Composition and phenology of insect pests of *Capsicum* (Solanaceae) cultivated in the Makana District, Eastern Cape Province, South Africa.

A thesis submitted in fulfilment of

the requirements for the degree of

MASTER OF SCIENCE

of

RHODES UNIVERSITY

by

Colleen Hepburn

December 2007

Abstract

Capsicum baccatum var. *pendulum* was first grown in the Makana District in 2005. Extremely little was known about best practices for cultivation or the insects and diseases associated with the crop in this area. The study was conducted during the second year of production, November 2005 and November 2006, in an attempt to identify the composition and phenology of insects occurring on *C. baccatum*.

In the more rural parts of the Eastern Cape, and more particularly in Grahamstown, there are very few industries. With the advent of this new agricultural venture, a processing factory has been opened in Grahamstown creating more than 600 seasonal jobs in the factory and 1000 seasonal jobs on farms for local people. This business enterprise has not only brought about the creation of jobs, but also training and skills development and empowerment, generating much-needed income in this area.

An extensive literature review yielded limited information on insect pests associated with *Capsicum*. Data from a pilot sampling trial undertaken were statistically analyzed to establish the number of plants to be scouted per site and the most effective scouting techniques to use. Based on the data available and insects collected during the pilot sampling trial, a surveillance programme was designed. Five different types of monitoring traps were placed in each of the eight study sites. Collection of trap catches and scouting of fifteen individual plants per site was undertaken on a weekly basis over the 52-week study period.

The most commonly occurring potential insect pests were African Bollworm *Helicoverpa armigera* (Hübner), False Codling Moth *Thaumatotibia leucotreta* (= *Cryptophlebia leucotreta*) (Meyrick), Mediterranean Fruit Fly *Ceratitis capitata* (Wiedemann) and several species of thrips. Population densities of these pests and their phenology on *Capsicum* were determined. Statistical analyses established the efficacy of the monitoring traps for each pest, tested for differences among and between study sites, calculated an estimate of the number of pods damaged and a measure of plant damage.

The results show that the majority of damage caused to the *Capsicum baccatum* cropping system was due to Mediterranean Fruit Fly populations. It was established that, although African Bollworm and False Codling Moth were present during the study period, their numbers were negligible and only nominal damage was caused by these pests. Damage caused by thrips species was apparent but not quantifiable.

Intervention strategies using an Integrated Pest Management approach, are discussed.

This thesis is dedicated to the memory of my parents,

Denis and Shirley Ardren,

who taught me so much,

… and I'm still learning.

Declaration

The following thesis has not been submitted to any university other than Rhodes University, Grahamstown, South Africa. The work presented here is that of the author.

_____ Date: _____

Acknowledgements

There are many people I wish to thank for their support, encouragement and advice throughout, not only for thesis, but my emergence in the entomological arena.

My sincere thanks go to my supervisors, Martin Hill and Martin Villet, for their continual advice, encouragement, guidance and support and for providing an intellectually stimulating environment of searching questions.

My deepest gratitude goes to Sarah Radloff (Department of Statistics, Rhodes University), for her constant support and encouragement in all my endeavours, and for her patience and invaluable statistical advice. Sarah is a true role model to women in science.

To my husband Randall, for introducing me to the fascinating world of entomology, his belief in me, patience, support and encouragement throughout. My world has totally changed since he came into it. I can only say “thank you”.

To the growers in the Belmont Valley and Bloukrantz areas: Roger Clayton, David Duncan, Charles Laverne and Ian Robertson, thank you for providing me full access to your lands and the opportunity of working with you. I would especially like to thank David Duncan for his enthusiasm, encouragement and support over the past couple of years as well as the ‘call out’ tractor service when the roads were impassable.

My sincere thanks to the numerous entomologists who helped with the identification of my collections: Ashley Kirk-Spriggs, Fred Gess and Sarah Gess (Albany Museum, Grahamstown) for the identification of the Diptera and Hymenoptera respectively; the Director, Gerhard Prinsloo, and specialist entomologists of the National Insect Collection, Beth Grobbelaar, Riaan Stals, Connal Eardley, Michael Stiller and Ian Millar (Agricultural Researach Council, Pretoria); and Martin Krüger (Transvaal Museum, Pretoria) for identification of the Lepidoptera.

I am grateful to Paul Bosland (New Mexico State University), for his invaluable advice on *Capsicum* and, together with Lynn Bohs (University of Utah) and Mats Pettersson (Sweden), for identifying the *Capsicum* species. My thanks also to Gerhard Booysen (Insect Science (Pty) Ltd) for guidance and advice on trapping methods; Sean Moore (Citrus Research International and River Bioscience) for his advice and continual encouragement, Loddie Greyling (Chicory SA Ltd), for the identification and classification of soil types and the South African Weather Bureau, Port Elizabeth, for providing climatic data.

A special thank you to Milton Ngeju, the stalwart of the Department, whose ongoing help and encouragement over the past many years is sincerely appreciated. I am also extremely grateful to Terry Butterworth for his technical assistance.

I thank my friends and fellow students, Jessica Cockburn and Kendall Crous, for their continual help, support, enthusiasm and encouragement. We have learnt a lot and grown individually, with a lot of fun and laughter along the way. I thank both my ‘girls’.

I would also like to thank my friends, Christian W.W. Pirk and Thomas Mürrle, who, over the many years I have know them, have always been there to encourage and support me with their friendship and knowledge.

To my sons, Keenan and Neil, thank you my boys for your love, encouragement, support and patiently putting up with me. To my family and extended family, Stuart and Sanet, Charles and Cynthia, Kirsten and David, David, Ashton and Rowan, thank you for your encouragement always.

Funding from the Rhodes University Joint Research Committee, National Research Foundation and Carara Agro Processing Services is gratefully acknowledged. Any opinion, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Research Foundation.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

BR	Brenthoek Ratooned Land	ABW	African Bollworm
BS	Brenthoek Seedling Land	FCM	False Codling Moth
IR	Imjabulo Ratooned Land	MFF	Mediterranean Fruit Fly
IS	Imjabulo Seedling Land	FCM Trap	FCM Yellow Delta Trap
LMS	Lower Melrose Seedling Land	MFF Trap	MFF Yellow Delta Trap
VR	Varnam Ratooned Land	Sensus Trap	Sensus Trap
VS1	Varnam Seedling 1 Land	Yellow Card	Yellow Card Trap
VS2	Varnam Seedling 2 Land	YBF Trap	Yellow Bucket Funnel Trap

I

INTRODUCTION

1.1 The Genus *Capsicum*

Some of the 2300 different plant species belonging to the family Solanaceae are of major agricultural and horticultural importance (Hunziker 2001). These include potato, *Solanum tuberosum* (Linnaeus 1753), aubergine, *Solanum melongena* (Linnaeus 1753), tobacco, *Nicotiana tabacum* (Linnaeus 1753) and tomato, *Lycopersicon esculentum* (Linnaeus 1753) (D'Arcy 1986). The genus *Solanum* is large and varied, accounting for almost 75% of the species in the Solanaceae (Snyman 1981). *Capsicum* (Linnaeus 1753) is another economically important genus within the Solanaceae, which includes five domesticated species (DeWitt & Bosland 1996):

Capsicum annuum (Linnaeus) meaning annual (which is inaccurate as *Capsicum* species are perennial plants). *Capsicum annuum* includes common varieties such as bell, jalapeño, New Mexican and wax peppers.

