclei*	celery aphid
Aphis craccivora	cowpea aphid	Brevicoryne brassicae	cabbage aphid
Aphis fabae	bean aphid	*Cavariella aegopodii*	an aphid
Aphis gossypii	cotton aphid, melon aphid	Cerataphis orchidearum	fringed orchid aphid
Aphis middletonii	erigeron root aphid,	*Dysaphis apiifolia*	rusty-banded aphid
Aphis nerii	oleander aphid	Hyperomyza lactucae	an aphid
Hysteroneura setariae	rusty palm aphid	*Myzus persicae*	green peach aphid
Lipaphis erysimi	turnip aphid	*Nasonovia lactucae*	sow thistle aphid
Macrosiphum euphorbiae	potato aphid	Neomyzus circumflexum	Crescent marked lily aphid
Melanaphis sacchari	sugarcane aphid	*Neotoxoptera formosana*	onion aphid
Myzus ornatus	ornate aphid	*Patchiella reaumuri*	taro root aphid
Pentalonia nigronervosa	banana aphid	*Sipha flava*	yellow sugarcane aphid
Rhopalosiphum maidis	corn leaf aphid	Sitobion luteum	orchid aphid
Rhopalosiphum nymphaeae	waterlily aphid	Toxoptera aurantii	black citrus aphid
Rhopalosiphum rufiabdominalis	rice root aphid	*Vesiculaphis caricis*	an aphid

TABLE A0. 2 Beetles species

Scientific names	Common names	*Scientific names*	Common names
Adoretus sinicus	Chinese rose beetle	*Carpophilus hemipterus*	dried fruit beetle
Anomala orientalis	oriental beetle	*Carpophilus humeralis*	Yellow shouldered souring beetle
Anthonomus eugenii	pepper weevil	*Chaetocnema confinis*	Sweet potato flea beetle
Aphanisticus cochinchinae seminulum	sugarcane leaf-mining beetle	*Coccotrypes carpohagus*	palm seed scolytid
Apomecyna saltator	cucurbit longicorn	*Cocotrypes pygmaeus*	pygmy palm seed scolytid
Asynonychus godmani	Fuller rose beetle	*Conoderus amplicollis*	Gulf wireworm
Brontispa chalybeipennis	blue coconut leaf beetle	*Cosmopolites sordidus*	banana root borer
Carpophilus dimidiatus	corn sap beetle	*Cryptorhynchus mangiferae*	mango weevil

Cylas formicarius elegantulus	sweetpotato weevil	*Omphisa anastomosalis*	Sweet potato vine borer
Diocalandra taitensis	Tahitian cocconut weevil	*Orchidophilus aterrimus*	orchid weevil
Elytroteinus subtruncatus	Fijian gonger weevil	*Orchidophilus peregrinator*	lesser orchid weevil
Epitrix hirtipennis	tobacco flea beetle	*Oryzaephilus mercator*	merchant grain beetle
Euscepes postfasciatus	West Indian sweetpotato weevil	*Otiorhynchus cribricollis*	cribate weevil
Hypothenemus obscurus	tropical nut borer	*Protaetia fusca*	mango flower beetle
Lagocheirus undatus	plumeria borer	*Rhabdoscelus obscurus weevil*	New Guinea sugarcane
Lema trilinea	threelined potato beetle	*Systena blanda*	palestriped fleabeetle
Listroderes difficilis	vegetable weevil	*Tribolium castaneum*	red flour beetle
Tribolium confusum	confused flour beetle	*Xyleborus ferrugineus*	a scolytid beetle
Uroplata girardi	lantana hispid	*Xyleborus fornicatus*	a scolytid beetle
Xyleborus affinis	a scolytid beetle	*Xylosandrus compactus*	black twig borer
Xyleborus crassiusculus	a scolytid beetle	*Scarab beetles*	

TABLE A0. 3 Mosquitoes species (Public Health, 2001)

Scientific name	Species and the vector they transmit
Aedes	Yellow-fever, encephalitis & dengue mosquito (*Aedes aegypti*) and Asian tiger mosquito (*Aedes albopictus*).
Anopheles	malaria mosquito *Anopheles quadrimaculatus*
Culex	vector of St. Louis Encephalitis and also play an active role in the transmission of filariasis , and West Nile Virus
Coquillettidia (co-quill-ah-tid-ee-ah)	vector for Eastern Equine Encephalitis
Toxorhynchites (tox-o-rine-ky-tees)	The larval stage, they are known to be predacious on other mosquito and aquatic insect larvae.

TABLE A0. 4 Slug

Scientific names	Common names
Vaginulus plebius	brown slug
Veronicella leydigi	black slug

TABLE A0. 5 Caterpillar species

Scientific names	Common names	*Scientific names*	Common names
Achaea janata	croton caterpillar	*Anacamptodes fragilaria*	koa haole looper
Acrolepia assectella	leek moth	*Anua indiscriminata*	guava moth
Acrolepiopsis sapporensis	Asiatic onion leafminer	*Bedellia orchilella*	sweetpotato leafminer
Agraulis vanillae	passion vine butterfly	*Cadra cautella*	almond moth

Agrius cingulatas	sweetpotato hornworm	*Chrysodeixis eriosoma*	green garden looper
Agonoxena argaula	coconut leafminer	*Cryptoblabes gnidiella*	Christmas berry webworm
Agrotis ipsilon	black cutworm	*Cryptophlebia illepida*	koa seedworm
Amorbia emigratella	Mexican leafroller	*Cryptophlebia ombrodelta*	litchi fruit moth
Achaea janata	croton caterpillar	*Anacamptodes fragilaria*	koa haole looper
Acrolepia assectella	leek moth	*Anua indiscriminata*	guava moth
Daphnis nerii	oleander hawk moth	*Opogona purpuriella*	a tineid moth
Elasmopalpus lignosellus	lesser cornstalk borer	*Opogona sacchari*i	banana moth
Hedylepta blackburni	coconut leafroller	*Othreis fullonia*	Pacific fruit-piercing moth
Helicoverpa zea	corn earworm	*Pelopidas thrax*	banana skipper
Hellula undalis	imported cabbage webworm	*Penicellaria jocosatrix*	mango shoot caterpillar
Keiferia lycopersicella	tomato pinworm	*Peridroma saucia*	variegated cutworm
Lampides boeticus	bean butterfly	*Phthorimaea operculella*	potato tuberworm
Lorita abornana	chrysanthemum flower borer	*Pieris rapae*	imported cabbageworm
Maruca testulalis	bean pod borer	*Plutella xylostella*	diamondback moth
Omiodes accepta	sugarcane leafroller	*Pseudaletia unipuncta*	armyworm
Spoladea recurvalis	Hawaiian beet webworm	*Spodoptera exempta*	nutgrass armyworm
Strymon bazochii gundlachianus	smaller lantana butterfly	*Spodoptera exigua*	beet armyworm
Strymon echion	larger lantana butterfly	*Trichoplusia ni*	cabbage looper
Vanessa cardui	painted lady butterfly		

TABLE A0. 6 Classification of some important natural beneficial insects (NBI)

SUPERFAMILY	Wasps	Habit (Endo)	Habit (Ecto)	Region
Stephanidea (<=345) species	Stephanids Cerambycidae Buprestidae	endoparasitoids xylophagous beetle larvae	ectoparasitoids	Tropical and subtropical
Evanoidea (> 400) species	Aulacidae Gasteruptiidae Evaniidae	Endoparasitoid predators	Ectoparasioids of cockroach	All over the world except polar region
Pimplinae (95) genera	Pimplini Polysphinctini Rhyssini Ephialtini	Solitary endoparasitoids of lepidopterous pupae	Solitary ectoparasitoids of spiders Solitary ectoparasitoids of wood-boring larvae Solitary ectoparasitoids of larvae and pupae concealed in fruit	Afrotropical region
Diptera (50% of 3,300) species	Pyrgotidae Cryptochetidae Tachinidae		Predators and parasite	all over the world, mid-

	Muscidae (Acridomyia) Sarcophagidae			Atlantic region of the U.S.A; except in regions with permanent ice-cover
Scolioidae (5) genera Strepsiptera (600) species	Scoliid Strepsiptera	Endoparasitoids of beetle larvae Endoparasite		America north of Mexico
Bethyloidea (>6000) species	Bethylid Dryinida,		parasitoid or cleptoparasitic wasps Predators of beetles & moth larvae	Indian region
Ceraphronoidea (800) species	Cerephronidae, Megaspilidae	Endoparasitoids of cecidomyiid flies,	ectoparasitoids	All part of the world, Neotropical region.
Proctotrupoidea (3) genera	Diapriidae Heloridae Proctotrupidae Scelionid Platygastroidae	Endoparasitoids in the pupae of flies Parasitoids on lacewings Endoparasitoids mainly beetles Endoparasioids on invertebrate eggs Endoparasitoids on flies		Florissant locality, United States; species around the world, broadly distributed throughout Neotropical region.
Cynipoidea Cephidea (1400-1500)species	Cynipoidea Figitidae Himalicynipida e Cephidae	Endoparasitoids Endoparasitoids	Gall wasps hyperparasitoids	Afro-tropical region and Ethiopian Zoogeograp hical Region Moscow region
Chalcidoidea (from 22000 – 500,000) species	Aphelinidae Chalcididae Elasmidae	Egg Parasitoids- mainly homoptera Solitary Endoparasitoids of the pupae of butterflies and moths	gregarious idiobiont ectoparasitoids of lepidopterous larvae and also pseudo-hyperparasitoids via	Around the world , north America and Afrotropical

	Encyrtidae Eucharitidae Eupelmidae Eulophidae Eurytomidae	Endophytic phytophages	Ichneumonoidea cocoons Egg Parasitoids Parasitoids of ants Parasitoids on a variety of insect order Parasitoids on eggs and larvae	region usually
	Mymaridae Ormyridae Perilampidae Pteromalid Tetracampidae Torymidae Trichogrammat idae	Endoparasitoids of insect including Thrips	Egg Parasitoids of insect eggs Parasitoids of gall forming insects Parasitoids Parasitoids Parasitoids on insects Parasitoids of gall- forming insects Egg	
Ichneumonoidea (3,000) species	Braconidae Ichneumonidae	Endoparasioids of commensals	Ectoparasioids of wasps larvae and on wide variety of invertebrates	North America, Europe
Chrysidoidea (98>2000) species Tiphiidae	Chrysididae Tiphiid	Endoparasitoids Endoparasitoids	Ruby-tailed wasps Ectoparasitoids and gregarious	mid-Atlantic region; Afrotropical region, subtropical and tropical zones Afrotropical Region
Vespoidea	Pompilidae		Ectoparasitoids	
	Trihiidae Vespidae Apidae Sphecidae	Endoparasitoids	Beetle parasitoids Communal wasps Bees Solitary wasp	Oriental region, Africa, Southeast Asia, India and Australia

Table A0. 6 shows categories of insects with parasitic, parasitoid and predatory characteristics as illustrated by (Shaw & Huddleston, 1991), and (Oliver et al., 2009) which are considered useful to the development of this work.

A1.0 TABLES OF THE LIFE CYCLE STAGES OF PEST AND NATURAL BENEFICIAL INSECT (NBI)

TABLE A0. 7 Diamondback moth life cycle

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 A0.7 as observed by (Etebari et al, 2011), (Capinera, 2012), (Harcourt, 1957); summarizing the maximum number of eggs laid by a typical diamondback moth and the expected life span of all the life cycle stages

TABLE A0. 8 Parasitoid wasp's life span

Parasitoid wasps species life span in days					
Egg (Trichogramma) (days)		Larval (*Diadegma semiclausum*) (days)		Pupal (*Diadromus collaris) (days)*	
No of eggs laid	1-2	No of eggs	1-2	No of eggs	2
egg incubation period	1-2	egg incubation period	1 -3	egg incubation	1-2
Larva	1-3	Larva - wasp larva emerges from larva	3-6	larva	2-6
pupa	4-5	Pupa stay with pest larva	6-9	pupa	6-9
Total time for adult wasp to emerge from egg ct	6-11	Adults emerge	9-11	Adult emerges	10-12
Wasp lifetime in the presence of food	8-11	Wasp lifetime	21 - 26	Wasp lifetime	12-31
Wasp lifetime in the absence of food	3-5	Wasp lifetime in the absence of food	3-5	Wasp lifetime in the absence of food	3-7

Table A0.8 as reported by (Knutson, 1998), (Khatri, 2008) and (Liu et al., 2001). 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 wasp's life span in the presence and absence of food.

TABLE A0. 9 Parasitoid wasp's life spans (*Cotesia Flavipes)*.

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

The Table A0.9 records the number of eggs produced by the *Cotesia Flavipes (Cameron)* 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. (Kfir, 2002), (Srinivasa et al., 2011), (Tanwar, 2002) and (Niyibigira, 2003)

TABLE A0. 10 *Spodoptera Exempta* development from egg to adult. (Mangano, 2006), (Glogoza, 2000), (Holt et al., 2006) and (Mahmoud et al., 2011)

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

TABLE A0. 11 The life span and average lifespan of the cocoyam or Taro beetles as demonstrated (Roy), (Autar et al., 1999) and (Sada, 2014)

Beetles life cycle	Length of Incubation period
Eggs	14 - 18 days
Larvae (1st and 2nd instar)	18 days
Larvae (3rd instar)	55 days
Pre-pupae	7 days
pupae	30 days
Adults	22 months or 660 days

TABLE A0. 12 Mosquitoes life cycle as described by (Cross, 2004) and (Wej et al, 2003)

Mosquitoes (*Anopheles*) Life cycle & expectancy in days	
Maximum no of eggs per day	50-100 singularly
Life expectancy of adult mosquito	7-28
Life expectancy of egg	1-12
Life expectancy of larva or (wigglers)	2-29
Life expectancy of pupa	1-16

TABLE A0. 13 The average life span of several classes of Mosquitoes

Mosquitoes Life cycle & expectancy in days	
Maximum no of eggs per day	100-250
Life expectancy of adult mosquito	4-30
Life expectancy of egg	2-3
Life expectancy of larva or (wigglers)	7-14
Life expectancy of pupa	2-7

derived from the works of (Hochedez, 2010); (Kim et al., 2005), (Adham et al., 1982), (SkeeterBite, 2007) and (Cross, 2004)

TABLE A0. 14 Life cycle of the predators as reported by (Smallshire et al., 2013), (British dragonfly)

Dragonfly (*Odonata)* Life cycle & expectancy in days	
Maximum no of eggs per day	50
Life expectancy of egg	12-16
Life expectancy of nymph	56-1516
Life expectancy of adult	60-184

TABLE A0. 15 The average life span of Tx.splendens life cycle stages

Toxorhynchites predatory life span in days	
No of eggs laid	8.26
egg incubation period	1.5-5
larval incubation period	4-79
pupa incubation period	4 - 12
Adult life span	13-107
Daily number of eggs per female	2.52 -13.3

Table A0.15 data as demonstrated by (Goettle, 1999), (Toma, 1992) and (Chowanadisai et al., 1984), (Wej et al., 2003), (Steffan & Evanhuis, 1981) and (Aditya et al., 2006)

A2.0 THE NATURALLY BENEFICIAL INSECTS (NBI) FREQUENCY OF CAPTURE

This models the scenario for the successive random trials that the predator and parasitoid wasps undertake, with each predation attempt having a probability of success 'p'. The number of attempts that the predator or wasps must perform in order to capture and parasitize a given number of prey r has a negative binomial distribution where 'I' is the indicator function, which ensures that 'r' only adopts integer values.