Capsicum baccatum (Linnaeus) meaning berrylike. Comprising the South American peppers known as ajis.

Capsicum chinense (Jacquin) meaning from China (this is misleading as the species originated in the Amazon Basin). *Capsicum chinense* includes the extremely hot varieties of habaneros.

Capsicum frutescens (Linnaeus) meaning shrubby. This species includes the well-known tabascos.

Capsicum pubescens (Ruiz & Pavon) meaning hairy. Includes *rocotos* from South America.

1.1.1 Classification

With cultivation, early collectors and taxonomists selected for size, shape and colour from at least three different species, resulting in what they thought to be distinct taxa. The accompanying plethora of nomenclature has only recently been revised. There is, however, disagreement amongst taxonomists as to how many wild, and more particularly, cultivated species there are in the genus (Eshbaugh 1993, Andrews 1995, Bosland 1996).

Capsicum annuum and *C. chinense* are widely utilized globally. The complex taxonomic problems begin with the placement of *Capsicum* within the Solanaceae; whether *Capsicum* is monophyletic (includes all of the descendants of the putative ancestral species), or polyphyletic (encompasses more than a single lineage); if it should be confined to the pungent taxa, or whether the genus is reconstructed to include non-pungent taxa based on morphological and anatomical traits (Eshbaugh 1993). Molecular techniques, genetic and phenetic analyses are being used to resolve these taxonomic problems. A phenetic analysis of *C. annuum*, *C. chinense* and *C. frutescens* published by Pickersgill *et al.* (1979, cited in Eshbaugh 1993) detailed the complexities encountered in trying to separate these taxa as they form a morphometric continuum. DeWitt and Bosland (1996) confirmed that three of the cultivated species, *C. annuum*, *C. chinense* and *C. frutescens* are closely related and share a common ancestor. Jarret and Phat Dang (2004) conducted experiments in which cultivated and wild species were cloned and sequenced, which showed that *C. pubescens* was distinct from the other cultivated species.

Different types of capsicums are classified according to fruit characteristics (i.e. colour, flavour, pungency, size, shape and use). Horticultural varieties are distinguishable by their pod types, of which there are several hundred (Fig. 1.1). When Spanish explorers arrived in Mexico, the Aztecs had developed many different pod types. These capsicums were the precursors to the large variety of pod types that presently occur in Mexico. Development of pod types is ongoing to meet the needs in industry, fill niche markets and improve quality and yield. The uses of various cultivars within the five cultivated species (*Capsicum annuum*, *C. baccatum*, *C. chinense*, *C. frutescens* and *C. pubescens*) have recently shown exponential growth.

Figure 1.1 *Capsicum* species pod types (Photo Credit: NMSU 2005).

1.1.2 Origin and distribution

The Central American Isthmus is a natural corridor between northern and southern America along which a number of solanaceous species have migrated between the two continents (D'Arcy 1986). Assigning the origin of a species is sometimes problematic and it is therefore difficult to determine migratory patterns.

The precise region where the five cultivated species originated is still under debate, but consensus has been reached that it is in Central and South America. McLeod *et al*. (1982, cited by Eshbaugh 1993), Eshbaugh (1983, cited in Eshbaugh 1993) and Andrews (1995) hypothesized that their centre of origin is Bolivia. According to some botanists, the genus originated in an area now bordered by the southern Brazilian mountains to the east, Bolivia in the west, Paraguay and northern Argentina to the south. The largest concentration of wild species of *Capsicum* is found in this area and all major domesticated species within the genus are grown here. Other botanists suggest the origin of *Capsicum* to be further east, in central Bolivia along the Rio Grande (DeWitt & Bosland 1996).

The most commonly cultivated and economically important species worldwide is *C. annuum*, which probably originated in northern South America, Central America and Mexico. Karyotype analysis suggested that the origin of domesticated *C. annuum* is southern Mexico (Pickersgill 1971, cited in Eshbaugh 1993). According to DeWitt (2005), *Capsicum baccatum* probably originated in northern Argentina, Bolivia or Peru and was first domesticated in Peru around 2500 B.C., which is consistent with archaeological evidence. It is presently cultivated in Argentina, Colombia, Ecuador, Peru, Brazil and Bolivia, and has been introduced to Costa Rica, India and the United States of America. *Capsicum chinense* (including *C. frutescens*) probably originated in the Amazon basin (Eshbaugh 1993, DeWitt & Bosland 1996), and various cultivars are grown in the Caribbean, Central and South America, Asia and Africa. *Capsicum pubescens* originated at high elevation in the Andes of Equador and Bolivia, and is cultivated there and in the mountainous regions of Mexico, Central and South America (DeWitt 2005).

The solanaceous flora of Mesoamerica has historically been augmented by introductions, some by man and some accidental (i.e. birds, mammals, in livestock feed). Seeds are dispersed in the wild predominantly by birds, which are apparently immune to the effects of capsaicin (the chemical compound that gives *Capsicum* species their pungency), a secondary metabolite produced by the plant as a defense mechanism to deter mammalian herbivores (DeWitt & Bosland 1996).

1.1.3 History

Early European explorers of the New World collected capsicums purely by chance. Herbarium specimens are scarce, and there is very little information on the orgins of the cultivars of the domesticated species. Information and material collected was often inadequate because only the fruit was collected and no information on floral anatomy and morphology was recorded. During the past three decades, with the introduction of germplasm collecting programmes, there has been an improvement in herbarium collections and the range of variation within species has become evident (Eshbaugh 1993).

Following his first voyage in 1492, Christopher Columbus was credited with the 'discovery' of a plant later described as *Capsicum annuum*. The fruit from this plant was pungent and the taste similar to that of black pepper, *Piper nigrum* L., to which it is not related. On his return to Spain in 1493, Columbus brought other plants from the New World and was responsible for introducing cassava, kidney beans, maize, sweet potatoes, tobacco and yams to Europe (Bosland 1996). However, the Amerindians had been using *Capsicum* for more than 9000 years and cultivating it for 5000 years. Columbus called this plant 'red pepper' as the pods were red. Due to subsequent voyages by the early explorers, *Capsicum* spread to India, China, Japan and Europe. *Capsicum* was quickly established in local cuisines and used as a substitute for the more expensive black pepper, which in those times only the wealthy could afford (Bosland 1996).

In the 16th Century, Spanish merchants named this new spice 'pimiento'. The terminology relating to *Capsicum* is somewhat confusing. The word 'chile' is a variation of 'chil' which is from the Nahuatl (Aztec) dialect. When Columbus explored the Caribbean Islands, the indigenous people called *Capsicum* plants 'aji', a variation of the word 'axi' from the now extinct Arawak dialect (Bosland 1996).

Capsicum species now grown in the tropics and in temperate regions dominate the world hot spice trade, India being the world's largest producer followed by Mexico, Indonesia and China. The non-pungent varieties of *Capsicum* are an economically important 'green' crop grown worldwide, especially in temperate regions (Eshbaugh 1993).

1.1.4 Cultivation

Although *Capsicum* species are perennial (Andrews 1995, DeWitt & Bosland 1996, California Antilles Trading Consortium 2005, Floridata 2005), almost all species are grown as annuals, even in tropical climates. Young seedlings are cold-sensitive but mature plants can tolerate light frost (Floridata 2005). *Capsicum* plants display low salinity tolerance, and prefer medium- to heavy-textured, well-drained, sandy or silt-loam soils with a pH of 4.3-8.7. Optimal ambient temperatures are 20-26°C with an absolute

minimum temperature of 15°C and maximum of 27°C (Floridata 2005), although the reported life zone for *Capsicum* peppers is 7-29°C (California Antilles Trading Consortium 2005). Fruit yield is greatest when plants receive daily rainfall or have an adequate water supply through irrigation, as they are not particularly drought-tolerant. The seedbeds or fields should be well prepared before planting with organic fertilizers such as cow manure, but soil analyses should be conducted prior to planting to prevent under-fertilizing or excessive fertilizing (University of Georgia 2006).

Capsicums are grown from seed that takes 7-10 days to germinate when planted in full sun. The seeds are planted *in situ* or in seed beds and mulch is added to protect the seedlings from being sun-scorched. Other organic material or residues can be placed between rows in standing crops as mulch, generally 5-8 t/ha dry basis and up to a thickness of 2-4 cm is recommended. Seedlings are transplanted when they are a bit hardier, 40-45 days after planting. In temperate climates, seeds are planted under protective cover about 6-8 weeks prior to the last predicted frost of the season. The seedlings are then transplanted, 0.6-1.2 m apart, after the last frost (Floridata 2005). Approximately three months after planting, the plants flower and, depending on the variety, produce fruits that are harvested for two months, from which six to ten pickings will be reaped. Hot, dry weather is desirable when the fruit is ripening. The fruits are harvested by cutting the stem rather than tearing the fruit off as the latter leads to damage to the plant. In India, the average yield of rain-fed *Capsicum* peppers is about 500 kg of dry chillies per hectare. That of an irrigated crop varies from 1000 to 2000 kg of fresh chillies per hectare. The percentage recovery of dry chillies in comparison to fresh weight is 25-30% (OISAT 2005).

1.1.5 Breeding

The objective of plant breeders is to obtain a cultivar with superior genetic properties for improved yield, quality and hardiness. Interspecific crosses have been made successfully between *C. annuum* and *C. chinense*. Hybridization of chillies has been commercially successful using hand-emasculation, genetic male-sterility and cytoplasmic male-sterility

techniques. Backcross, mass, single plant and pedigree selection methods, and single seed descent and haploid breeding, are being practiced (Bosland 1996). Genetic transformation research on *Capsicum* is in progress. BoShou (2005) reviewed the status of genetic crop enhancement, including genetic transformation technology, for resistance to bacterial wilt, (*Ralstonia solanacearum*), worldwide. Progress is being made regarding genetic resources and breeding of resistant cultivars of *Capsicum* as well as other crops. Biochemically-assisted selection techniques may also provide new initiatives in *Capsicum* breeding.

Capsicum is considered a self-pollinating crop, but several specialists argue that it should be regarded as facultatively cross-pollinating because the rate of out-crossing associated with natural insect pollinators varies between 7-91% (Bosland 1996). Cross-pollination not only affects breeding methods, but requires special precautions in seed production. Plant breeders therefore must take precautions to eliminate pollination by insects to promote self-pollination (DeWitt & Bosland 1996).

1.1.6 Pungency

Capsaicinoids are the class of pungency compounds found in *Capsicum* plants (Fig. 1.2). Capsaicin is produced in glands in the placenta and stored in the tissue membrane where the seeds are attached to the pod. Seeds are not a source of pungency although occasionally they will absorb capsaicin because of their proximity to the placenta. The pungency of a chillie can be considerably reduced if the seeds and interior membranes are removed. If the fruit is to be ground, the stalks, placenta, membranes and seeds are removed, thereby reducing the pungency and increasing the colour (Simon *et al*. 1984).

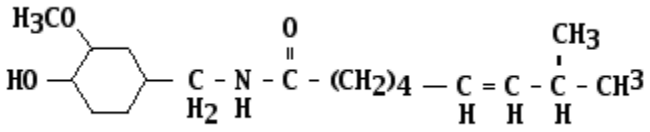


Figure 1.2 Chemical formula of capsaicin.

The pungency of chillies used to be measured using a method developed by a pharmacist, Wilbur Scoville, in 1912 called the Scoville Organoleptic Test. The number of Scoville Heat Units was determined by how many parts of sugar water it took to dilute the extracted sample of a given chillie, so the 'heat' was no longer detected. Generally accepted pungency and Scoville ratings of chillies are listed in Tables 1.1 and 1.2. James Woodbury invented a mechanical method of testing the pungency of chillies. Dried chillies are dissolved in ethanol saturated with sodium acetate, the remaining liquid is then tested for pungency using High Performance Liquid Chromatography (HPLC) (Caselton 2005).

Capsaicin levels vary considerably depending on the type of chillie, climate and growing conditions (hot, dry weather produces more pungent chillies) and even between pods on the same plant. Plant breeders have developed cultivars with varying degrees of pungency. Pungency is also correlated to the amount of environmental stress to which a plant is subjected: the more stress, the higher the capsaicin content of the fruit. For instance, it has been observed in New Mexico that after furrow irrigation, the pungency of the fruits increased, presumably because the plant responded to the flooding of its root zone, and reacted by increasing the level of capsaicin in the pods. If chillies of the same cultivar are cultivated in a hot semi-arid region and a cool coastal region, capsaicin in the fruit of the former would be higher than the latter (Bosland 1996). Ripe chillies are generally sweeter and hotter than green chillies.

Table 1.1 Guide to common chillies and average ratings using the Scoville pungency scale (DeWitt & Bosland 1996).

Pungency	**Rating in Scoville Units**
Mild	0-5 000
Medium	5 000-20 000
Hot	20 000-70 000
Extreme	70 000-300 000

Table 1.2 The pungency of various *Capsicum* pods (DeWitt 2005).

Chillie	**Rating in Scoville Units**
Bell pepper	0
New Mexico	1 000
Jalapeno	3 000-6 000
Chipolte (smoked Jalapeno)	10 000
De Arbol	15 000-30 000
Piquin, Aji*, Cayenne, Tabasco	30 000-50 000
Habañero, Scotch Bonnet	80 000-300 000+
Red Savina Habanero	577 000

* *Capsicum baccatum* measure between 30,000 and 50,000 Scoville Heat Units.