The program code to determine the capturing frequency of the predator (adult and nymph and Toxorchynchites larvae) on its prey is shown below.

```
%model the capturing frequency of NBI both predators and parasitoid wasps
%Author: MATLAB: MODIFIED : Fina Faithpraise :  % created: 2014
----------------------------------------------------------------------------------------------------


% %%% Capture frequency of  Odonata adult & nymph and Toxorchynchites larva
figure

P  =  0.09;% the probability of success
r  =  48; % odonata adult approximate number of successful catch
r1 =  29; %odonata nymph approximate number of successful catch
r2 =  9; % Toxorchynchites larva approximate number of successful catch
x  =  48:800;%odonata adult number of trial survey
x1 =  29:550;%odonata nymph adult number of trial survey
x2 =  9:250;% Toxorchynchites adult number of trial survey
plot(x,nbinpdf(x,48,.09),'k-');
legend({'r1 = 489'})
title(' Capturing capability of Toxorhyn, Odonata and nymph','FontSize',12);
%legend({'r = 1' 'r = 2' 'r = 3' 'r = 4'})
xlabel('Number of Trials survey(x)')
ylabel('Probability of capture(p)','FontSize',12)
hold on
plot(x1,nbinpdf(x1,29,.09),'--');%
```

```
legend({'r1 = 29'})
%title(' Capturing capability of Odonata nymph','FontSize',12);
hold on
plot(x2,nbinpdf(x2,9,.09),'r-');
legend({'r2 = 9'})

%%%%%%% using the CDF to determine the cumulative frequency of capture

P  =  0.09;% the probability of success
r  =  48; % odonata adult approximate number of successful catch
r1 =  29; %odonata nymph approximate number of successful catch
r2 =  9; % Toxorchynchites larva approximate number of successful catch
x  =  48:800;%odonata adult number of trial survey
x1 =  29:550;%odonata nymph adult number of trial survey
x2 =  9:250;% Toxorchynchites adult number of trial survey
plot(x,nbincdf(x,48,.09),'k-');
legend({'r1 = 489'})
title(' Capturing capability of Toxorhyn, Odonata and nymph','FontSize',12);
%legend({'r = 1' 'r = 2' 'r = 3' 'r = 4'})
xlabel('Number of Trials survey(x)')
ylabel('Probability of capture(p)','FontSize',12)
hold on
plot(x1,nbincdf(x1,29,.09),'--');% Capturing effecientcy (ζ, ξ)
legend({'r1 = 29'})
%title(' Capturing capability of Odonata nymph','FontSize',12);
hold on
plot(x2,nbincdf(x2,9,.09),'r-');
legend({'r2 = 9'})
```

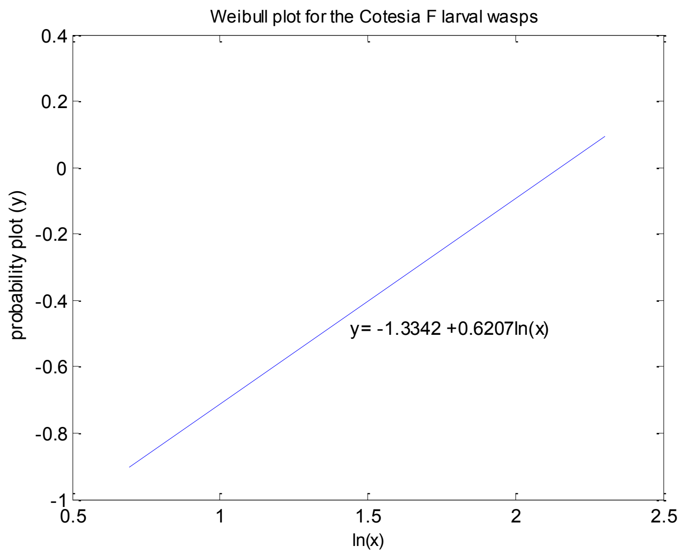
A2.1 PARASITOID WASPS (TRICHOGRAMMA AND TACHINIDS) PARASITIZING PROBABILITY.

The program code to determine the probability the parasitoid wasps (Trichogramma and Tachinids) locate and parasitize its host.

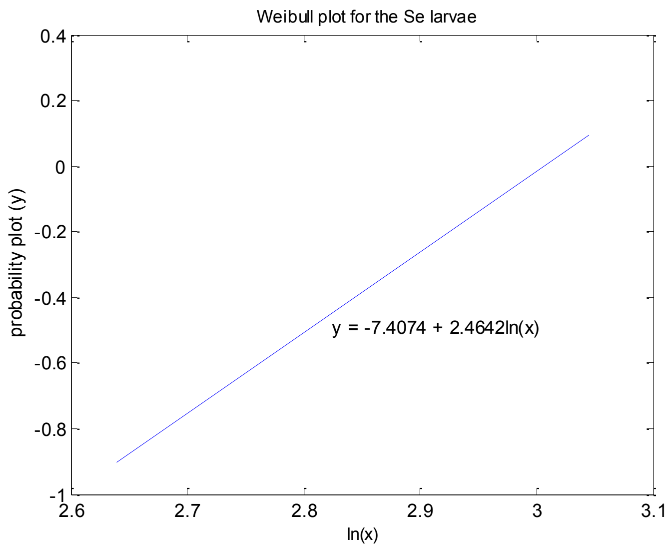
```
figure
p  =  0.09;
re =  5; % approximate minimum number the Trichogramma wasps can parasitize
rL =  6; %approximate minimum number the Tachinid wasps can parasitize
x  =  5:200; %%Trial number of survey
x2 =      6:250;%%%Trial number of survey
plot(x,nbinpdf(x,5,.09),':k');
hold on
title(' Capturing probability of egg,& larval parasitoid wasps','FontSize',12);
xlabel('Number of Trials (x)')
ylabel('Probability of capture(p)','FontSize',12)
hold on
plot(x2,nbinpdf(x2,6,.09),'--r');
```

A3.1 WEIBULL PLOT

The Weibull plots used in combination with the several equations 6.11 to 6.60 to obtained the results of the mortalities of Table 6.1 and Tables A0.19 to A0.23 -Appendix A4



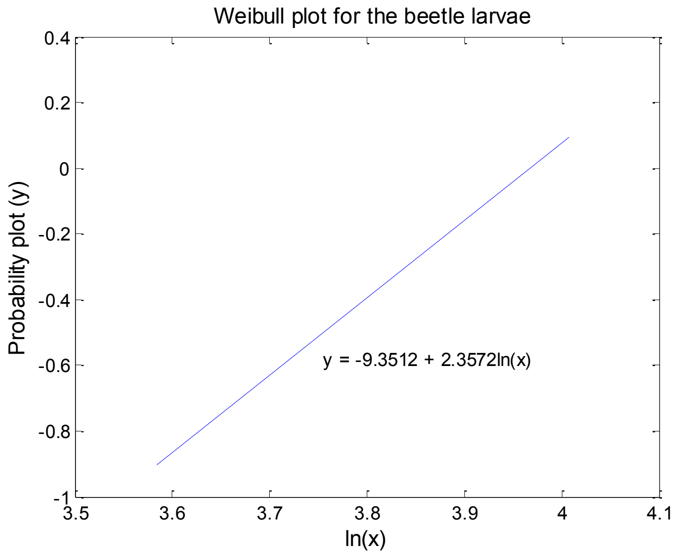
(a)



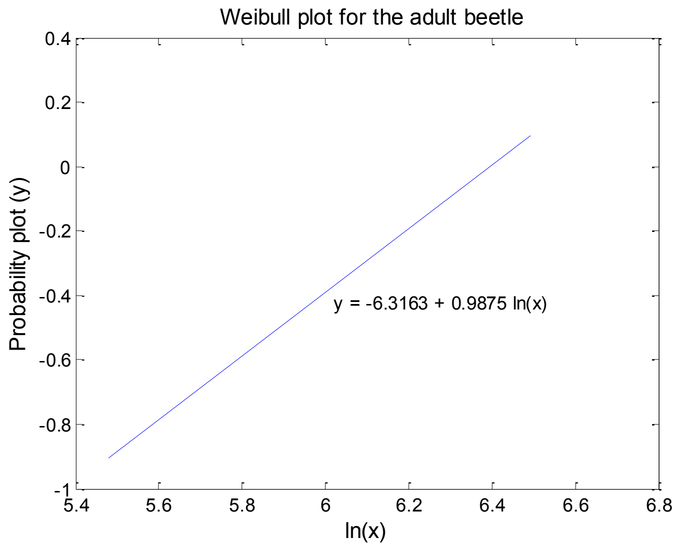
(b)

FIGURE A4. 1 Weibull plots of the Spodoptera Exempta and Cotesia Flavipes Cameron

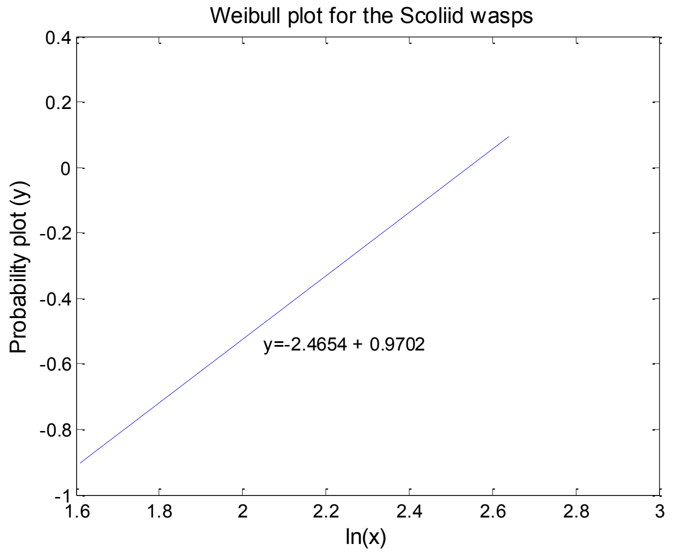
APPENDIX A3_WEIBULL PLOT



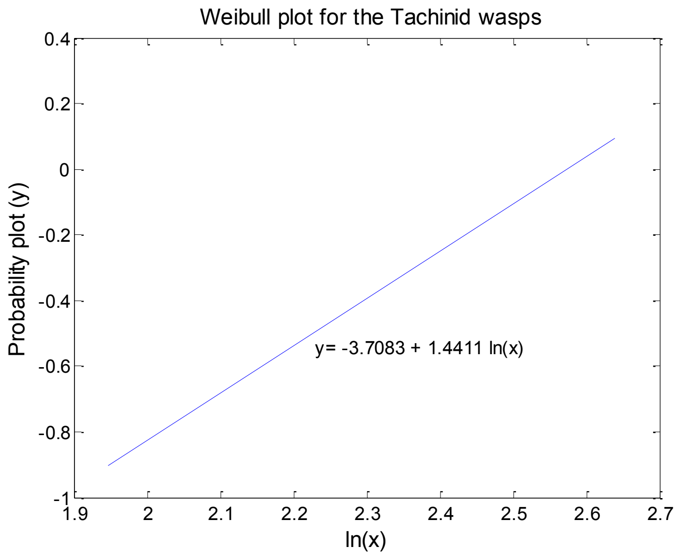
(a)



(b)



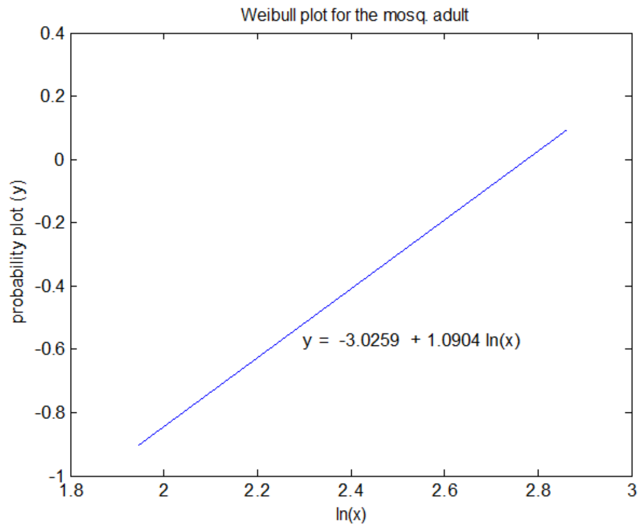
(c)



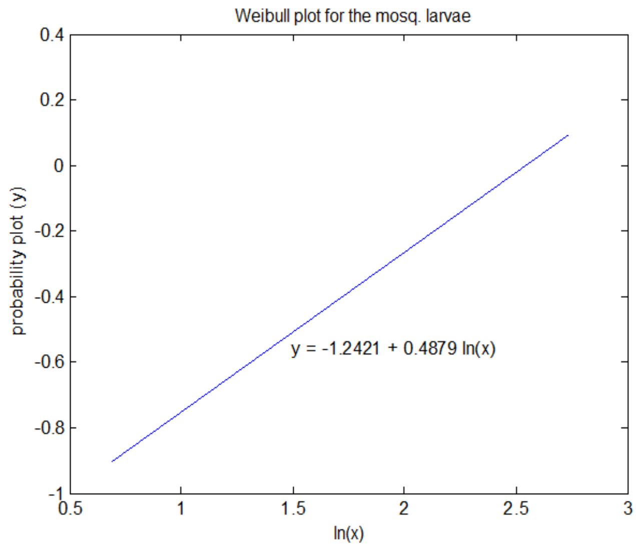
(d)

FIGURE A4. 2 Weibull plots of the Scarab beetles and combine Scoliid and Tachinid larval wasps

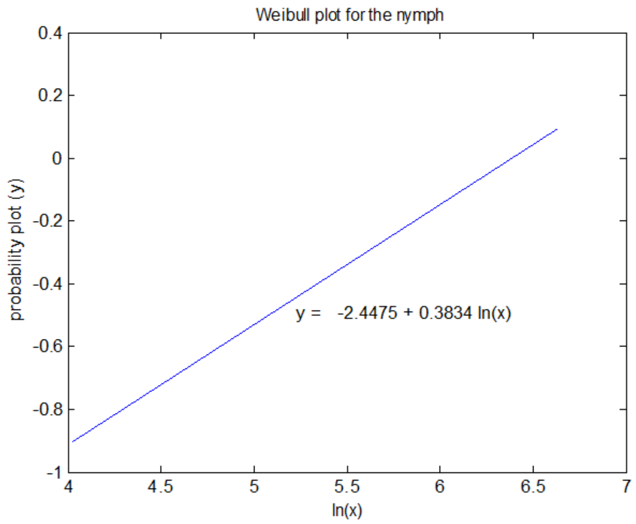
APPENDIX A3_WEIBULL PLOT



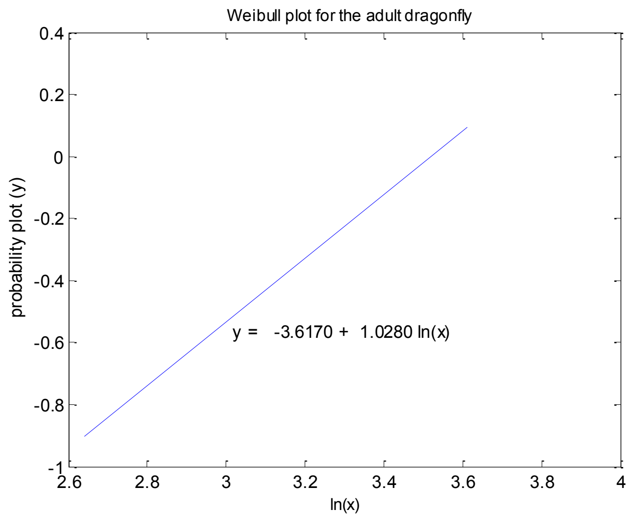
(a)



(b)

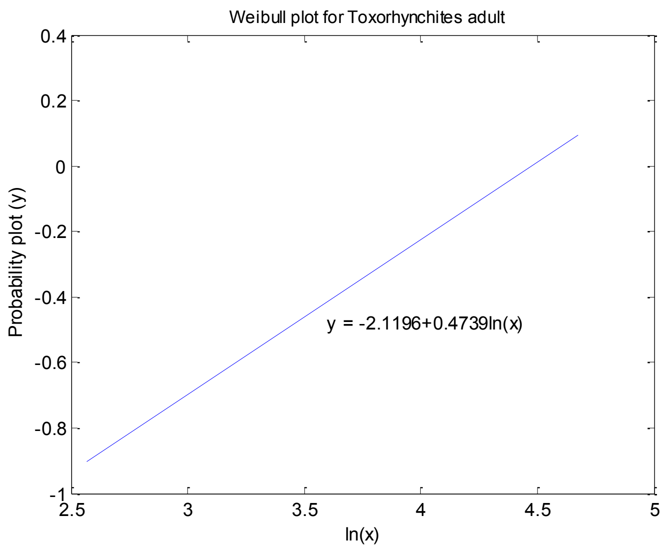


(c)

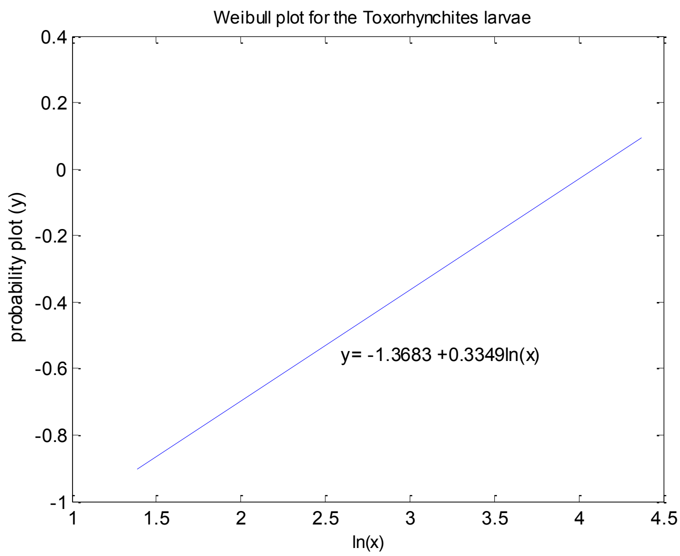


(d)

FIGURE A4. 3 Weibull plots of the Anophele mosquitoes and the predator (dragonfly)



(a)



(b)

FIGURE A4. 4 Weibull plots of the predators Toxorhynchites adults and larvae.