1.1.7 Uses

Capsicum can be processed in a number of ways, used fresh or dried, whole or ground and combined with other flavouring agents. *Capsicum frutescens* is used in Tabasco™ sauce and paprika and paprika oleoresin, which derive from *C. annuum*, are widely used as colouring agents in a wide range of foods, drugs and cosmetics. Paprika and paprika oleoresin are also used for their carotenoid compounds which improve feather colour in birds and pigmentation in fish (Bosland 1996). 'Pepper' sprays have been developed and are used as self-defense aids. Organic gardeners and farmers use a dried chillie powder as an organic repellant spray application on their crops to deter insects and small vertebrates (Floridata 2005).

Capsicums have been used for medicinal purposes dating back almost 2000 years to the Mayas. Asthma, coughs and sore throats were treated with capsaicinoids. The Aztecs used *Capsicum* to relieve toothaches. Capsaicin causes the brain to release endorphins, the body's natural pain killers, and has the effect of deadening pain receptors (Bosland 1996). Today capsaicin topical applications are prescribed to treat arthritis, phantom limb pain, tendonitis, sore muscles and shingles. Mouth washes and nasal sprays containing

capsaicin are prescribed for toothache, bronchitis, asthma and migraine headaches. Capsaicin also aids digestion and appetite, lowers blood sugar and cholesterol and reduces blood clotting (Floridata 2005).

1.2 *Capsicum baccatum*

The *Capsicum* species in this study is *C. baccatum* var. *pendulum* (Bohs, pers. comm., Bosland, pers. comm., Pettersson, pers. comm.). The description of a cultivar (cultivated variety), as outlined under the International Code of Nomenclature of Cultivated Plants is, "a group or assemblage of cultivated individual plants that when reproduced sexually or asexually retain their distinguishing features that have been described morphologically, physiologically, cytologically, chemically or in other ways that have significant meaning to agriculture, horticulture, or forestry" (Gilmour 1969). In other words, a cultivar is a plant which has been selected or hybridized and would probably not survive outside cultivation (Andrews 1995).

Capsicum baccatum is easily distinguishable from other species: the flower corollas are white, cream or greenish, slightly revolute and solitary at each node, with distinctive green, tan, or yellow markings or spots on the corolla lobes. The anthers are initially white and turn tan or yellow with age. The pedicels are either erect or declining at anthesis; pods are usually erect, becoming pendant as they ripen. The calyx lobes are prolonged into noticeable 'teeth' (Fig. 1.3).

Figure 1.3 *Capsicum baccatum* var. *pendulum* flower showing markings on corollas and bud with prolonged calyx lobes.

Capsicum baccatum plants grow up to 1.5m in height, with an erect habit and multiple stems. The leaves are large, dark green on the upper side and slightly lighter on the underside. The size and shape of the fruit pods are diverse, ranging from erect, short, pointed pods, to pendant, elongate pods.

A diagram of a typical *Capsicum* pod in cross-section is shown in Fig. 1.4. The calyx of a ripe mature pod is without annular constriction at the junction with the pedicel, although sometimes it can be irregularly wrinkled, and the veins are prolonged into prominent teeth. When mature, the flesh of the pod is firm and the seeds straw-coloured (Caselton 2005). During the ripening process, the fruit colour can range from green to orange, red, yellow or brown.

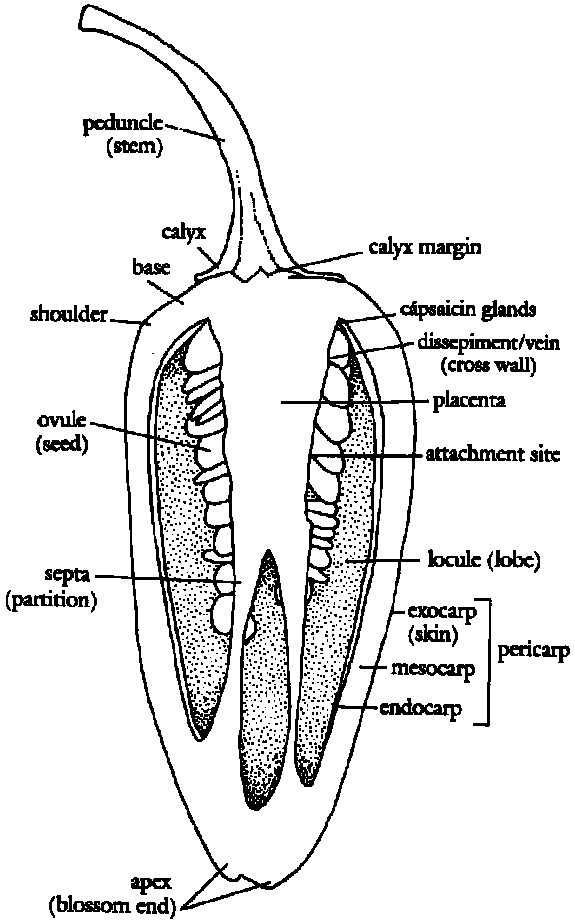


Figure 1.4 Diagram of cross-section of a *Capsicum* fruit (Andrews 1995).

Seedlings of the cultivar grown in the Makana District, *Capsicum baccatum* var. *pendulum*, are erect in habit although the previous season's ratooned (cut-back) plants are inclined to have a more compact form. Mature plants can grow to a height of 150-160 cm although the average height is around 120-130 cm. The leaf-form is simple and asymmetrical. Pods are conical and about 4.5 cm wide and 4 cm long. As pods mature their colour changes from green, through green and purple, orange/red and bright red, to deep red (Fig. 1.5).

Figure 1.5 Variation in colour of *Capsicum baccatum* var. *pendulum* pods ripening.

There are numerous varieties of *Capsicum baccatum*; *C.b.* var. *baccatum*, *C.b.* var. *microcarpum*, *C.b.* var. *pendulum*, *C.b.* var. *praetermissum*, and *C. frutescens* var. *baccatum*. *Capsicum b.* var. *baccatum* and *C.b.* var. *microcarpum* are wild forms of *C. baccatum* (DeWitt 2005). *Capsicum b.* var. *baccatum* has a high crossability index with domesticated *C.b.* var. *pendulum* and grows from Peru to Brazil. The greatest centre of diversity of wild *C.b.* var. *baccatum* is Bolivia, and Eshbaugh (1993) suggests this to be the centre of origin. *Capsicum b.* var. *pendulum*, a cultivated variety, is grown in the lowland tropical regions of South America.

1.2.1 Background to Capsicum baccatum *variety* pendulum *cultivated in the Makana District, Eastern Cape Province, South Africa*

Capsicum baccatum var. *pendulum* was first grown in the area in 2005. Very little is known about best practices for local cultivation or about the local insects and diseases

associated with it. This study therefore focused on the second growing season of this 'new crop'.

There are a number of contracted growers in the district, each of whom has allocated a certain number of hectares to be planted with *Capsicum*. The growers have predetermined planting times, thus ensuring a continuous supply of pods to the factory for processing throughout the season. A factory processing the pods has been opened in Grahamstown, bringing a much-needed boost to the local economy by creating jobs, training and skills development within the local community. During the past three years, from when the processing factory was first established, 600 seasonal jobs have been created at the factory itself and an additional 1000 seasonal jobs created on farms where the crop is grown.

Seedlings are reared and transplanted from mid-September to November. The pods are harvested from mid-March to May, tailing off towards the end of June. Some of the growers ratooned the previous season's plants, cutting them back to approximately 25-30 cm in height. By ratooning plants that are already established, this provides the advantage of an early harvest. In addition, the processing factory is supplied with a constant supply of pods over an extended period of time as opposed to dealing with a glut should all the growers have planted and harvested simultaneously. Pods from ratooned plants are harvested from mid-January, tailing off during May. After processing at the factory, 98% of the finished product is exported to markets in Germany, Holland, England, Scotland, Ireland, Greece, Italy, Denmark and Australia (D. Duncan pers. comm.).

1.3 Insects associated with *Capsicum* species grown in other areas

One of the aims of this study was to identify the insects associated with the *Capsicum* variety grown in the Makana District. Preliminary trapping with Yellow Delta Traps in *Capsicum* lands in May 2005 indicated that the Mediterranean Fruit Fly, *Ceratitis capitata* (Weidemann) (Diptera: Tephritidae) is of major importance as it causes the most

insect damage to the crop. It was expected that these flies would also be associated with the harvested pods in storage before processing or export.

In the absence of any entomological knowledge about the insects on *Capsicum* in the Makana District, information on insects associated with *Capsicum* elsewhere was obtained, thereby providing a rough guide as to insects that may occur in the crop in the Eastern Cape. In New Mexico, herbivorous (Table 1.3) and beneficial insects (Table 1.4) of *Capsicum* species have been identified (NMSU 2005). *Capsicum* variant Piquanté is commercially grown under the brand name Peppadew® in the Tzaneen region of Limpopo Province, South Africa. The most common pests associated with this crop are set out in Table 1.5 (G. Booysen pers. comm.).

1.4 Aims of this study

An ideal opportunity to implement integrated crop management (ICM) has arisen with the recent cultivation of *Capsicum baccatum* var. *pendulum* in the Makana District. Because so little is known about the insects associated with this crop, the purpose of this study was to collate sufficient information on the biology of the system to manage crop production using integrated pest management (IPM) within the context of ICM. The aims of this study were to:

1) identify the *Capsicum* species and cultivar;
2) make an insect reference collection and database of insects associated with *Capsicum baccatum* var. *pendulum* cultivated in the Makana District;
3) characterize the composition of the insect community;
4) determine the major insect pests;
5) quantify the composition and densities of these insect pest communities and evaluate how they vary over time;
6) estimate economic cost of damage; and
7) establish an intervention strategy.

Table 1.3 Herbivorous insects associated with *Capsicum* species in New Mexico (NMSU 2005).

Order	Family	Species	Common Name
Coleoptera	Chrysomelidae	*Acalymma vittatum*	Striped Cucumber Beetle
		Diabrotica undecimpunctata howardi	Spotted Cucumber Beetle
		Epitrix spp., *Phyllotreta* spp. and possibly others	Flea Beetle
	Elateridae	*Aeolus, Alaus, Cardiophorus, Conoderus, Dicrepidius, Drasterius, Glyphonyx, Melanotus* and others	Click Beetle (Adult) Wireworm (Larva)
Diptera	Agromyzidae	*Liriomyza* spp.	Serpentine Leafminer Fly
Hemiptera	Aleyrodidae	*Trialeurodes, Bemisia* and several other genera	Whitefly
	Cicadellidae	*Circulifer tenellus*	Beet Leafhopper
	Lygaeidae	*Nysius* spp.	False Chinch Bug
	Pentatomidae	*Murgantia histronica*	Harlequin Bug
Lepidoptera	Noctuidae	*Agrotis, Peridroma, Euxoa, Feltia, Spodoptera* and other spp.	Miller Moth, Cutworm, Armyworm, Corn Earworm
Thysanoptera	Thripidae	*Thrips tabaci*	Onion Thrips
		Frankliniella occidentalis	Western Flower Thrips

Table 1.4 Beneficial insects associated with *Capsicum* species in New Mexico (NMSU 2005).

Order	Family	Species	Common Name
Coleoptera	Coccinellidae	*Olla vnigrum*	Ashgrey Ladybird
		Harmonia axyridis	Asian Ladybird
		Hippodamia convergens	Convergent Ladybird
		Adalia bipunctata	Two Spot Ladybird
	Melyridae	*Collops bipunctatus*	Collops Beetle
Diptera	Syrphidae	*Diaeretiella rapae*	Syrphid/Hover Fly
Hemiptera	Geocoridae	*Geocoris* spp.	Big Eyed Bug
	Reduviidae	sp. indeterminate	Assassin Bug
	Nabidae	*Nabis* spp.	Damsel Bug
	Anthocoridae	*Orius tristicolor*	Minute Pirate Bug
Neuroptera	Chrysopidae	*Chrysoperla carnea*	Green Lacewing

Table 1.5 Common insect pests associated with the *Capsicum* sp., Peppadew®, cultivated near Tzaneen, Limpopo Province, South Africa (G. Booysen pers. comm.).

Order	Family	Species	Common Name
Diptera	Tephritidae	*Ceratitis capitata*	Mediterranean Fruit Fly
		Ceratitis cosyra	Marula Fruit Fly
		Ceratitis rosa	Natal Fruit Fly
Lepidoptera	Noctuidae	*Helicoverpa armigera*	American Bollworm
	Tortricidae	*Thaumatotibia leucotreta***	False Codling Moth
Thysanoptera	Thripidae	*Frankliniella occidentalis**	Western Flower Thrips

* It is thought that the species occurring is *Frankliniella occidentalis* but it has not been verified.

** The scientific name for False Codling Moth has recently changed from *Cryptophlebia leucotreta* to *Thaumatotibia leucotreta*.

II

MATERIALS AND METHODS

2.1 Study sites

2.1.1 Site characteristics

Eight study sites were chosen on four farms located between 15 and 25 km south-east of Grahamstown in the Belmont Valley and Bloukrantz areas (Fig. 2.1). Temperatures for the inland region of the district vary from a minimum of 3.3ºC to a maximum of 32.3ºC and the range in annual rainfall recorded for is between 300-650 mm (Vlok & Euston-Brown 2002). An agronomist, Mr Loddie Greyling (Chicory SA Ltd, Alexandria), conducted a soil analysis for each of the study sites and classified the samples according to soil types as set out in "*Soil Classification: a Taxonomic System for South Africa*" (Soil Classification Working Group 1991) (Appendix 1).