APPENDIX A3_WEIBULL PLOT

A4.1 RESULTS OF MORTALITIES OF THE PEST AND NBI OBTAINED FROM WEIBULL DISTRIBUTION

The Mortalities of Tables A0.18 to A0.21 were obtained from the average life span of the various species of pests and NBI of Tables A0.7 to A0.17- Appendix A1 by applying the Weibull probability distribution function as shown below.

TABLE A0. 16 Life expectancy of Cotesia Flavipes (larval wasps).

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

TABLE A0. 17 Mortality rates of the predator (dragonfly) and pest (Anopheles mosquito)

Mortality	Life span *(x)*	Average life span	*In (x)*	p_i p_{ii}	Gradient ψ	(b_0/b_1)	θ	Mortality obtained
m_m^e	1-12	6.1	1.8083	0.333-0.666	0.5832	-1.6454	5.1831	0.10
m_m^l	2-29	15.5	2.7408	0.333-0.666	0.4879	-2.5458	12.7535	0.035
m_m^p	1-16	8.5	2.1401	0.333-0.666	0.4886	-1.9456	6.9975	0.0632
m_m^a	7-28	17.5	2.8622	0.333-0.666	1.0904	-2.7750	16.0392	0.0685
m_d^e	12-16	14	2.6391	0.333-0.666	10.2462	-2.6298	13.8712	0.805
m_d^n	56-1516	758	6.6307	0.333-0.666	0.3834	-6.3837	592.098 1	0.000055
m_d^a	14-60	37	3.6109	0.333-0.666	1.0280	-3.5185	33.7332	0.0306

TABLE A0. 18 Life expectancy of Toxorhynchites life cycle

Mortalities	life span in days (x)	ln (x1)	ln (x2)	*ψ= b₁*	*(b₀/b₁)*	$\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$	Mortality obtained
m_e^h	13-107	2.5649	4.6728	0.4739	-4.4727	87.5906	0.0049
m_e^e	1.5-5	0.4055	1.6094	0.8298	-1.4949	4.4591	0.183
m_e^l	4 - 79	1.3863	4.3694	0.3349	-4.0857	59.4834	0.0047
m_e^p	2-12	0.6931	2.4849	0.5575	-2.3146	10.1211	0.0511

Table A0.20 as illustrated by Goettle, (Toma, 1992) and (Chowanadisai et al., 1984), (Wej et al., 2003), (Steffan et al., 1981)and (Aditya et al., 2006).

TABLE A0. 19 Mortality rates of scarab beetles and Scoliid and Tachinidae wasps

Mortalities	life span in days (x)	ln (x)	$\psi = b_1$	(b_0/b_1)	$\theta \approx e^{-\left(\frac{b_0}{b_1}\right)}$	Mortality obtained
m_b^h	660	6.4922	0.9875	-6.3963	599.5942	0.0016
m_b^e	18	2.8904	3.9753	-2.8665	17.5758	0.2428
m_b^l	91	4.5109	2.3572	-2.6327	13.9112	0.0225
m_b^p	37	3.6109	1.9421	-3.5175	33.6995	0.0324
p_{tlm}	14	2.6391	1.4411	-2.5732	13.1083	0.1132
p_{lm}	14	2.6391	0.9702	-2.5411	12.6940	0.0762

A5.1 THE PROGRAM CODES FOR THE CALCULATION OF THE MORTALITY RATES OF THE SEVERAL SPECIES OF PEST AND NBI.

The application of the Weibull probability distribution function is applied in the determination of the mortality rates of all classes of insects (pest & NBI) used in this research work as modelled and run by the program below. To achieve realistic results, the data is varied in accordance to the particular insects' life span or incubation period.

```
%Weibull Distribution
%exponential distribution is widely use to model the lifetimes of system component.
%model the life length or mortality of insects both pest, predators and parasitoid wasps
%Author: Fina Faithpraise :  % created: 2013
-----------------------------------------------------------------------------------------------------

% % gradient slope for Scoliid wasps larval parasitoid


Linx1   =  1.6094;
Linx2   =  2.6391;
y1      = -0.904;
y2      =  0.0950;
x       =  [Linx1 Linx2];
y       =  [y1 y2];
plot (x,y)
title(' Weibull plot for the Scoliid wasps','FontSize',12);
xlabel('ln(x)','FontSize',12);
ylabel('Probability plot (y)','FontSize',12);

% % % % compute intermidiate quantities

Dx = Linx2-Linx1;
 Dy = y2-y1;
% % % compute slope
```

```
 s = Dy/Dx
 p = y-(x*s)
%compute mortality of Scoliid wasp

Mdt   =   14;
Smdt  =  0.9702;
Pmdt  =  -2.4654;
udt     =  pmdt/smdt
Gmdt  =  exp(-1*(1*udt))
Mort_dt = (smdt/Gmdt)*((mdt/Gmdt)^(smdt-1))
```

B0. 1 PEST UAV SURVEILLANCE CARRIAGE BOX DESIGN (PUSCB)

B0.2 NBI WEIGHT

A ladybug size ranges from 0.8 to 18 mm (0.0315 to 0.708 inches), weighs approximately . (for this illustration, we shall consider a ladybug whose size is 6 mm).

0.021 grams (0.000021kg), (Seago, 2011) .

Let the volume of ladybug be 8mm x 4mm x 3mm = 96mm$^{3.}$

The dragonfly weighs around 0.0001 ounce (0.003 grams) or (0.000003kg) for the smallest, to 0.1 ounce (3 grams) or (0.003kg) for the largest (Wageningen, 2011) .

The Parasitoid wasps: the insect are estimated to weigh only about 1/40,000th of a gram and 2mm long (Sykes, 2005) .

The several boxes that houses the NBI are designed with carbon fiber materials which weighs approximately 0.5mm ~ 0.005cm. Since the payload capacity of the proposed surveillance system for the deployment of the NBI for the 90 x 90 m^2 field size is 1.4kg, we then put the following into consideration. Thus:

The Volume of ladybug v = 96mm^3

The weight of NBI (ladybug) (w_l) = 0.011g

If the potato field size (s^p) = 8100

Let the initial population of the NBI $({}_iN)$ for instance (adult and larvae ladybug) = 50*2 = 100.

The expected quantity of NBI (ladybugs) $(q_l) = s^p * {}_iN$ = 810,000.

Therefore the expected total weight of the NBI $(w_t) = q_l * w_l$ = 810000*0.011g =8.9kg

So 8.9kg is the total weight of the NBI (ladybugs) expected to deployed into the potato field size of 90 x 90m^2 with a Pest UAV Surveillance system of 1.4kg payload capacity.

To successfully control the pest population in the field and to avoid over loading the drone, the number of flight trips required by the surveillance system to deploy 8.9kg weights of the NBI is 8.9/1.4 =6.4.

B1.1 EXACT WEIGHT OF THE NBI PER BOX DESIGN

The proposed number of small boxes to be use in each flight to transport the NBI to the field (N_b)= 52

Total weight of NBI to deploy per small box (w_b) = $(q_l/N_b) * w_l$ =15,577*0.011 = 0.17kg

For the 6.4 flights, each small box will carry 0.17kg/6.4 = 0.027kg

So that the total weight of the NBI in the 52 boxes per each trip = 0.027kg * 52 = 1.4kg.

The total number of NBI to be deployed for each flight trip T_i = The expected quantity of NBI (ladybugs) /Total flight trip = $810000/6.4$ = 126,562

The total number of NBI per each box = T_{i/N_b} = 126,562/52 = 2434.

For every flight, each of the 52 small boxes will house a total of 2434 NBI (both larvae and adult ladybugs).

B2.1 VOLUME OF THE CARRIAGE BOX DESIGN

- ***THE SMALL BOXES***

Therefore the volume of each box = the total number of NBI per each small box * the volume of the NBI (ladybug)

1298 * $96mm^3$ = $124{,}608mm^3$ ~ $125cm^3$

$125cm^3$ is the total volume of the 52 boxes.

Therefore the size of each small box =$(\sqrt[3]{125})/2$ = $\sqrt[3]{62.5} = 4$cm.

So the dimension (Length*Width*Depth) of the small box = 44mm*44mm*84mm as shown in Fig. 7.4. this design is applied to all the 52 small boxes.

- ***THE CARRIAGE MAIN BOX DESIGN***

The dimension of the carriage main box is dimension as follows 204*348*252. The design was accomplished using Solidworks version 2013 development environment. For further illustration of the PUSCB main design and construction, see Fig. 7.5

REFERENCES

REFERENCES

Adamo, S.A., 1997. “How parasites alter the behaviour of their insect hosts”. In: Beckage, N. (Ed.), Parasites and Pathogens. Effects on Host Hormones and Behaviour. Chapman and Hall, New York, pp. 231–245

Adamo SA (2002). “Modulating the modulators: Parasites, neuromodulators and host behavioural change”. Brain Behaviour and Evolution Vol. 60, No. 6. (2002), pp. 370-377, doi:10.1159/000067790 Key: citeulike:2938672

Adeola, R. G. (2012). “Perceptions of Environmental Effects of Pesticides Use in Vegetable Production by Farmers in Ogbomoso, Nigeria”. Global Journal of Science Frontier Research Agriculture & Biology Volume 12 Issue 4 Version 1.0 April 2012

Adham Fatma K., Leaf HL. (1982) “Establishment of a colony Culiseta Longiareolata under laboratory condition”. Cellular and Molecular Life Sciences *(CMLS)* 38 (12): 1498–1499. doi:10.1007/BF01955792.

Aditya G., Ash A., Saha G.K. (2006). “Predatory activity of Rhantus sikkimensis and larvae of Toxorhynchites splendens on mosquito larvae in Darjeeling”, India. J Vector Borne Dis. 2006 Jun;43(2):66-72.

Adnan Abidi and Reuters (2013). “Indian Food Poisoning”. http://www.guardian.co.uk/ world/ 2013/ jul/24/ indian-food-poisoning-school-headteacher-arrested, (Retrieve July 19, 2013 - 6:03pm)

Agogino Adrian, Parker Chris Holmes, Tumer Kagan. (2012). “Evolving Large Scale UAV Communication System”. GECCO’12, July 7-11, 2012, Philadelphia, Pennsylvania, USA. Copyright 2012 ACM 978-1-4503-1177-9/12/07

Alabama Nursery and Landscape Association certified Landscape Professional Manual,(website/Photographer/institutions)

Alfalou **A.,** and Brosseau **C**., (2010). "Understanding Correlation Techniques for Face Recognition: From Basics to Applications, Face Recognition", Milos Oravec (Ed.), ISBN: 978-953-307-060-5, InTech, Available from: http://www.intechopen.com/

Al-Hiary H., Bani-Ahmad S., Reyalat M., Braik M., and Al Rahamneh Z. (2011). "Fast and Accurate Detection and Classification of plant disease". International Journal of computer Application,17(1): 0975-8887

Alkandri Ahmad T., Gardezi Akber A., Young Rupert C. D., Birch Philip M., Chatwin Chris (2011). "Parameter optimization of the Optimal Trade-off Maximum Average Correlation Height filter (OT-MACH) for FLIR imaging in high clutter environments". SPIE Defense and Security Symposium, Optical Pattern Recognition XXI, Proc. SPIE, Vol. 8055, art no. 805503 pp. xx to xx, Editors: D.P. Casasent, T-H. Chao, Kissimmee, Florida, USA, SPIE,

Amir, Ahmad & Lipika Dey, (2005). "Algorithm for Fuzzy Clustering of Mixed Data with Numeric and Categorical Attributes". Distributed computing and Internet Tecnology. Lecture notes in Computer Science Volume 3816, 2005 pp 561-572

Andreu V., Pico' Y. (2004). "Determination of pesticides and their degradation products in soil: critical review and comparison of methods". Trends Anal Chemistry 23(10–11): 772–789.

Annen A., Nebiker, S., Oesch, D., (2007). "A Light-Weight Multispectral Sensor For Micro Uav – Opportunities For Very High Resolution Airborne Remote Sensing. the

International Archives Of the Photogrammetry", Remote Sensing and Spatial Information Sciences. Vol. Xxxvii. Part B1. Beijing

Aphid "Damage to Plants". The Columbia Electronic Encyclopedia, 6th ed. Copyright © 2012, Columbia University Press, aphid: Damage to Plants | Infoplease.com http://www.infoplease.com/encyclopedia/science/aphid-damage-to-plants.htm (Retrieved 14/10/13)

Askew, R.R. & Shaw, M.R. (1986). "Parasitoid Communities": Their size, structure and development. In Insect Parasitoids (eds. J. Waage and D. Greathead), Academic Press, London. pp. 225-264

Asuquo U.E., Obisung E. O. and Faithpraise, F. O., (2010). "Sound absorbing properties of different density local acoustic materials". International Research Journals Educational Research Vol 1(2) pp. 039-041 March 2010

Autar M. & Singh J. (1988). Biology of taro beetle (*Papuana uninodis* Prell) infesting taro (*Colocasia esculenta*) in Fiji. Fiji Agricultural Journal. 15-21.

Axtell R., Axelrod R., Epstein J., Cohen M. (1996). "Aligning simulation models: A case study and results". Computational and Mathematical Organization Theory 1: 123–141.

Balaji T., Sumathi M., (2013) "Relational Features of Remote Sensing Image Classification using Effective K-Means Clustering". International Journal of Advancements in Research & Technology, Volume 2, Issue 8, August-2013 103 ISSN 2278-7763 Copyright © 2013 SciResPub. *IJOART*

Barber D. B., Redding J. D., McLain T.W., Beard R.W., and Taylor C. N.,(2006). "Vision-based target geo-location using a fixed-wing miniature air vehicle." Journal of Intelligent and Robotic Systems, vol. 47, no. 4, pp. 361–382, 2006.

Barclay H.J., Otvos, I.S. (1985). "Models of periodic inundation of parasitoids for pest control", Canad. Entomol. 117, pp. 705–716.

Barratt, Barbara I.P., (2005). "Aspects of reproductive biology and behaviour of scoliid wasps" Doc Science Internal Series 147 Published by Department of Conservation PO Box 10-420 Wellington, New Zealand October 2003, ISSN 1175.6519. ISBN 0.478.22513.X http://www.doc.govt.nz

Bean B., and Carl P., (2012). "Corn Development and Key Growth Stages", Texas A&M. Agricultural Research & Extension Centre Amarillo. osti.gov › National Agricultural Statistics Service, August 2012. http://publications.tamu.edu/ (Retrieved 25/02/14)

Bhattacharjee, S., Saha, S. & Raychaudhuri D., (2010). "Scoliid wasps (Hymenoptera: = Vespoidea) of Jaldapara Wildlife Sanctuary, West Bengal, India". Munis Entomology & Zoology, 5 (2): 661-669

BioControl Reference CenterAcosta, EW (1995-2006). "The History of Integrated Pest Management (IPM)". http://www.biconet.com/reference/IPMhistory.html

Birkhoj M., Nellemann C., Jarfelt K., Jacobsen H., Andersen HR., Dalgaard M., Vinggaard AM. (2004). "The combined antiandrogenic effects of five commonly used pesticides". Toxicol. Appl. Pharmacol. 2004;201:10–20.

Bliss C.I. (1953). " Fitting the negative binomial distribution to biological data," Biometrics 9:176-200, 1953.

Blood, B.N. & Kryger, J.P. (1922). "A new mymarid from brocken burst". Ectomologist's monthly magazine 58: 229 – 230

Bohmfalk, G.T., R.E. Frisbie, W.L. Sterling, R.B. Metzer and A.E. Knutson. "Identification, Biology And Sampling Of Cotton Insects Issued in furtherance of Cooperative Extension Work in Agriculture and Home Economics", Acts of Congress of May 8, 1914, as amended, and June 30, 1914, in cooperation with the United States Department of Agriculture. Ed Smith, Director, Texas AgriLife Extension Service. Electronic Revision, 2011. http://www.soilcropandmore.info/ (Retrieved 01/11/2013)

Boissard P., Vincent Martin, and Sabine Moisan, (2010). "A Cognitive Vision Approach to Early Pest Detection in Greenhouse Crops". Computers and Electronics in Agriculture 62(2): 81-93 & inria 00499603, pp.1-24

Bolme, David S. (2011) "Theory and applications of optimized correlation output filters", ProQuest Dissertations and Theses, 2011

Bolton B. & Collingwood, C.A. (1975). "*Hemenoptera, Formicidae".* Handbooks for the identification of British insects 6, 3(c): 1- 34

Bone P., Young, R., and Chatwin, C. (2005) "Position, rotation, scale and orientation invariant multiple object recognition from cluttered scenes," Conference Proc SPIE, 5816, (2005):66–77.

Booker R. H. (1964). “Pests of cowpea and their control in Northern Nigeria”. Bull. Entomology Resources, 55: 663-672.

Bourtzis Kostas, Zabalou Sofia, Riegler Markus, Theodorakopoulou Marianna, Stauffer Christian, Savakis Charalambos, (2004). “Wolbachia-induced cytoplasmic incompatibility as a means for insect pest population control”. PNAS vol. 101 _ no. 42, pp 15042–15045 www.pnas.org_cgi_doi_10.1073_pnas.0403853101

Buffington M.L., & van Noort S. (2007). “A world revision of Pycnostigminae (Cynipoidea: Figitidae) with descriptions of seven new species”. Zootaxa 1392: 1-30

Buglady, Aphid Control, Products and Pricing (2014) http://www.thebuglady.ca/buying.htm #products (Retrieved 19/04/04).

Buss E. A., “Aphids on Landscape Plants”. assistant professor, Department of Entomology and Nematology, Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, 32611, http://edis.ifas.ufl.edu

Butcher, John (2007), “Runge-Kutta methods”. Scholarpedia, 2(9):3147.

Caglioti C., Lalle E., Castilletti C., Carletti F., Capobianchi MR., Bordi L. (2013). Chikungunya virus infection: an overview. The new microbiologica **36** (3): 211–27.

Campbell F.T., & Schlarbaum, S.E. (1994). “Fading Forests: North American Trees and the Threat of Exotic Pests”. Natural Resources Defence Council, New York.

Cancrini G., Frangipane di, Regalbono A., Riccia I., Tessarin C., Gabrielli S., and Pietrobelli M., (2003). "Aedes albopictus is a natural vector of Dirofilaria immitis in Italy".

Veterinary Parasitology **118** (3–4): 195–202. doi:10.1016/j.vetpar.2003.10.011. ISSN 0304-4017

Candel (2012). “Nigeria loses N35bn foreign exchange on agric pesticides”. http://www.vanguardngr.com/2012/03/nigeria-loses-n35bn-foreign-exchange-on-agric-pesticides-candel/ (Retrieved 22/06/13)

Capinera J.L., (2012) “Diamondback moth, Featured creatures” – Entomology & Nematology, University of Florida, EENY-119, Retrieved 23/07/13

Carr TP., Weller Curtis L., Schlegel Vicki L., Cuppett Susan L. , Guderian Jr David M., and Johnson Kyle R. (2005) “Grain Sorghum Lipid Extract Reduces Cholesterol Absorption and Plasma Non-HDL Cholesterol Concentration in Hamsters”. Journal of Nutrition. 2005 Sep; 135(9):2236-40

Chakravarty P., and Sidhu SS. (1987). “Effects of glyphosate, hexazinone and triclopyron in vitro growth of five species of ectomycorrhizal fungi”. Euro J For Path 17: 204–210

Champion, R. H.; Roberts, S. O. B.; Carpenter, R. G.; Roger, J. H. (1969). "Urticaria and Angio-Oedema". British Journal of Dermatology 81 (8): 588–97. doi:10.1111/j.1365-2133.1969.tb16041.x

Chandwani. G. H., Balakrishnan, M. S . Padmanabhan. S. Y. (1963). “Hclminthosporium disease of rice. V. A study of the spore population of Helminthosporium oryzae over paddy fields”. J. Indian Bot. Soc. 62: 1-14

Chatfield, Christopher. “Statistics for technology: a course in applied statistics”, third edition (Revised) (1992) Chapman & Hall, London, ISBN 0-412-25340-2: pp. 327-330

Chaudhari Sv. " Biometrial Measurments Of Life Stages Of Senometopia Illota Curran (Diptera: Tachinidae) A Larval Pupal Parasitoid On Helicoverpa Armigra Hubner". Int. J. Bioassays, 2013, 02 (06), 850-857. Issn: 2278-778x Www.Ijbio.Com Accepted: May 21, 2013

Chikwenhere G. P., "Status of armyworm outbreaks and control in Zimbabwe," NewsdzeZimbabwe . January 06, 2013 http://www.newsdzezimbabwe.co.uk. (Retrieved 12/03/2014)

Chowanadisai L., Benjaphong N., & Phanthumachinda B. (1984) "Laboratory observations on Toxorhynchites splendens Wiedemann in Thailand". The Southeast Asian journal of tropical medicine and public health (impact factor: 0.6). 10/1984; 15(3):337-41

Chunlei Yan Li, & Lee Xia Jangmyung (2009). "Vision-based Pest Detection and Automatic Spray of Greenhouse Plant, Pusan National University Intelligent Robot Lab". IEEE International Symposium on Industrial Electronics (ISIE 2009) Seoul Olympic Parktel, Seoul, Korea.

Ciacci Carolina, Maiuri Luigi, Caporaso Nicola, Bucci Cristina, Giudice Luigi Del, Massardo Domenica Rita, Pontieri Paola, Di Fonzo Natale, Bean Scott R., Ioerger Brian, Londei Marco "Celiac disease: In vitro and in vivo safety and palatability of wheat-free sorghum food products". Clinical Nutrition. 2007 Dec;26(6):799-805. Epub 2007 Aug 24. http://dx.doi.org/10.1016/j.clnu.2007.05.006

Cock M. (2011). “Plant pests: The biggest threats to food security?”. BBC News, Science and Environment. 8 November 2011, http://www.bbc.co.uk/news/science-environment-15623490 (Retrieved 01/06/12)

Community Heritage Initiative. Ladybug Fact Sheet .Holly Hayes Environment and Heritage Resources Centre, Leicestershire County Council, 216 Birstall Road, chi@leics.gov.uk,http:// www.leics.gov.uk/celebrating_wildlife. (Retrieved 13/12/13)

Coronado P. L., Stetina, F., & Jacob, D., (2003). “New technologies to support NASA's Mission to Planet Earth satellite remote sensing product validation: use of an unmanned autopiloted vehicle (UAV) as a platform to conduct remote sensing”. Proceedings of SPIE, 3366, 38.

Corum J. M., Battiste R. L., Liu K. C., & Ruggles M. B.(2000). “Basic Properties of Reference Crossply Carbon-Fiber Composite”. Oak Ridge National Laboratory, Ornlflm-2000/29 . Owl-27 (3-669)

Cristobal G., Schelkens Peter & Hugo Thienpont (Eds.), (2011). “Optical and Digital Image Processing Fundamentals $ Applications,” WILEY-VCH (2011): 643-682

Crocus (2014). Live ladybirds to eat your aphids. http://www.crocus.co.uk/product/_/live-ladybirds-to-eat-your-aphids/classid.2000013999/ (Retrieved 19/04/2014)

Cross, Caroline - (11/8/04) “The life cycle of Anopheles mosquitoes Female Anopheles species mosquitoes are the only vector of malaria parasites”. http://malaria.wellcome.ac.uk/doc_WTD023872.html (Retrieved 16/09/13)

Crosskey, R. W. (1951). “the morphology, Texonomy and biology of the British Evanioidea (Hemenoptera)”. The transactions of the Royal Entomological Society of London 102:247-301

Cui Di, Qin Zhang, Minzan Li, Glen L. Hartman, Youfu Zhao (2010). “Image Processing Methods for quantitatively detecting Soybean rust from multispectral image”. Biosystems Engineering DOI:10.1016/j.biosystemseng 2010.06.004

Cyber Aerospace, UAV History, Copyright (2004). Proxity Digital Network.Inc, December 06

Daane K.M., Yokota G.Y., Zheng Y., Hagen K.S., (1996). “Inundative release of common green lacewings (Neuroptera: Chrysopidae) to suppress Erythroneura variabilis and E.elegantula (Homoptera: Cicadellidae) in vineyards” - Enviromental Entomology, 25(5): 1224 - 1234

Datt B., Apan A., and Kelly R. (2006). “Early detection of Exotic Pests and Diseases in Asian vegetable by imaging Spectroscopy, Rural Industrial Research and Development corporation”. 2006 RIRDC Publication No 05/170 ISBN 1 74151 233 6, ISSN 1440-6845

Davies AP., Pufke US., Zalucki MP. (2011). “Spatio-temporal variation in Helicoverpa egg parasitism by Trichogramma in a tropical Bt-transgenic cotton landscape”. Agricultural and Forest Entomology 13, 247-258.

Day M.c., (1988). Handbooks for the identification of British insects 6, (part4): Spider wasps(pompilidae).

Dean D., Thomas Christ A., Donnelly Roger J., Alphey Wood Luke S. (2000). “Insect Population Control Using a Dominant, Repressible, Lethal Genetic System”. SCIENCE VOL 287 pp 2474-76. www.sciencemag.org.

Dempsey, Martin E. (2010), “Eyes of the Army” – U.S. Army Roadmap for Unmanned Aircraft Systems 2010–2035 Size: 9MB United States Army, 9 April 2010. (Retrieved 6 02 2014).

Dorigo, W., Zurita-Milla, R., de Wit, A., Brazile, J., Singh, R., & Schaepman, M., (2007). “A review on reflective remote sensing and data assimilation techniques for enhanced agro-ecosystem modelling”. International Journal of Applied Earth Observation and Geo-information, 9(2), 165-193

Dormand J. R., and Prince P. J. (1981). “High order embedded Runge-Kutta formulae”, J. Comput. Appl. Math. 7 (1981), no.1, 67-75.

Dowell R.V., and Krass, C.J., (1992). “Exotic pests pose growing problem for California”. California Agriculture 46 (1), 6–12.

Dragonfly Habitats, The Life-Cycle Of A Dragonfly. http://www.british-dragonflies.org.uk/content/dragonfly-habitats. (Retrieved 13/09/2013)

Dreistadt SH., Clark JK., and Flint ML. (1994). “Pests of landscape trees and shrubs. An integrated pest management guide. University of California Division of Agriculture and Natural Resources”. Publication 3359.

Drone 6™ GPS Hexcopter, http://www.helipal.com. (Retrieved 01/12/13)

Eady R.D., & Quinlan, J. (1963). "Hymenoptera, Cynipoidea. Key to the families and subfamilies and Cynipinae (including galls)". Handbooks for the identification of British insects. 8, 1(a): 1-81

Eddleston M., (2000). "Patterns and problems of deliberate self-poisoning in the developing world". Q J Med 93: 715–31.

Edson K.M., Vinson, S.B., Stoltz D.B., and Summers M.D. (1981). "Virus in a parasitoid wasp": Suppression of the cellular immune response in the parasitoid's host. *Science*, 211, 582-583.

Eisenbeiss, H. (2004). "A mini unmanned aerial vehicle (UAV): system overview and image acquisition". International Workshop on" Processing and visualization using high-resolution imagery, 18-20

Ekundayo, E. O. (2003). "Effect Of Common Pesticides Used In The Niger Delta Basin Of Southern Nigeria On Soil Microbial Populations", Environmental Monitoring and Assessment 89: 35–41

Elliott, Michael G. (2011). "Annotated catalogue of the Australian Scoliidae (Hymenoptera)". Technical Reports of the Australian Museum, Online 22: 1–17. [16 February 2011] doi:10.3853/j.1835-4211.22.2011.1562 . ISSN 1835-4211

Environews Forum. (1999). "Killer environment". Environ Health Perspect 107: A62

Etebari K., Palfreyman RW., Schlipalius D., Nielsen LK., Glatz RV., Asgari S. (2011) "Deep sequencing-based transcriptome analysis of *Plutella xylostella* larvae parasitized by *Diadegma semiclausum"*. BMC Genomics 12: 446

Ettinger Stephen J., Feldman Edward C. (2010). Textbook of Veterinary Internal Medicine (7th ed.). W.B. Saunders Company. ISBN 978-1-4160-6593-7.

Eugster H., & Nebiker S., (2008). "UAV-based Augmented Monitoring – Real-time Geo-referencing and Integration of Video Imagery with Virtual Globes". XXIst ISPRS Congress, Beijing.

European Commission, (1998). "Monitoring of Pesticide Residues in Products of Plant Origin in the European Union". Report 1996: 15. European Commission. (2001). Monitoring of Pesticide Residues in Products of Plant Origin in the European Union, Norway and Iceland. Report 1999: 46

Faber V., Mundt O., Saltzman Jeffrey S., and White James M. (1994). "Clustering and the Continuous k-Means Algorithm". Paradigm Concepts, Inc., Santa Fe, NM. Los Alamos Science Number 22, 138-149

Fabra A., Duffard R., and Evangelista DDA. (1997). "Toxicity of 2,4-dichlorophenoxy- acetic acid in pure culture". Bull Environ Contam Toxicol 59: 645–652.