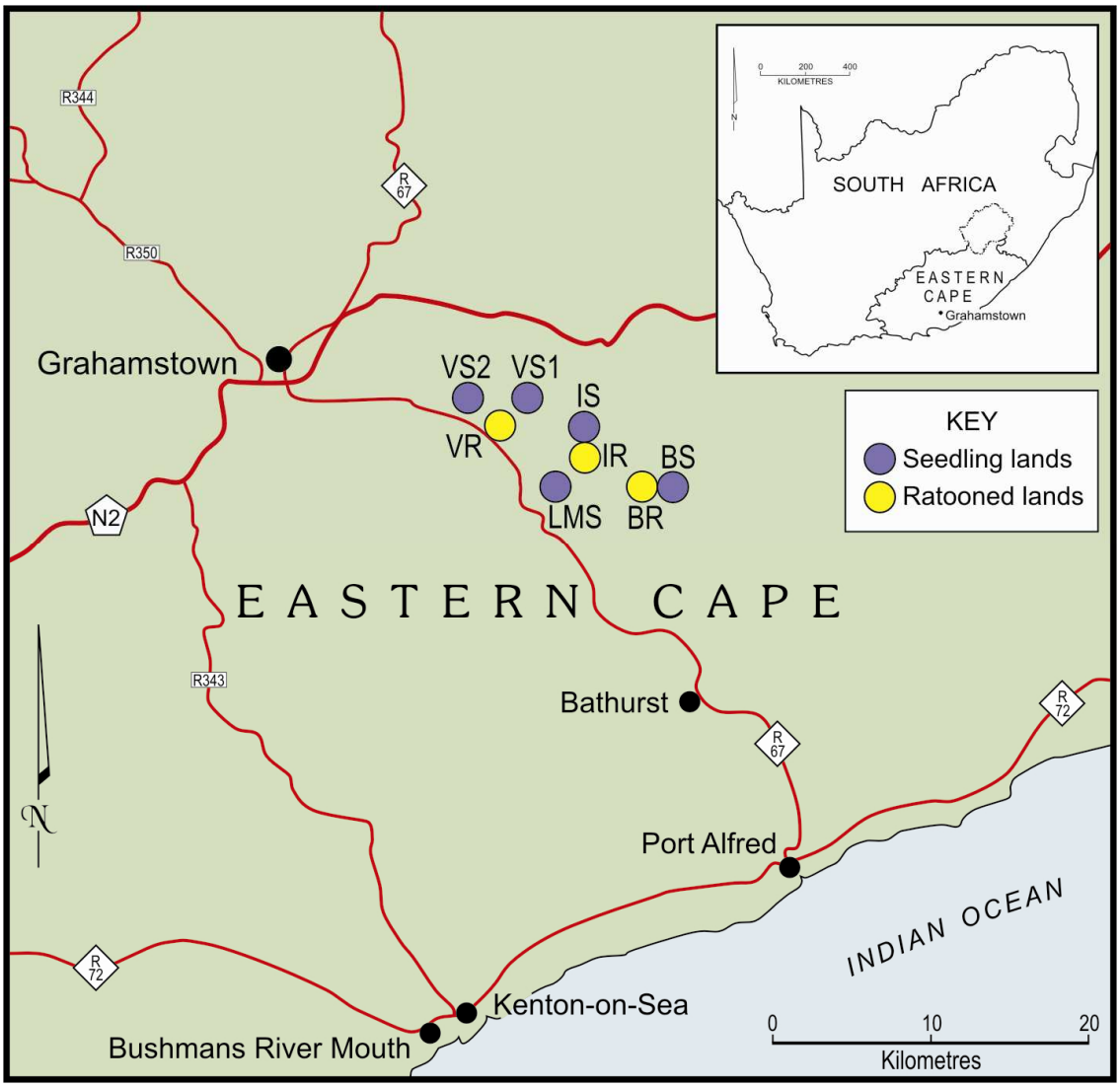


Figure 2.1 The localities of the eight study sites in relation to Grahamstown. BR = Brenthoek Ratooned; BS = Brenthoek Seedling; IR = Imjabulo Ratooned; IS = Imjabulo Seedling; LMS = Lower Melrose Seedling; VR = Varnam Ratooned; VS1 = Varnam Seedling 1; VS2 = Varnam Seedling 2. (Map Drawing Credit: D. Brody, Graphics Printing Unit, Rhodes University).

2.1.2 Surrounding vegetation

The vegetation in the district where the study was conducted is extremely diverse; the flora in this area represented by many vegetation types (Palmer 2004). The endemic vegetation was first described by Acocks in 1953 as Valley Bushveld: “an extremely

dense, semi-succulent thorny scrub 2 metres high" (Acocks 1953, cited in Palmer 2004). A comprehensive study on the flora of the whole of South Africa, Lesotho and Swaziland was completed in 2004 by the National Botanical Institute, and the vegetation in this area was re-defined as Albany Thicket (Palmer 2004). However, this description has been superseded by Mucina & Rutherford (2006) who conducted a further study on the vegetation of South Africa, Lesotho and Swaziland. Albany Thicket has been reclassified as Kowie River Thicket and Fish River Thicket which occur in the semi-arid valleys of the Eastern Cape Province (Fig. 2.2). A wide range of flora is included in this community: annuals, C3 and C4 grasses, deciduous and semi-deciduous woody shrubs and dwarf shrubs, geophytes, stem and leaf succulents (Cowling 1983, cited in Palmer 2004).

The surrounding vegetation plays a significant role in the ecology of a crop system as a number of alternative host plants may be present, providing a refuge for insects, (pests, natural enemies and parasitoids) and location ideal for population build-up. Refuges in surrounding vegetation also provide a harbour for pesticide-susceptible pests, playing a vital role in the management and control against the onset of pesticide resistance in pests. Indigenous plants have been identified as alternative hosts to a number of polyphagous pests (White & Elson-Harris 1992, Thomas *et al.* 2001, Copeland *et al.* 2002).

Figure 2.2 Thicket surrounding most of the *Capsicum baccatum* fields.

2.1.3 Ratooned and seedling lands

Some of the growers ratooned, or cut back, the previous season's plants (cf. Chapter 1) to assess whether this would be economically viable and what impact it would have on yield. The eight study sites were divided into two groups; being either 'ratooned' or 'seedling' lands to distinguish between lands where plants of the previous growing season had been cut back, and lands that were newly planted with seedlings (Table 2.1). This provided an opportunity to make entomological and phenological comparisons of insects between ratooned and seedling lands.

It was not possible to attain the use of a 'control' site on which there would be no insecticide spray and/or bait applications throughout the study period. This would have provided an opportunity to quantify differences among treated and non-treated lands with regard to loss of yield. However, the focus of this study was to ascertain the composition and phenology of insect pests on *Capsicum baccatum*, and although a comparison between treated and non-treated lands would have added important data, it was not essential to this study. The same applications of insecticide, herbicide and fungicide treatments were applied to the two Varnam Seedling lands, thus providing an opportunity

to compare the presence and densities of pest populations in two similarly treated seedling lands.