Faithpraise, F., Chatwin C. R., Obu J., Olawale B., Young R., and Birch P.,(2014a) "Sustainable Control of Anopheles Mosquito Population," Environment, Ecology & Management, Vol 3(1). 1-19, Feb. 2014.

Faithpraise Fina, Idung Joseph, Chatwin Chris, Young Rupert, Philip Birch (2014b). "Biological Control of Taro Scarab Beetle *(Papuanauninodis,Coleoptera: Scarabaeidae)* Instars via *scoliid and Voria tachinidae".* International Journal of Applied Biology and Pharmaceutical Technology, Volume 5, Issue 3, in press, 27th April 2014. July –Sept 2014, ISSN: 0976-4550.

Faithpraise Fina, Idung Joseph, Chatwin Chris, Young Rupert, Philip Birch (2014c). Prevention and Control of African Armyworm (*Spodoptera Exempta*) Infestations of Cereal Crops by Deploying Naturally Beneficial Insects (NBIs). Technical Report, TR/SU/FF/041401, 01 April. 2014, Page 1-14

Faithpraise, Fina., Joseph Idung, Chris Chatwin, Rupert Young, Philip,(2014d) "Natural Control of the population density of mosquito species via Odonata and Toxorhynchites," Journal of Innovative Research in Science, Engineering and Techology, Vol. 3, Issue 5, May 2014. ISSN: 2319-8753

Faithpraise, Fina., Joseph Idung, Chris Chatwin, Rupert Young, Philip Birch.(2014e) "Eco Control of Agro Pests using Imaging, Modelling & Natural Predators," IJETI, inpress. July 2014. http://www.ijeti.com

Faithpraise, Fina, Birch Philip, Young Reupert, Obu J., Faithpriase Bassey and Chatwin Chris (2013a*). "*Automatic Plant pest Detection & Recognition using k-means clustering algorithm & correspondence filters". International Journal of Advanced Biotechnology and Research ISSN 0976-2612, Online ISSN 2278–599X,Vol 4, Issue 2, pp. 1052-1062 http://www.bipublication.com

Faithpraise Fina., Chatwin C., Joseph Idung, Young R. and Birch P. (2013b), "Targeting the life cycle stages of the Diamond Back Moth (PlutellaXylostella) with three different parasitoid wasps," Technical Report, Sussex University, TR/SU/FF/131202, 02 Nov. 2013, Page 1-18

Faithpraise Fina., Chatwin C., Obu, J., Young R. and Birch P., (2013c) “Timely Control of Aphis craccivora Using an automatic robotic drone management system (ARDMS),” Systems Science & Control Engineering – An Open Access Journal, Taylor & Francis, in press

Fantke P., Friedrich R., Jolliet O. (2012). "Health impact and damage cost assessment of pesticides in Europe". Environ Int 49: 9–17. doi:10.1016/j.envint.2012.08.001

Farrar JL., Hartle DK., Harqrove JL., and Greenspan P. (2008). “A novel nutraceutical property of select sorghum (Sorghum bicolor) brans: inhabition of protein glycation”. Phytotherapy Research. 2008 Aug;22(8):1052-6. Doi: 10.1002/ptr.2431

Fehlberg E. (1969). “Klassische Runge-Kutta-Formeln fünfter and siebenter Ordnung mit Schrittweiten-Kontrolle“, Computing (Arch. Elektron. Rechnen) 4 1969 93-106.

Ferguson Kenneth I., & Stiling Peter (1996). “Non-additive effects of multiple natural enemies on aphid populations.” Oecologia (1996) 108:375-379. Springer-Verlag 1996

Fitday. “The nutrition of Taro”. http://www.fitday.com/fitness-articles/nutrition/healthy-eating/the-nutrition-of-taro.html (Retrieved 04/04/14)

Flanders S., Quednau W. (1960). “Taxonomy of the genus Trichogramma (Hymenoptera, Chalcidoidea, Trichogrammatidae)”. BioControl 5, 285-294

Frampton R.A., and Keirl J.M., UK Ministry of Defence (2006). “Autonomy and its Application to Unmanned Systems”. Proceedings of the 1st Moving Autonomy

Forward Conference, 21–22 June 2006, De Vere Belton Woods Hotel, Grantham, UK, Muretex Ltd.

Frampton R., and Dstl F., UK Ministry of Defence (2008). “UAV Autonomy”. Defence Codex – The Journal for Defence Engineering and Science, Issue 1, Summer 2008, UK Ministry of Defence

Focks DA., Sackett SR., Bailey, DL., (1982). “Field experimentes on the control of Aedes aegypti and Culex quinquefasciatus by Toxorhynchites rutilus rutilus Diptera: Culicidae”. Journal of Medical Entomology, 193: 336-339

Forget G. (1993). “Balancing the need for pesticides with the risk to human health. In: Impact of Pesticide Use on Health in Developing Countries”. Eds. Forget G, Goodman T and de Villiers A IDRC, Ottawa: 2.

Gámez M., López I., and Shamandy A., (2010). “Open-and closed-loop equilibrium control of trophic chains”, Ecol. Modell. 221, pp. 1839–1846

Gaszczak A., Breckon T.P., Han J.W., (2011). “Real-Time people and Vehicle detection from UAV imagery”, Proc. SPIE Conference Intelligent Robots and Computer Vision XXVIII: Algorithms and Techniques 7878 (78780B). doi:10.1117/12.876663

Gel R., Libersat F., Gel R. (2010). “A wasps manipulates Neuronal activity in the sub-Esophageal Ganglion to Decrease for walking in its cockroach prey”. E10019.doi:10.1371/journal.pone.0010019

Gess F. W., and Gess S. K. (1980). “Spider vanquishers: the nesting of Tachypompilus ignitus (Smith) and Batozonellus fuliginosus (Klug)”. The Eastern Cape Naturalist, Number 69: 4-7.

Ghoshal A., Das S., Ghosh S., Mishra MK., Sharma V., Koli P., Sen E., Basu A., (2007). “Proinflammatory mediators released by activated microglia induces neuronal death in Japanese encephalitis”. Glia **55** (5): 483–96. doi:10.1002/glia.20474.

Gianpaolo Conte and Patrick Doherty (2007). “Integrated UAV Navigation System Based on Aerial Image Matching”.1-4244-1488-1/08/$25:00c 2008 IEEE. IEEEAC Paper #1276, Version I Updated 23/10/2007.

Gibson G. A. P., Huber J. T., and Woolley J. B. (1997). “Annotated keys to the genera of Nearctic Chalcidoidea (Hymenoptera)”. NRC Research Press

Ginsberg L. (March 2004). “Difficult and recurrent meningitis” Journal of Neurology, Neurosurgery, and Psychiatry. 75 Suppl 1 (90001): i16–21. doi:10.1136/jnnp.2003.034272.

Glogoza P., (2000). “The Armyworm and the Army Cutworm. North Dakota State University Agriculture and University Extension,” 2000. http://www.ag.ndsu.edu/pubs/plantsci/pests/ e830w.htm (retrieved 23 /02/ 2014).

Glotfelty and Schomburg. (1989). “Volatilization of pesticides from soil in Reactions and Movements of organic chemicals in soil. Eds. BL Sawhney and K. Brown. Madison, WI”: Soil Science Society of America Special Pub.

Goettle, Bradley James and Adler, Peter H. (199). "Elephant (or Treehole) Predatory mosquito". www.dnr.sc.gov/cwcs/pdf/Predmosquit (Retrieved 22/02/14)

Gonzalez R.C., and Woods R. E. (1992). "Digital Image Processing (third edition)", Reading, Massachusetts: Addison-Wesley, 1992.

Greathead, D.J. (1976). "Review of biological control in western and southern Europe". Technical Communication of the commonwealth institute of Biological Control 7.

Greathead D.J., and Waage, J.K. (1983). "Opportunity for biological control of agricultural pests in developing countries". World Bank Technical paper 11

Greenwood M., and Yule Udny G., (1920). "An inquiry into the nature of frequency distributions representative of multiple happenings with particular reference to the occurrence of multiple attacks of disease or of repeated accidents," Journal of the royal statistical society 83:255-229, 1920,

Grissell E.E. (2007). "Scoliid Wasps of Florida, Campsomeris, Scolia, and Trielis spp. (Insecta: Hymenoptera: Scoliidae)," Featured Creatures, DPI Entomology Circulars 179 and 185, University of Florida

Grosman AH., Janssen A., De Brito EF., Cordeiro EG., Colares F., et al. (2008). "Parasitoid Increases Survival of Its Pupae by Inducing Hosts to Fight Predators". PLoS ONE 3(6): e2276. doi:10.1371/journal.pone.0002276

Haggis M. J. (1996). "Forecasting the severity of seasonal outbreaks of African armyworm, Spodoptera exempta (Lepidoptera: Noctuidae) in Kenya from the previous year's rainfall". Bulletin of Entomological Research 86: 129–136.

Hall J.P., Moody B., (1994). “Forest Depletions Caused by Insects and Diseases in Canada 1982–1987. Forest Insect and Disease Survey Information”. Report ST-X-8, Ottawa, Canada: Forest Insect and Disease Survey, Canadian Forest Service, Natural Resources Canada.

Hallem, Elissa A., Fox Nicole A., Zwiebel Laurence J., Carlson John R. (2004). “Olfaction: Mosquito receptor for human-sweat odorant”. *Nature* 427 (6971): 212–213. doi:10.1038/427212a PMID14724626

Hamilton Paul S., Insect Picture, www.biodiversityphotography.org/ (last accessed October, 2012)

Harcourt DG. (1957) “Biology of the diamondback moth, *Plutella maculipennis* (Curt.) (Lepidoptera: Plutellidae), in Eastern Ontario. II. Life-history, behaviour, and host relationships”. Canadian Entomologist 89: 554-564

Hardacre A. K., and Turnbull H. L. (1986) “The Growth and Development of Maize (Zea mays L.) at Five Temperatures,” Annals of Botany 58, 779-787, 1986 779, 1986.

Harmer A. M. T. (2010) “High – performance spider webs: integrating biomechanics, ecology and behaviour”. Journal of Royal Society Interface (2010)

Harvey A. W., And Mallya, G. A. (1995). “Predicting the severity of Spodoptera exempta (Lepidoptera: Noctuidae) outbreak seasons in Tanzania”. Bulletin of Entomological Research 85: 479–487

Hassell M.P. (2002). “The Spatial and Temporal Dynamics of Host–parasitoid Interactions”, Oxford University Press, Oxford. exempta (Lepidoptera: Noctuidae) outbreak seasons in Tanzania”. Bulletin of Entomological Research 85: 479–487

Hausamann D. (2002). “Civil Applications of UAVs – User Approach”, Shephard’s Civil UAV Symposium, London, UK, 17 – 19 July (2002).

Hawman DW., Stoermer KA., Montgomery SA., Pal P., Oko L., Diamond MS., Morrison TE. (Dec 2013). “Chronic joint disease caused by persistent chikungunya virus infection is controlled by the adaptive immune response”. Journal of Virology **87** (24): 13878–88. doi:10.1128/JVI.02666-13.

Hay SI., Guerra CA., Tatem AJ., Atkinson PM., Snow RW. (2005). “Urbanization, malaria transmission and disease burden in Africa”. Nat Rev Microbiol. 2005;3:81-90.

Hester Charles F., and Casasent David. (1980) “Multivariant technique for multiclass pattern recognition”. Appl. Opt., 19(11):1758–1761, 1980.

Hewitt C.C. Jr., (1960). “The negative binomial applied to the Canadian merit rating plan for individual automobile risks,” Proceedings of the casualty Actuarial Society 47:55-65, 1960.

Hilbe Joseph M. (2011). "Negative Binomial Regression, second edition", Cambridge, UK: Cambridge University Press

Hochedez P. S., Debruyne M., Bossi P., Hausfater P., Brucker G., Bricaire F., Caumes E., (2006). “Chikungunya Infection in Travelers”. Emerging Infectious Diseases 12 (10): 1565–1567. doi:10.3201/eid1210.060495. ISSN 1080-6040

Hoell H.V., Doyen J.T., & Purcell A.H. (1998). “ Introduction to Insect Biology and Diversity”, 2nd ed. Oxford University Press. pp. 493–499. ISBN 0-19-510033-6

Hoffmann W. A., Poorter H., (2002). "Avoiding Bias in Calculations of Relative Growth Rate". Annals of Botany 90 (1): 37. doi:10.1093/aob/mcf140.

Holt J., Mushobozi W., Day R.K., Knight J.D., Kimani M., Njuki J. and Musebe R. (2006). "A simple Bayesian network to interpret the accuracy of armyworm outbreak forecasts," Annals of Applied Biology 148: 141-6, 2006.

Houdkov´a K., & Kindlmann P. (2006). "Scaling up population dynamic processes in a ladybird-aphid system". Population Ecology, 48,323–332

Hugo L.F., Rooney L.W., and Taylor J.R.N. (2003). "Fermented sorghum as a function ingredient in composite breads". Cereal Chemistry (2003) in press.

Igbedioh SO. (1991). "Effects of agricultural pesticides on humans, animals and higher plants in developing countries". Arch Environ Health 46: 218.

IGI mbH., (2007). "DigiCAM-H/39 Product Specification". http://www.igi-systems.com / downloads/specifications/specifications_digicam_h39.pdf (Retrieved 17/05/2013)

Illingworth J.F., & Jarvis E., (1920). "Cane grub investigation". Queensland Agricultural Journal 13(1): 33–36

Imms' General Textbook of Entomology: Volume 1: Structure, Physiology and Development Volume 2: Classification and Biology. Berlin: Springer. 1977. ISBN 0-412-61390-5

Iñigo-Nuñez S., Herreros MA., Encinas T., Gonzalez-Bulnes A. (2010). "Estimated daily intake of pesticides and xenoestrogenic exposure by fruit consumption in the female population from a Mediterranean country (Spain)". Food Control. 2010;21:471–477.

Iannotti Maria (2012), Guide Picture source, insect of diseases of plants, http://gardening.about.com/ od/ gardenproblems/ig/Insects-and-Diseases-of-Plants/ (last accessed October, 2012)

Instruction manual, Drone 6^{TM} GPS Hexcopter . www.helipal.com/images/helipal-ne-a002-comabt-twister-manual.pdf (Retrieved 01/12/13).

IPM Guidelines (2009). UMassAmherst: Integrated Pest Management, Agriculture and Landscape Program. 2009 . http://www.umass.edu/umext/ipm/publications/ guidelines/index.html (Retrieved 13/03/ 2012).

Iwuoha, Chinyere I. & Kalu, Florence A. (1995) Calcium oxalate and physico-chemical properties of cocoyam (Colocasia esculenta and Xanthosoma sagittifolium) tuber flours as affected by processing Food Chemistry 54 (1995) 61-66 1995 Elsevier Science Limited

Ivanova-Kasas O.M. (1970). “Polyembryony in insects”. In Developmental Systems: Insects (eds S.J. Counce and C.H. Waddington), Academic Press, London. pp. 243-271.

Jean, Williams-Woodward (2011). “Georgia Plant Disease Loss Estimates, UGA Cooperative Extension.” Annual Publication (AP) 102-4 http://www.caes.uga.edu

Jeyaratnam J. (1990). “Acute pesticide poisoning: a major global health problem”. World Health Stat Q 43 (3): 139–44. PMID 2238694

Jiang J.A., Tseng C.L., Lu F. M., Yang E. C., Wu Z.S., Chen C.P., Lin S.H., Lin K.C., Liao C. S. (2008). “A GSM based remote wireless automatic monitoring system for field information: a case study for ecological monitoring of oriental fruit fly, *Bactrocera dorsalis(Hendel)”.* Computer Electronics Agric. 62, 243-259

Johnson L., Herwitz S., Dunagan S., Lobitz B., Sullivan D., & Slye R., (2003). “Collection of Ultra High Spatial and Spectral Resolution Image Data over California Vineyards with a Small UAV”. Proceedings of the International Symposium on Remote Sensing of Environment

Jordan W.R., and Sullivan C.Y. (1982). “Reaction and resistance of grain sorghum to heat and drought”. In ‘Sorghum in the Eighties, Vol 1,’ (J.V. Mertin, ed), ICRISAT, Patancheru, India (1982), pp 131-142.

Karunakaran C.O., (1958). “The Kerala food poisoning”. J Indian Med Assoc 31:204.

Karungi J., Adipala E., Ogenga-Latigo M.W., Kyamanywa S., Oyobo N., Jackai L.E.N. (2000). “Pest management in cowpea. Integrating planting times, plant density and insecticides application for management of cowpea field insect pests in Eastern Ugnada”. Crop Protect., 19, 237-245.

Kent J.H., Chapman L.E., Schmeltz L.M., Regnery H.L., Cox N.J., Schonberger L.B., (1992). “Influenza surveillance—United States, 1991–92”. Morbidity and Mortality Weekly Report Surveillance Summaries 41 (SS-5), 35–43.

Kenya Agricultural Research Institute (1986). “Agricultural Research Department Record of Research”: Annual report 1977-1980. Nairobi, Kenya Agricultural Research Institute

Kfir R., Overholt W. A., Khan Z. R., and Polaszek A., “Biology and management of economically important lepidopteran cereal stem borers in Africa,” Annual Review of Entomology. 47: 701-731, 2002.

Khatri D., Wang Q., & He X.Z. (2008). “Developnment and reproduction of Diadegma semiclausum (Hymenotera: Ichneumonidae) on Diamondback moth (Plutellidae)”.

New Zealand Plant protection. 61； 322-327 and Reproduction of Diadegma semiclausum, thesis 2011, Massey University, Palmerston North, New Zealand

Kim, Heung Chul, Wilkerson Pecor, Lee Lee, O'guinn Klein. (March 2005). “New Recordes and Reference Collection of Mosquitoes on Jeju Island”, Republic of Korea Entomological Research. 1 35: 55–66. Retrieved 15 Feb. 2014.

Kimber C.T. (2000). “Origins of domesticated sorghum and its early diffusion into India and China”. In ‘Sorghum: Origin, History, Technology, and Production’, (C. Wayne Smith and R.A. Frederiksen, eds), John Wiley & Sons, New York (2000) pp 3-98.

Kindlmann P., & Dixon A.F.G. (1999). “Generation time ratios – determinants of prey abundance in insect predator – prey interactions”. Biological Control, 16, 133–138.

Klenk K., Snow J., Morgan K.,; Bowen R., Stephens M., Foster F., Gordy P., Beckett S., Komar N., Gubler D., Bunning M. (2004). “Alligators as West Nile Virus Amplifiers”. Emerging Infectious Diseases **10** (12): 2150–2155. doi:10.3201/eid1012.040264

Knutson A. (2005). “The Trichogramma Manual: A guide to the use of Trichogramma for Biological Control with Special Reference to Augmentative Releases for Control of bollworm and Budworm in Cotton”. (Texas Agricultural Extension Service). 1-42

Knutson, Allen. (1998). “The *Trichogramma* manual: a guide to the use of *Trichogramma* for biological control with species reference to augmentative releases for control of bollworm and budworm in cotton”. Publ. No. B–6071. Texas Agric. Ext. Serv., Texas A&M Univ.Res. and Ext. Center, Dallas, TX.

Kole RK., Banerjee H., and Bhattacharyya A. (2002). “Monitoring of pesticide residues in farm gate vegetable samples in west Bengal”. Pest Res J 14(1): 77–82.

Kole RK, Banerjee H., and Bhattacharyya A. (2001). “Monitoring of market fish samples for Endosulfan and Hexachlorocyclohexane residues in and around Calcutta.” Bull Envirron Contam Toxicol 67: 554–559

Kolpin DW., Thurman EM., Linhart SM. (2000). “Finding minimal herbicide concentrations in ground water? Try looking for their degradates”. Sci. Total Environ. 2000;248:115–122

Krafsur E. (1998). “Sterile Insect Technique for Suppressing and Eradicating insect Population: 55 Years and Counting” J. Agric. Entomol. 15(4): 303-317 <October 1998)

Krombein K. V. (1963). “ The Scoliidae of New Guinea, Bismarck Archipelago, and Solomon Islands”. Nova Guinea, Zoology,22:543-651.

Kumar B.V.K. Vijaya, Mahalanobis A., Juday R.D. (2005). “Correlation Pattern Recognition,” Cambridge University Press, Cambridge (2005):

Kumar B.V.K Vijaya. (1992). “Tutorial Survey of composite filter designs for optical correlators”, Applied Optics, Vol. 31, No. 23, (1992): 4773-4801

Kumar B. V. K. Vijaya and Hassebrook L. (1990). “A Performance measure for correlation filters,” Appl. Opt. 29, No. 20, (1990): 2997-3006.

Kumar B. V. K. Vijaya, Bahri Z., and Mahalanobis A., (1988). “Constraint phase optimization in minimum variance synthetic discriminant functions,” Appl. Opt. 27, (1988):409-413

Kumar B.V.K. Vijaya. (1986). "Minimum-variance synthetic discriminant functions". Journal of the Optical Society of America. A, Optics and image science, 3(10):1579–1584, 1986.

Kypraios Ioannis, Young Rupert, Philip Birch, Chris Chatwin, (2004). "Object recognition within cluttered scenes employing a hybrid optical neural network filter", Optical Engineering, Journal, 43(8) pp. 1839-1850

Kypraios I., Young R., & Chatwin C. R., (2003). "An investigation of the non-linear properties of correlation filter synthesis and neural network design," Asian Journal of physics, Vol. 11, No. 3, (2003) .

Lehrer Steven (2010). "Anopheles mosquito transmission of brain tumor" . Medical Hypotheses 74 (1): 167–168. doi:10.1016/j.mehy.2009.07.005

Lemckert F. (2000). "An observation of predation on an adult toadlet *(*Uperoleia laevigata*)* by a dragonfly nymph"*,* Herpetofauna (Sydney) 30(1): 50.

Liebold A.M., MacDonald W.L., Bergdahl D., Mastro V.C. (1995). "Invasion by exotic forest pests: a threat to forest ecosystems". Forest Science 41 (2), 1–49.

Liu S., Wang X., Shi Z., Gebremeskel ZH., (2001). "The biology of Diadromus collaris (Hymenoptera: Ichneumonidae), a pupal parasitoid of Plutella xylostella (Lepidoptera: Plutellidae), and its interactions with Oomyzus sokolowskii (Hymenoptera: Eulophidae)". Bulletin of Entomological Research. 91(6):461-69. http://www.ncbi.nlm.nih.gov/pubmed/11818041 (Retrieved 15/07/13)

Lloyd D. C. (1940). "Host Selection by Hymenopterous Parasites of the Moth Plutella maculipennis Curtis". Proc. Roy. Soc. Lond., Ser. B, no. 853, vol. cxxviii, pp. 451–484

Lord Cynthia C. (2007). “Modeling and biological control of mosquitoes”. J Am Mosq Control Assoc. 2007 ; 23(2 Suppl): 252–264.

Lucchese L. & Mitra S. K. (2001). “Color image segmentation: A state of-the-art survey,” In Proc. of the Indian National Science Academy (INSA-A), vol. 67, (2001a): 207–221, pp 2 – 23

MacQueen J. (1967). “Some methods for classification and analysis of multivariate observations”. In Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability. Volume I, Statistics. Edited by Lucien M. Le Cam and Jerzy Neyman. University of California Press

Maguire JD., Sumawinata IW., Masbar S. (2002). “Chloroquine-resistant” Plasmodium malariae in south Sumatra, Indonesia. Lancet. 2002;360:58-60.

Mahalanobis A., Kumar BVK. Vijaya, Song S., Sims SRF., and Epperson JF. (1994). “Unconstrained correlation filters. Applied Optics”, 33(17):3751–3759, 1994

Mahalanobis Abhijit, Kumar B. V. K. Vijaya, and David Casasent. (1987). “Minimum average correlation energy filters”. Appl. Opt., 26(17):3633, 1987.

Mahmoud A.M.A., de Luna-Santillana E. J., and Rodríguez-Perez M. A. (2011). “Parasitism by the endoparasitoid, *Cotesia Flavipes (Cameron)* induces cellular immunosuppression and enhances susceptibility of the sugar cane borer, Diatraea saccharalis to Bacillus thuringiensis” Journal of Insect Science 11:119 available online: insectscience.org/11.119, 2011.

Mandrioli, Mauro (2012). “Where are aphids during the winter”? http://theaphidroom.

wordpress.com /2012/02/07/ where-are-aphids-during-the-winter/ (Retrieved 04/11/13)

Mangano P. (2006),"Armyworm in Cereal Crops," Entomology Branch, Department of Agriculture and Food, South Perth. Replaces Farmnote 110/84, 1804-08/06-ID6567 ISSN 0726-934X site www.agric.wa.gov.au

Marblehead Pesticides and Your Health. http://www.turi.org/community/PDF/PESTS.pdf (Retrieved 02/2012)

Marroquin, J. L. & Girosi, F. (1993). "Some extensions of the k-means algorithm for image segmentation and pattern classification," Tech. rep., Massachusetts Institute of Technology, Cambridge, MA, USA. (1993a): 31

Mattiacci, L., M. Dicke, and M. A. Posthumus.(1995). "b-Glucosidase: An elicitor of herbivore-induced plant odor that attracts host-searching parasitic wasps". Proc. Natl. Acad. Sci. USA 92:2036-2040

Maure, F., Brodeur, J., Ponlet, Doyon, Firlej, Elguero & Thomas.(2011). "The cost of a bodyguard". Biology Letters http://dx.doi.org/10.1098/rsbl.2011.0415

May, R.M., Hassell, M.P. (1988). "Population dynamics and biological control", Phil. Trans. R. Soc. Lond. B. 318, 129-169

McKenzie, FE (2000). "Why model malaria? Parasitology", Today. 16: 511–517

Mehlis, M., Bakker T. C. M., Engqvist L., and Frommen J. G.. (2010). “To eat or not to eat: egg-based assessment of paternity triggers fine-tuned decisions about filial cannibalism”. Proceedings of the Royal Society B-Biological Sciences 277:2627-2635

Meihls, Lisa N., Clark Thomas L., Bailey Wayne C., and Ellersieck, Mark R., (2004), “Population growth of soybean aphid, Aphis glycines, under varying levels of predator exclusion”. Journal of Insect Science: Vol. 10 | Article 144

Melrose WD (2002). "Lymphatic filariasis: New insights into an old disease". Int J Parasitol 32 (8): 947–60. doi:10.1016/S0020-7519(02)00062-0

Meunkaewjinda A., Kumsawat P., Attakitmongcol K. & Srikaew A. (2008). “Grape leaf disease detection from color imagery system using hybrid intelligent system”. Proceedings of ECTICON, IEEE, PP-513-516

Miller G.T. (2004), “Sustaining the Earth, 6th edition”. Thompson Learning, Inc. Pacific Grove, California. Chapter 9, Pages 211-216

Mills NJ, Daane KM (2005). “Biological and cultural controls, non-pesticide alternatives can suppress crop pests”. Cal Ag 59(1): 23-8

Mills N. J, Getz W.M. (1996). “Modelling the biological control of insect pests: a review of host-parasitoid models”. Ecological Modelling, 92, pp.121-143

Misra, R.M. (1996). “ Some observations on the life history and behaviour of Scolia (Discolia) affinis Guerin (Hymenoptera: Scoliidae) a parasite of Holotrichia consanguinea Blanch (Coleoptera: Scarabaeidae)”. Indian Forester 112: 1174.1178.

Mohammed Ei – Helly, Ahmed Rafea, Salwa Ei – Gamal and Reda Abd Ei Whab (2004). “Integrating Diagnostic Expert System With Image Processing Via Loosely Coupled Technique”. Central Laboratory for Agricultural Expert System(CLAES)

Mondor, Edward B., Awmac Caroline S,. and Lindroth, Richard L. (2010). “Individual growth rates do not predict aphid population densities under altered atmospheric conditions”. Agricultural and Forest Entomology (2010), 12, 293–299 DOI: 10.1111/j.1461-9563.2010.00478.x

Moran, N.A. (1992). “The evolution of aphid life cycles”. Annual Review of Entomology, 37, 321–348.

Morgan, D. (1884). Handbooks for the identification of British insects 6, part(5): Cuckoo-wasps (Chrysididae)

Murdoch W.W. (1990). “The relevance of pest-enemy models to biological control”. In M. Mackauer, L.E. Ehler and J. Roland (Editors), Critical Issues in Biological Control. Intercept, Andover, pp. 1-24.

Murray CJL and Lopez AD. (1996). “The global burden of disease: a comprehensive assessment of mortality and disability from diseases, injuries and risk factors in 1990 and projected to 2020” [Volume 1 of 10 in the Global Burden of Disease and Injury Series]. Cambridge, MA: Harvard School of Public Health

Muttenz FHNW., and Bento M. D. F., (2008). “Unmanned Aerial Vehicles: An Overview. Inside”. GNSS (January/February 2008), 54-61.

Nash D., Mostashari F., Fine A., (2001).The outbreak of West Nile virus infection in the New York City area in 1999. N. Engl. J. Med. **344** (24): 1807–14. doi:10.1056/NEJM200106143442401

National Board of Agriculture (NBA). (1988). "Action programme to reduce the risks to health and the environment in the use of pesticides in agriculture". General Crop Pro-duction Division, NBA, Stockholm, Sweden

National Food Reserve Agency (NFRA). (2008). Report of the 2007 Agricultural Production Survey (ASP) Federal Ministry of Agriculture and water Resources, Abuja-Nigeria

National Geographic http://animals.nationalgeographic.co.uk/animals/bugs/ladybug; http://insects.about.com/od/beetles/a/10-facts-ladybugs.htm (Retrieved 21/11/2013)

Neitzel, Frank (2011). "Mobile 3D Mapping with a Low-Cost UAV-System UAV-g Zurich, Switzerland 16 September 2011 Institute of Geodesy and Geo-information Science", Chair of Geodesy and Adjustment Theory

Nelissen H., Rymen B., Coppens F., Dhondt S., Fiorani F., and Beemster G.S. (2013) "Kinematic analysis of cell division in leaves of mono- and dicotyledonous species: A basis for understanding growth and developing refined molecular sampling strategies. In Plant Organogenesis (Methods in Molecular Biology Vol. 959, I. De Smet (ed.), New York, Humana Press, pp. 247-264, 2013.

New T.R. (1991). "Insects as predators". UNSW Press, Sydney.

Ngi-Song A. J., Overholt W. A., Njagi P. G. N., Dicke M., Ayertey J. N., and Lwande W. (1996). Volatile infochemicals used in host and host habitat location by Cotesia flavipes cameron and Cotesia sesamiae (Cameron) (Hymenoptera: Braconidae), larval parasitoids of stemborers on Graminae. J. Chem. Ecol. 22:307-323.

Niehuis O., Hartig G., Grath S., Pohl H., Lehmann J., Tafer H., Donath A., Krauss V., Eisenhardt C., Hertel J., Petersen M., Mayer C., Meusemann K., Peters RS., Stadler PF., Beutel RG., Bornberg-Bauer E., McKenna DD., Misof B. (2012). "Genomic and Morphological Evidence Converge to Resolve the Enigma of Strepsiptera". Curr Biol

Niels, G. Becker (1970). "Control of a Pest Population". Biometrics, Vol. 26, No. 3 (Sep., 1970), pp. 365-375 Published by: International Biometric Society Stable http://www.jstor.org/stable/ 2529093 .Accessed: 13/12/2013 04:23

Nisikado Y. and Nakayama T. (1943). "Notes on the Pathological anatomy of rice grains affected by Helminthosporium Oryzae". Ibid. 9. 208-213 Niyibigira E. I., (2003) "Genetic variability in *Cotesia Flavipes (Cameron)* and its importance in biological control of lepidopteran stem borers," PhD Thesis, Wageningen University, 162pp, 2003.