Each grower had prepared their crops differently (i.e. soil preparation, application of herbicides, fertilizer and irrigation). Given these variables, each site was considered as an individual treatment.

Table 2.1 Details and co-ordinates of the study sites, for both ratooned and seedling lands.

Farm Name	**Site/Land**	**Co-ordinates**	**Altitude (m a.s.l.)**
Brenthoek	Ratooned (BR)	33º21'24"S 26º43'12"E	288
Brenthoek	Seedling (BS)	33º21'21"S 26º43'18"E	288
Imjabulo	Ratooned (IR)	33º19'52"S 26º39'51"E	371
Imjabulo	Seedling (IS)	33º19'52"S 26º39'49"E	378
Lower Melrose	Seedling (LMS)	33º19'43"S 26º38'41"E	420
Varnam	Ratooned (VR)	33º19'33"S 26º38'03"E	430
Varnam	Seedling 1 (VS 1)	33º19'30"S 26º38'09"E	444
Varnam	Seedling 2 (VS 2)	33º19'26"S 26º37'23"E	443

Although Sections 2.1.4 and 2.1.5 are not directly relevant to understanding the entomological problems associated with *Capsicum*, they do provide a general context to understand the agronomy of this crop.

2.1.4 Land preparation and cultivation

Ideal soil for the cultivation of *Capsicum* should be light, fertile with good drainage, but with proper soil management, peppers can be grown in a wide range of soil types (University of Georgia 2006). Depending on soil type, growers need to alter agronomic practices with regard to irrigation and the application of herbicides and fertilizers. Land to be used for growing peppers should stand fallow for at least three months prior to planting. During this period, in preparation for planting, the land should be ploughed and tilled, turning over and loosening the soil to a fine consistency (Carara 2006). A plant's

root development may be limited by compacted soil and tilling will provide a greater air space that promotes vigorous root growth. With a more extensive root system, the plant is able to extract nutrients and water more efficiently (University of Georgia 2006).

After land preparation, herbicides are applied to eradicate weeds (Carara 2006). In the ratooned lands, preparation involved cultivating or ripping between rows to control weed growth, and herbicides were applied along the edges of rows using knapsack sprayers. Throughout the season, weeds were managed using herbicides or hoeing (Appendix 2).

To facilitate good drainage, peppers should be planted on a ridge, the most practical being a bed-type, double-row ridge with an irrigation dripper line placed between the two rows (Carara 2006) (Fig. 2.3A). Spacing between ridges can be 1.6-2.0m. A planting of approximately 24700 plants per hectare can be achieved by leaving a space of 45 cm between plants and 1.8 m between rows. It is recommended that a “blank bed” or “skip row” be allowed at strategic intervals to facilitate the use of a boom spray within the field without causing damage to the crop (Fig. 2.3B). Alternatively all spraying would have to be undertaken by motorized or manual knapsack sprayer (Carara 2006). These recommendations are consistent with those of the University of Georgia (2002).

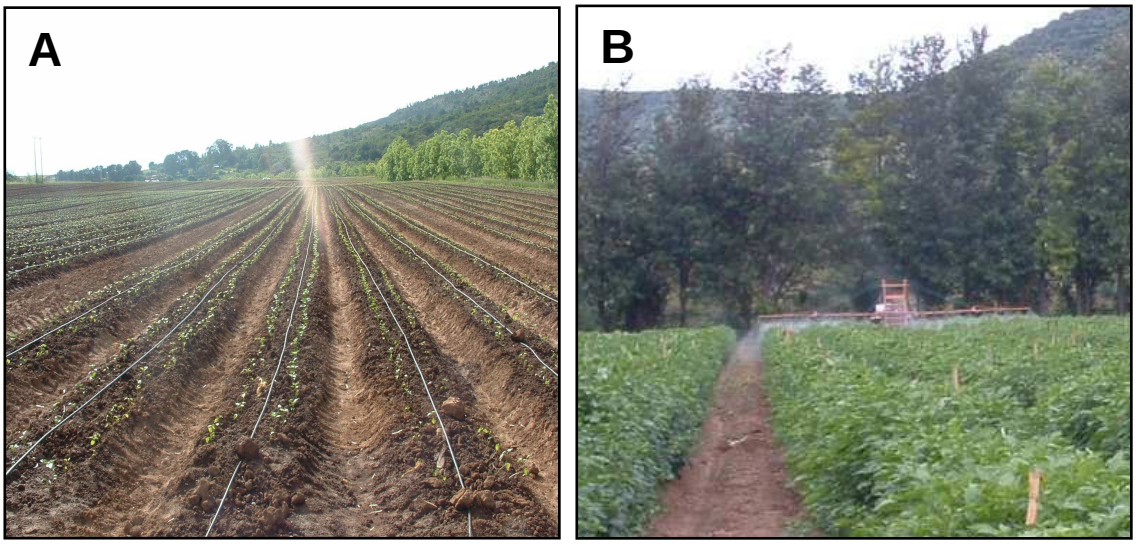


Figure 2.3A. Bed layout in *Capsicum baccatum* seedling beds showing double-ridge row spacing and dripper line placement for irrigation. **B.** Boom spray operating in *Capsicum baccatum* fields, with a blank bed on the left. (Photo Credits: D. Duncan).

2.1.5 Transplanting

Seedlings are raised in a nursery until they reach 10-15 cm in height, and then pulled and packed into bags or crates for transportation. They should be stored in a cool, damp environment and the soil around the roots should be kept moist (University of Georgia 2006). The land to be planted should be pre-irrigated and planting is done manually. The sooner the seedlings are planted after pulling, the better their chances of establishing properly. As soon as they have been transplanted, a post-planting irrigation of the land is done to ensure that the roots are sealed and the plants settle (Carara 2006).

2.1.6 Phenology of Capsicum baccatum *var.* pendulum

In the ratooned lands flowering occurs from mid-October and small pods are present from early November. During December the pods mature and by mid- to late January early harvests commence. Fruit from ratooned lands are harvested from January to May. Seedlings transplanted in November are harvested in mid-March through to May, declining towards the end of June. The growing season for both ratooned and seedling plants last approximately 7 months.

2.2 Sampling

To determine the best methods of sampling and surveillance for this study a literature review was made of the most prevalent insect pests occurring in *Capsicum*, and information on composition and presence of insects in New Mexico, USA (Tables 1.3 and 1.4) and Limpopo, South Africa was also taken into account (Table 1.5).

A problem that sometimes arises in applied entomology is that a ‘mimetic’ approach is sometimes used where successful past projects are used as templates, not taking into consideration the differences between crop systems, localities and species. This leads to false assumptions and invalid generalisations. It is a fundamental requirement that research approaches continue to adjust and improve (Walter 2003).