Noma T. & Brewer M.J. (2008), "Seasonal abundance of resident parasitoids and predatory flies, corresponding soybean aphid densities,with comments on classical biological control of soybean aphid in the Midwest". Journal of Economic Entomology, 101, 278–287

Obinna Onwujekwe, Kara Hanson and Julia Fox-Rushby, (2004) "Inequalities in purchase of mosquito nets and willingness to pay for insecticide-treated nets in Nigeria: Challenges for malaria control interventions". Malaria Journal 2004, 3:6 http://www.malariajournal.com /content/3/1/6

Obu J. A., and Faithpraise F.O. (2011). “A Kinematic Model for Calculating the Magnitude of Angular Momentum Transfer in an Accretion Disk: Time – Independent case”, Global Journal of Pure and Applied Science, Vol. 17, No. 3, 2011, ISSN 1118 – 0579

Oerke E.-C. (2006). “Centenary Review Crop Losses To Pests”. Journal Of Agricultural Science (2006), 144, 31–43. Doi:10.1017/S0021859605005708

Ogbaluand O.K. Umeozor O.C. (2003). “Recent trends in field crop pest management in Nigeria” –A review Agric. Rev., 24(1): 49-56

O'Hara, James E; Usupensky, Igor; Bostanian, N. J.; Capinera, John L.; Chapman, Reg; Barfield, Carl S.; Swisher, Marilyn E.; Barfield, Carl S.; Heppner, John; Fitzgerald, Terrence D.; Scheffrahn, Rudolf H.; Constantino, Reginaldo; Sanborn, Allen; Gayubo, Severiano F.; Arthurs, Steven; Tipping, Christopher; Lysyk, Tim; Coons, Lewis B.; Rothschild, Marjorie; Randolph, Sarah; Choate, Paul M.; Heppner, John B.; Jolivet, Pierre; Rogers, Michael E.; Potter, Daniel A.; Capinera, John L.; Webster, Thomas C.; Nation, James L.; Hoy, Marjorie A.; Agrios, George N. (2008). “Tachinid Flies (Diptera: Tachinidae),”. Encyclopedia of Entomology (Dordrecht: Springer Netherlands) (2nd edition): 3675–3686. doi:10.1007/978-1-4020-6359-6_2344. ISBN 978-1-4020-6242-1

Oliver C. Johnson, Weston Edens, Thomas T. Lu, Tien-Hsin Chao, (2009), “Optimization of OT-MACH filter generation for target recognition” Proc. SPIE 7340, Optical Pattern Recognition XX, 734008 (April 13, 2009); doi:10.1117/12.820950

Oliver Kerry M., Degnan Patrick H., Hunter Martha S., Moran Nancy A., (2009), “Bacteriophages Encode Factors Required for Protection in a Symbiotic Mutualism” Science Journal, Vol. 325 no. 5943 pp. 992-994 DOI: 10.1126/science.1174463.

Oluwagbemi O., Fornadel CM., Adebiyi EF., Norris DE., Rasgon JL. (2013). “ANOSPEX: A Stochastic, Spatially Explicit Model for Studying Anopheles Meta-population Dynamics”. PLoS ONE 8(7): e68040. doi:10.1371/journal.pone.0068040

Oluwole, Oluwafemi and Cheke Robert A. (2009*).* *“*Health and environmental impacts of pesticide use practices: a case study of farmers in Ekiti State, Nigeria”. International Journal of Agricultural Sustainability, 7 (3). pp. 153-163. ISSN 1473-5903 (Print), 1747-762X http://dx.doi.org/10.3763/ijas.2009.0431

Omolehin R. A., Adeola S. S., Ben Ahmed, Ebukiba E. O. and Adeniji O. B. (2011). “Economics of Insecticides Usage among Cowpea Farmers in Kaduna State, Nigeria”. American Journal of Experimental Agriculture, 1(4): 353-362, 2011

Orloci L. (1967). “An Agglomerative Method for Classification of Plant Communities,” The Journal of Ecology, Vol. 55, No. 1, (1967):193-206.

Osman KA., Al-Humaid AI., Al-Rehiayani SM., Al-Redhaiman KN. (2010). “Estimated daily intake of pesticide residues exposure by vegetables grown in greenhouses in al-qassim region; Saudi Arabia”. Food Control. 2010 doi: 10.1016/j.foodcont.2010.11.031.

Ostle Bernard, Turner Kenneth V., Hicks Jr. Charles R., & McElrath Gayle W. (1996). “Engineering Statiatics, the Industrial Experience”, Duxbury Press, United State of America, ISBN 0-534-26538-3: pg. 161-165.

Patil Jayamala K., Kumar Raj. (2011). “Advances in image processing for detection of plant diseases”. Journal of Advanced Bioinformatics Applications and Research ISSN 0976-2604 2(2):135-141

Pell M., Stenberg B., and Torstensson L. (1998). "Potential DE nitrification and nitrification tests for evaluation of pesticide effects in soil". Ambio 27: 24–28.

Photographs From Nature © Jay Cossey/ Blue Dasher dragonfly eggs laid on Water Lily. Insect Egg Gallery , 14/01/2007 . jay@images.on.ca. http://www.images.ca/ Cossey/ Eggs%20Gallery/pages/Dragonfly%20Blue%20Dasher%20eggs%20opt.htm (Retrieved 05/12/13)

Pickett Pickett C. H., Schoenig S. E., and Hoffmann M. P. (1996). " Establishemnt of the squash bug parasitoid, Trichopoda pennipes Fabr. (Diptera: Tachnidae), in northen California". Pan Pacific Entomologist 72: 220-226.

Pimentel D., Greiner A., (1997). "Environmental and socio-economic costs of pesticide use". In: Pimentel, D. (Ed.), Techniques for Reducing Pesticide Use: Economic and Environmental Benefits. John Wiley and Sons, Chichester, UK, pp. 51–78.

Pimentel D., (1993a). "Habitat factors in new pest invasions". In: Kim, K.C., McPheron, B.A. (Eds.), Evolution of Insect Pests—Patterns of Variation. John Wiley and Sons, New York, pp. 165–181

Pimentel David, Lori McLaughlin, Andrew Zepp, Benyamin Lakitan, Tamara Kraus, Peter Kleinman, Fabius Vancini, W. John Roach, Ellen Graap, William S. Keeton, Gabe Selig (1993b). "Economic Effects of Reducing pesticide use in Agriculture", Agriculture, Ecosystems and Environment, 46 (1993) 273-288 Elsevier Science Publishers B.V., Amsterdam

Pimentel D., McLaughlin L., Zepp A., La-kitan B., Kraus T., Kleinman P., Vancini F., Roach W. J., Graap E., Keeton W. S., and Selig G. (1991). “Environmental and economic impacts of reducing U .S. agricultural pesticide use”. Pages 679-718 in D. Pimentel, ed. Handbook of Pest Management in Agricul-ture. vol. 1. CRC Press, Boca Raton, FL**.**

Pingali, Prabhu L., Roger Pierre A. (1995). “Impact of pesticides on farmer health and the Rice environment: an overview of results from a multidisciplinary study in the Philippines. Natural Resource Management & Policy”. Ariel Dinar & David Zilberman, series Editors. International Rice Research Institute (IRRI), USA. ISBN 0-7923-9522-0(pbk).

Pokharkar S.R. and Thool V. R. (2012). “Early pest Identification in green house crops using image processing techniques”. IJCSN 1(3)

Polaszek A., Rugman-Jones P., Stouthamer R., Hernandez-Suarez E., Cabello T., Del Pino Pérez M. (2012) “Molecular and morphological diagnoses of five species of Trichogramma: biological control agents of Chrysodeixis chalcites (Lepidoptera: Noctuidae) and Tuta absoluta (Lepidoptera: Gelechiidae) in the Canary Islands”. BioControl 57, 21-35

Polis G. A., (1981). “The evolution and dynamics of intraspecific predation”. Annual Review of Ecology and Systematics 12, 225-251 (1981)

Posey Drew L., O’rourke Thomas, Roehrig John T., Lanciotti Robert S., Weinberg Michelle, and Maloney Susan. (2005). “Short Report: o’nyong-nyong fever in west Africa” Am. J. Trop. Med. Hyg., 73(1), 2005, p. 32

Potato Farmers Association of Nigeria Designed by Jewelry Tips. http://pofan.org/ (Retrieved 18/11/13)

Potting R. P. J., (1996).“Hunting for hiding hosts: the behavioral ecology of the stemborer parasitoid Cotesia Flavipes (Cameron),” - 111. Thesis Wageningen. - With ref. - With summary in Dutch. ISBN 90-5485-551-7, 1996.

Potting R. P. J., Vet L. E. M., and Dicke M. (1995). “Host microhabitat location by stem-borer parasitoid Cotesia flavipes”: The role of herbivore volatiles and locally and systemically induced plant volatiles. J. Chem. Ecol. 21:525-539

Public Health Pest Control: Applicator training manual. 2001. FL DACS, Bureau of Entomology. Jacksonville, Fl. http://www.celebrationcdd.org/services/mosquito-control/types-of-mosquitoes (Retrieved 15/12/13)

Pyramid of Energy *(www.original.britannica.com)*. (Retrived 10/04/2014)

Quicke D. L. J. and Belshaw R., (1999). “Incongruence between morphological data sets: an example from the evolution of endoparasitism among parasitic wasps (Hymenoptera: Braconidae)”. Syst. Biol. 48: 436-454

Radcliffe E.B., Ragsdale D.W. and Flanders K.L. (1993). “Management of aphids and leafhoppers”, Pp 117-136 In: Potato health management, R.C. Rowe (Ed); APS Press, New York

Rafikov M., Balthazar J.M. and von Bremen H.F. (2008). “Mathematical modeling and control of population systems”: application in biological pest control, Appl. Math. Comput. 200 pp. 557–573.

Rakesh Kaundal; Kapoor Amar S., and Raghava Gajendra P.S. (2006). “Machine learning techniques in disease forecasting: a case study on rice blast prediction”. BMC Bioinformatics **7**:485 doi:10.1186/1471-2105-7-485

Reed H. C., Tan S. H., Haapanen K., Killmon M., Reed D. K., and Elliott N. C., (1995). “Olfactory responses of the parasitoid Diaeretiella rapae (Hymenoptera: Aphidiidae) to odor of plants, aphids, and plant-aphid complexes”. J. Chem. Ecol. 21:407-418.

Reffstrup TK., Larsen JC., Meyer O. (2010). “Risk assessment of mixtures of pesticides. Current approaches and future strategies”. Regul. Toxicol. Pharmacol. 2010;56:174–192.

Refregier P., (1991) “Optimal trade-off filters for noise robustness, sharpness of the correlation peak, and Horner efficiency”. Optics Letters, 16:829–832, June 1991

Reg A. (2010). “Unmanned Aircraft Systems: UAVs Design, Development and Deployment”. A John Wiley and sons, Ltd., publication, 2010.

Reiter P., (2010-03-11). “Yellow fever and dengue: a threat to Europe”? . Euro Surveill **15** (10): 19509.

Rhainds Marc, Yoo Ho Jung S., Kindlmann Pavel, Voegtlin Dave, Castillo Diana, Rutledge Claire, Sadof Clifford, Yaninek Steve and O’Neil Robert J. (2010). “Two-year oscillation cycle in abundance of soybean aphid in Indiana.” Agricultural and Forest Entomology (2010), 12, 251–257. DOI: 10.1111/j.1461-9563.2010.00471.x

Rhainds M., Brodeur, J., Borcard, D. & Legendre, P. (2008). "Toward management guidelines for soybean aphid, Aphis glycines, in Qu´ebec. II. Spatial distribution of aphid populations in commercial soybean fields". Canadian Entomologist, 140, 219–234.

Richards O.W., (1980). "Scolioidea, Vespoidea and sphecoidea. Hemenoptera, Aculeata". Handbooks for the identification of British insects 6, 3(b): 1- 118.

Rob Yarham. (2013) "Nymphs and aliens emerge from the pond

Roy Masamdu, (2013). " Taro beetles life cycle Fact Sheet". edited by Dr. Grahame Jackson http://www.ediblearoids.org/portals/0/taropest/lucidkey/taropest/media/Html/Arthropods/TaroBeetles/TaroBeetles.htm " http://www.theguardian.com/environment/2013/aug/29/pulborough-brooks-west-sussex-nymphs(Retrived 05/12/13)

Ruizhen Han, Yong He, Fei Liu. (2012). "Feasibility Study on a Portable Field Pest Classification system design based on DSP and 3G wireless communication technology." Sensor 12, 3118-3130

Rutledge C.E., & O'Neil R.J. (2006). "Soybean plant stage and population growth of soybean aphid". Journal of Economic Entomology, 99, 60–66.

Sada N. Lal. Taro Beetle Management In Papua New Guinea And Fiji Final Project Report Aacr2 Isbn: 978-982-00-0304-0 Web: Http://Www.Spc.Int

Salleh, Anna (2000). "Spider drugged by parasitic wasp" http:// www.abc.net.au /science/news/stories/s154197.htm (Retrieved Nov 10, 2012).

Samanta R. K., and Indrajit Ghosh. (2012). "Tea Insect Pests Classification Based on artificial Neural Networks". IJCES 2(6)

Samit, Bhattacharyya and Suma Ghosh (2013). "A Mathematical Study Oscillation in Pest Population and Its Management". International Journal of Mathematics and Mathematical Sciences Volume 2013, Article ID 653080, 12 pages. Hindawi Publishing Corporation http://dx.doi.org/10.1155/2013/653080

Sandler, Hilary A. (2010). "Integrated Pest Management". Cranberry Station Best Management Practices **1** (1): 12-15.

Santos A. and Flores M. (1995). "Effects of glyphosate on nitrogen fixation of free-living heterotrophic bacteria". Lett. Appl. Microbiol. 20: 349–352.

Sardar D., and Kole RK. (2005). "Metabolism of Chlorpyriphos in relation to its effect on the availability of some plant nutrients in soil". Chemosphere 61: 1273–1280

Sasaki Y., Okamoto, T. Imou, K. & Torii,T. (1998). "Automatic diagnosis of plant disease-Spectral reflectance of healthy and diseased leaves", In Proc. of 3rd IFAC/CIGR Workshop on Artificial Intelligence in Agriculture. Makuhari, Chiba, (1998):158-163.

Sauer Frank, Schoernig Niklas (2012). "Killer drones: The 'silver bullet' of democratic warfare?", in: Security Dialogue 43 (4): 363–380, http://sdi.sagepub.com, (Retrieved 25 Sept. 2012.)

Savonen C. (1997). "Soil microorganisms object of new OSU service. Good Fruit Grower". http: //www.goodfruit.com/archive/ 1995/6other.html

Schiøler KL., Samuel M., Wai KL., (2007). "Vaccines for preventing Japanese encephalitis". Cochrane Database Syst Rev (3): CD004263. doi:10.1002/14651858.CD004263.

Schreiber, Rob (2007), "MATLAB" Scholarpedia, 2(7):2929.

Seago Ainsley E., Giorgi Jose Adriano, Jiahui Li, Ślipiński Adam, (2011). "Phylogeny, classification and evolution of ladybird beetles (Coleoptera: Coccinellidae) based on simultaneous analysis of molecular and morphological data", Molecular Phylogenetics and Evolution, Volume 60, Issue 1, July 2011, Pages 137-151, ISSN 1055-7903,http://dx.doi.org/10.1016/j.ympev.2011.03.015. http://www.sciencedirect.com/science/ article/ pii/S105579031100154

Shaw M.R., & Huddleston T., (1991) "Classification and biology of Braconid wasps" Handbooks for the identification of British insects (part 11)

Shelton A.M. and Andaloro J. T. (1982). "Effect of lepidopterous larval populations on processed cabbage grades". J. Econ. Entomol. 75: 141-143

Silva De PM, & Marshall JM. (2012). "Factors contributing to urban malaria transmission in sub-saharan Africa: a systematic review". J Trop Med. 2012;2012:819563. doi: 10.1155/2012/819563.

Singh R. K., Dhiman R. C. & Singh S. P. (2003). "Laboratory studies on the predatory potential of dragon-fly nymphs on mosquito larvae". Journal of Communicable Diseases **35** (2): 96–101

SkeeterBite (2007) The Life Cycle of Mosquitoes. http://www.skeeterbite.info/ article_3.html (Retrieved 21/02/14)

Smallshire, Dave & Swash Andy Dragonfly site: "What Do Dragonflies Eat?" http://www.dragonfly-site.com. (Retrieved 10/03/14)

Smith SM. (1996). "Biological control with Trichogramma: advances, successes, and `potential of their use". In 'Annual Review of Entomology' pp. 375-406

Snyder, William E. and Ives Anthony R. (2003). " Interactions Between Specialist And Generalist Natural Enemies": Parasitoids, Predators, And Pea Aphid Biocontrol. Ecology, 84(1), 2003, pp. 91–107q (2003) by the Ecological Society of America

Solis-Sanchez L.O., Castaneda-Miranda R., Castaneda-Miranda C.L., Alaniz-Lumbreras J.J., Torres-Pacheco I., Guevara-Gonzalez R.G., Alaniz-Lumbreras P.D. (2001). "Scale invariant feature approach for insect monitoring". Comput. Electron. Agric. 75,92-99

Souza De., Renato P., Foster Peter G., Sallum Maria Anice M., Coimbra Terezinha L.M., Maeda Adriana Y., Silveira Vivian R., Moreno Eduardo S., Silva Fernanda G. da, Rocco Iray M., Ferreira Ivani B., Suzuki Akemi, Oshiro Fabíola M., Petrella Selma M.C.N., Pereira Luiz E., Katz Giselda, Tengan Cilea H., Siciliano Melissa M., Santos Cecília L.S. dos (2010). "Detection of a new yellow fever virus lineage within the South American genotype I in Brazil". J Med Virol **82** (1): 175–185. doi:10.1002/jmv.21606.

Srinivasa, Murthy K. and Rajeshwari R., (2011). "Host Searching Efficiency of Cotesia Flavipes (Cameron) Cameron (Hymenoptera: Braconidae) an Important Parasitoid of the Maize Stem Borer Chilo Partellus Swinhoe," Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231-6345 . http://www.cibtech.org/jls.htm Vol. 1 (3) July-September, pp. 71-74, 2011.

Stankova Abate K., & Sabells A. M. (2013). "Irreversible prey diapause as an optimal strategy of a physiologically extended Lokta-Volterra model", J. Math. Biol. 66:767–794, DOI 10.1007/s00285-012-0599-5

Steffan W. A., Evenhuis N. L. (1981). "Biology of Toxorhynchites". Annual Review of Entomology **26**: 159. doi:10.1146/annurev.en.26.010181.001111

Sterling W. L., Dean D. A., Fillman D. A., and Jones D. (1984). "Naturally-occurring biological control of the boll weevil (Col.: Curculionidae)". Entomophaga 29: 1-9.

Stimac J. L., and O'Neil R. J. (1985). "Integrating influences of natural enemies into models of crop pest systems, in M. A. Hoy and D. C. Herzog (eds.)", Biological Control in Agricultural IPM Systems. Academic Press, Inc., Orlando, FL. pp. 48-56.

Stireman John O., O'Hara, James E., Monty Wood D. (2006). "Tachinidae: Evolution, Behavior and Ecology," . Annual Review of Entomology (Annual Reviews) 51: 525–555. doi:10.1146/annurev.ento.51.110104.151133

Straathoff H. (1986). "Investigations on the phytotoxic relevance of volatilization of herbicides". Mededelingen van de Faculteit Landbouwweten-schappen, Rijksuniversiteit Gent 51(2A): 433–8.

Sudharsanan S. I., Mahalanobis A. and Sundareshan M. K. (1990). "Selection of optimum output correlation values in synthetic discriminant function design," J. Opt. Soc. Am. A 7, (1990): 611-616

Sykes, Edward Mathison. Life-history evolution in the parasitoid wasp Nasonia vitripennis. Degree thesis sumitted to the University of Edinburgh 2007, pp 187

Sykes, E. M. and S. A. West (2005). "Evolution: Revenge of the clones!" Current Biology 15(14): R547-R549.

Tamworth, Fiona Scott. (2011). **“**Agricultural Production Systems Simulator (APSIM)” http://www.dpi.nsw.gov.au/archive/agriculture-today-stories/ag-today-archives/june-2011/adapting-sorghum-to-climate-in-the-north-west

Tan S., R.C.D. Young, C.R. Chatwin (2002). “Markovian and Auto-regressive Clutter Noise Models for a Pattern Recognition Wiener Filter”. Applied Optics 41(32): 6858-6866

Tanwar R., and Varma A., (2002) “Field trials with *Cotesia Flavipes (Cameron) Cameron* against Sugar Cane Borers in sub-Tropical India,” Short Communication Vol 4(3&4) 153-156, 2002.

The Life-Cycle Of A Dragonfly. http://www.british-dragonflies.org.uk/ content/ biology-ecology; http://www.dragonfly-site.com/dragonfly-facts.html; Lifespan of Dragonflies - http://www.desertusa.com/ mag98/nov/papr/drangon.. (Retrived 25/09/13)

Tijani A. A. (2006). “Pesticide Use Practices and Safety Issues: The Case of Cocoa Farmers in Ondo State”, Nigeria J. Hum. Ecol., 19(3) 183-190 (2006)

Toma T., & Miyagi I. (1992). “Laboratory evaluation of Toxorhynchites splendens (Diptera: Culicidae) for predation of Aedes albopictus mosquito larvae”. Medical and Veterinary Entomology 08/1992; 6(3):281-91

Tonnang H.E.Z., Nedorezov L.V., Owino J.O., Ochanda H., Lo B. (2010). “ Host–parasitoid population density prediction using artificial neural networks: diamondback moth and its natural enemies”, Agricultural and Forest Entomology. 12, 233-242.

Tóth V.R., Mészáros I., Palmer S.J., Veres Sz., Précsényi I., "Nitrogen Deprivation Induces Changes in the Leaf Elongation Zone of Maize Seedlings," Biologia Plantarum 2002, Volume 45, Issue 2, pp 241-247

Tzionas Panagiotis, Papadakis Stelios E. and Dimitris Manolakis (2005). "Plant leaves classification based on morphological features and fuzzy surface selection technique". 5th International Conference on Technology and Automation ICTA'05, Thessaloniki, Greece, 365-370, pp15-16.

Udoh Augustine J. and Umoh Comfort E. (2011). "Utilization Pattern of Pesticides by Nigerian Farm Households", Indian Res. J. Ext. Edu. 11 (2), May, 2011

Underwood. D.L. A. "Insect as predators and parasitoids". Biology 316, General Entomology

United States Environmental Protection Agency (2012). "Integrated Pest Management (IMP) Principles". http://www.epa.gov. (Retrieved 11/01/2013)

United States Geological Survey. (1999). "The quality of our nation's waters – nutrients and pesticides". Circular 1225. Reston VA: USGS. http: //water.usgs.gov/pubs/circ/ circ1225/. In U.S. Geological Survey. (1998). National Water-Quality Assessment. Pesticide National Synthesis Project. Pesticides in surface and ground water of the United States; Summary of results of the National Water Quality Assessment Program. http: //water.wr.usgs.gov

United States Protection Agency (2011). "Pesticides and Food: What Integrated Pest Management Means". http://www.epa.gov (Retrieved 11/01/2013) van de Beek D., de Gans J., Tunkel AR., Wijdicks EF. (2006). "Community-acquired bacterial meningitis in adults". The New England Journal of Medicine **354** (1): 44–53. doi:10.1056/NEJMra052116

Vanderlip R.L. (1972). "How a Sorghum Plant Develops". Kansas State Univ. Coop. Ext. Serv. Pub. C447

Varga Z. (2008). "Applications of mathematical systems theory in population biology, Period". Math. Hungar. 56 (1) pp. 157–168

Vikram Goel, (Oct 08, 2010). "Components-of-UAV" http://www.scribd.com /doc/38943946 /Components-of-UAV (Retrieved 12/13)

Villarini G., Vecchi G.A., and Smith J.A. (2010). "Modeling of the dependence of tropical storm counts in the North Atlantic Basin on climate indices". Monthly Weather Review 138 (7): 2681–2705. doi:10.1175/2010MWR3315

Volker H., & Rudolf W. (2008). "Impact of Cannibalism on Predator–Prey Dynamics Size-Structured Interactions and Apparent Mutualism". Ecology, 89(6), 2008, pp. 1650–1660 _ 2008 by the Ecological Society of America

Wageningen University and Research Centre (2011, May 25). "Smallest insect filmed in flight". *ScienceDaily*. Retrieved December 24, 2013, http://www.sciencedaily.com

Wang X-G., and Liu S-S. (2002). "Effects of host age on the performance of Diadromus collaris, a pupal parasitoid of Plutella xylostella". BioControl. 47. 293-307.

Wasim, Aktar Md., Sengupta Dwaipayan, and Chowdhury Ashim (2009). "Impact of pesticides use in agriculture: their benefits and hazards". Interdisciplinary

Toxicology. 2009 March; 2(1)1 Interdiscip Toxicol. 2009 March; 2(1): 1–12. doi: 10.2478/v10102-009-0001-7

Wattiez, Catherine and Williamson Stephanie, PAN Europe. (2003) “Pesticide use reduction is working Report: An assessment of national reduction strategies in Denmark, Sweden, the Netherlands and Norway”. December 2003 http://www.epha.org (Retrieved 17/07/2013)

Wayne, Bailey “Don't Neglect Scouting of Pastures, Corn, and Wheat Fields” http://bulletin.ipm.illinois.edu/print.php?id=293 (Retrieved 25/03/2014)

Wej, Choochote; Atchariya Jitpakdi, Teerayut Suntaravitun, Anuluck Junkum, Kanisa Rongsriyam, Udom Chaithong, (2003). “A Note on Laboratory Colonization of Toxorhynchites splendens by Using an Artificial Mating Technique and Autogenous Aedes togoi Larva as Prey”. The Journal of Tropical Medicine And Parasitology J.Trop Med Parasitol 2002;25:47-50. Vol 26 (No. 1) June 2003

White, Gray C., and Bennetts Robert E., (1996). “Analysis of frequency count data using negative binomial distribution,” Ecology, 77(8), 1996. Pp.2549-2557

White NJ. Malaria. In Cook, G. C. & Zumla, A. (eds.), (2009). “Manson's Tropical Diseases”. p. 1202. Elsevier Science 2009.

Whitehorn J., & Farrar J. (2010). "Dengue". Br. Med. Bull. **95**: 161–73. Doi:10.1093/bmb/ldq019

WHO. The world health report. (2001). “Mental health: new understanding, new hope”. Geneva: World Health Organization, 2001

WHO. “Public Health Impact of Pesticides Used in Agriculture”. (1990). World Health Organization, Geneva: 88.

Wilcox B.A., & Ellis, B. (2006). “Forests and emerging infectious diseases of humans”. Unasylva **57**. ISSN 0041-6436

Wilensky U., & Rand W. (2007). “Making models match: Replicating an agent-based model”. Journal of Artificial Societies and Social Simulation 10: 1–22.

William, James; Berger, Timothy; Elston, Dirk; (2005). “Andrews' Diseases of the Skin: Clinical Dermatology (10th ed.)”. Saunders. p. 150. ISBN 0-7216-2921-0.

Wilson J. R., (1991). “Suddenly Everyone Wants a UAV” Interavia Aerospace Review, December 1991, p43

Wissem Mnif, Aziza Ibn Hadj Hassine, Aicha Bouaziz, Aghleb Bartegi, Olivier Thomas, Benoit Roig, (2011). “Effect of Endocrine Disruptor Pesticides: A Review Int J Environ Res Public Health”. 2011; 8(6): 2265–2303. doi: 10.3390/ijerph8062265

Wood D. M. (1987). Chapter 110. “Tachinidae”. Pp. 1193-1269 in McAlpine, J.F., Peterson, B.V., Shewell, G.E., Teskey, H.J., Vockeroth, J.R. and D.M. Wood (eds.), Manual of Nearctic Diptera. Volume 2. Agriculture Canada Monograph 28: i-vi, 675-1332 deposit a hatching larva onto the host

Wood J. (1996). “Invariant pattern recognition: A review”, Pattern Recognition, Vol.29, No1, (1996): 1-17

Woodford B. J., Kasabov N. K., and Wearing C. Howard (1999). "Fruit Image Analysis using Wavelets". Proceedings of the ICONIP/ANZIIS/ANNES'99 international workshop, University of Otago Press, pp. 88-91.

Wright Mark G., (2005), Pest Group Menu. The Crop Knowledge Master http://www.extento.hawaii.edu/kbase/crop/Type/Croppest.htm. markwrig@hawaii.edu (Retrieved 14/12/13)

Yang L., Browning JD., and Awika JM. "Sorghum 3- deoxyanthocyanins possess strong phase 11 enzyme inducer activity and cancer cell growth inhibition properties". J. Agric Food Chem. 2009 Mar 11; 57(5): 1797-804. Doi: 10.1021/jf8035066

Yeates David K., Logan David P., and Lambkin Christine. (1999). "Immature stages of the bee fly Ligyra satyrus (F.) (Diptera: Bombyliidae): A hyperparasitoid of canegrubs (Coleoptera: Scarabaeidae)", Australian Journal of Entomology (1999) 38, 300–304

Youdeowei A., (1979). "Report - Rothamsted Experimental Station". Nigerian Journal of Entomology, 3:2 -8.

Young Ed. (2009). "Wasps use genes stolen from ancient viruses to make biological weapons".http://blogs.discovermagazine.com.wasps-use-genes-stolen-from-ancient-viruses-to-make-biological-weapons.(Retrieve 12/12/2012)

Young R.C.D. and Chatwin C. R. (1992). "Design and Simulation of a synthetic discriminate function filter for implementation in an up-dateable photorefractive correlator", SPIE Optical Pattern Recognition 111, Vol.1701, 239 – 263 (1992)

Yu D.S., van Achterberg K., Horstmann K. (2011). “World Ichneumonoidea” 2011. Taxonomy, biology, morphology and distribution. Available from Vancouver, Canada: Taxapad. www.taxapad.com

Yuceer C., and Oflazer K., (1993). “A rotation, scaling, translation, invariant pattern classification system”, Pattern Recognition, Vol. 26, No. 5, (1993): 687-710

Zadoks J. C., Chang T. T., and Konzak C. F., (2006). “A decimal code for the growth stages of cereals”, Weed Research Volume 14, Issue 6 pages 415–421, December 1974 Article first published online: 28 JUL 2006. DOI: 10.1111/j.1365-3180.1974.tb01084.x

Zhou H., and Chao T. H. (1999). “MACH filter synthesizing for detecting targets in cluttered environment for grey-scale optical correlator”. SPIE Vol. 715 : 394 – 398

Zulhaidi Mohd Shafri H., and Nasrulhapiza Hamdan (2009). “Hyperspectral Imagery for Mapping Disease Infection in Oil Palm Plantation Using Vegetation Indices and Red Edge Techniques”. American Journal of Applied Sciences 6(6):1031- 1035

TO GOD BE THE GLORY

THANK YOU JESUS