Estimating the density of a pest population is generally accomplished by sampling. A sampling technique is the method whereby data are gathered from a sampling unit (Bechinski 1994, Pedigo & Rice 2006). A number of sampling techniques are frequently used to establish population size, and in devising a sampling programme one needs to determine which of these to employ in time and space. Bechinski (1994) recommended that the following aspects be considered when designing a sampling programme:

a) to create a system which provides an accurate estimate of population densities;
b) a system should be implementable on all geographical scales, in any habitat and at all times;
c) a sampling method should collect life stages of the pest that are representative of the demographic composition of the population.

Pedigo & Rice (2006) also recommend various fundamental elements which need to be considered when designing a sampling programme:

a) the number of study sites to sample, taking into account any variability between sites;
b) all study sites should be sufficiently comparable and have an equal chance of infestation;
c) the number of units to be sampled and the spatial pattern to be employed;
d) the biology of the insect (development, physiology, behaviour, mobility);
e) plants should be sampled at different growth stages (newly transplanted, pre-flowering, flowering, fruiting, harvest and post-harvest).

When seedlings are scouted, the whole plant is surveyed whereas on established, mature plants, a certain number of leaves, stems, flowers, buds or pods can be counted, bearing in mind that stratification (insects occurring on different parts and heights of a plant) may occur (Pedigo & Rice 2006).

The field under study is divided into a defined number of sampling units. A unit may be a set area (i.e. a 1 m² quadrat), an individual plant or a certain number of sweeps with an insect net. The total number of units is referred to as a sample, and from this sample the population is estimated (Pedigo & Rice 2006).

2.2.1 Pilot sampling trial

A pilot sampling trial was undertaken on the 25th of October 2005 on the Varnam Ratooned study site, where the previous season's *Capsicum* plants were already established. This trial was necessary to determine statistically how many plants should be sampled at each study site. This was achieved by sampling as many plants as possible and calculating the mean number of insects present per plant. An unrestricted sampling pattern was employed to avoid any unconscious bias. Sampling began by counting ten rows along the edge of the field (at one of the corners) and 10 paces into the field where a plant was scouted, using predetermined sampling techniques (cf. Section 2.2.2). The scout then counted 10 rows to the left and 10 paces further into the field, and this pattern was repeated until the opposite side of the field, to the side where the sampling began, was encountered. The scout then went to the opposite corner of the field and counted 20 rows to the right and 10 paces into the field thus ensuring that sampling crossed hexagonally across the study site. This pattern ensured that no plant was sampled twice (Fig. 2.4).

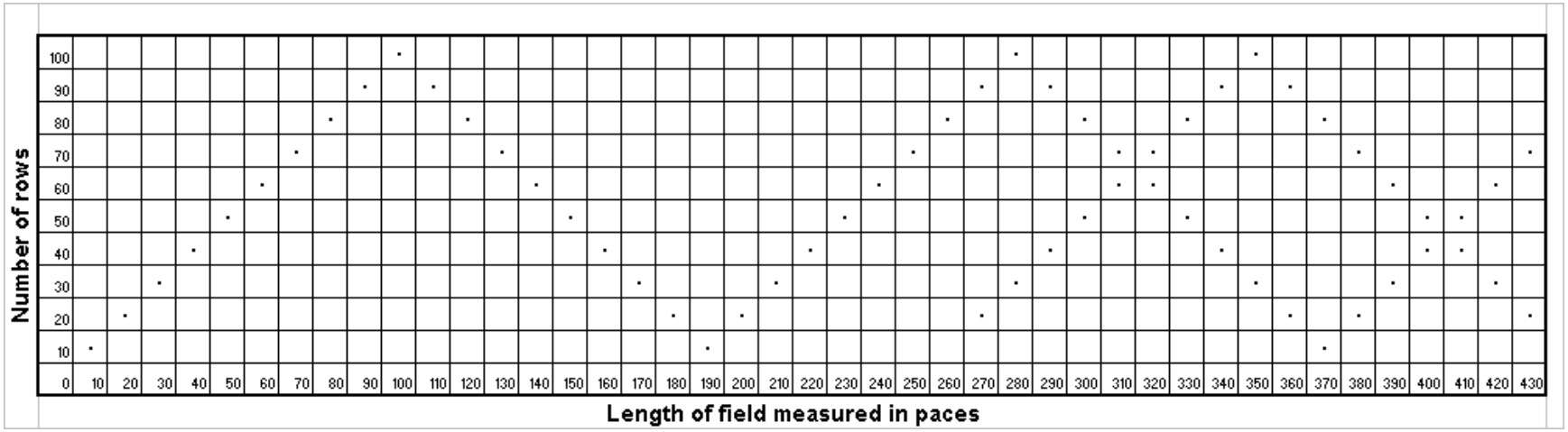


Figure 2.4 Pilot sampling trial undertaken in *Capsicum baccatum* land, Varnam Ratooned Study Site, on the 25th of October 2005, showing the sampling pattern used.

2.2.2 Scouting techniques

The six scouting techniques used, in order of sequence, were:

a) sweep netting (3 passes with the net);
b) visually inspecting the whole plant and, if insects were present, manually picking them off the plant;
c) scouting the soil directly beneath the plant;
d) gently shaking the plant over a white collecting sheet;
e) manually going through the plant working from the tips of the new growth to the bottom of the plant, looking at both sides of the leaves to check for eggs, nymphs, larvae, pupae or adults; and
f) scoring any damage to the plant.

The scouting techniques used for the pilot sampling trial were chosen as they would cross-validate one another and give a definitive picture of insects present and damage to the plants. The sweep netting technique was modified as it was not possible sweep an individual plant as the proximity of neighbouring pepper plants was extremely close. The area covered in a sweep encompassed six plants, therefore the number of flying insects collected using this technique were divided by six, to avoid bias and standardize the sweep catch, and the mean number of flying insects per plant calculated.

A total of 60 individual plants were sampled in the pilot sampling trial. The insects collected from each plant were stored in separate, marked collecting vials and taken to the laboratory for identification. Insects collected during the pilot scouting trial were collected and recorded.

2.2.3 Analyses of pilot sampling trial

The data were analysed using STATISTICA 7.0 software. A runs test was preformed to test for randomness of the number of insects on the 60 plants sampled. The results showed that the number of insects were randomly distributed on the 60 plants (runs test:

sweep net per plant R = 0.33, n = 60, p = 0.065; total per plant R = 0.92, n = 60, p = 0.602). Monte Carlo procedures based on 10 000 samples confirmed the randomness of the number of insects on the 60 plants (99% confidence interval p-values: sweep net per plant (0.069-0.083); total per plant (0.683-0.706)). The mean number of insects per plant caught with a sweep net was 0.47 ± 0.06 ($\bar{x}$ ± s.e.), n = 60, range (0 to 2.0) and the mean number of insects caught using the other five scouting techniques was established as 1.04 ± 0.11, ($\bar{x}$ ± s.e.), n = 60, range (0 to 3.833) (Table 2.2).

Table 2.2 Pilot sampling trial: means and standard errors of insects caught (either by the sweep net, or using the other five scouting techniques) showing the total number of insects caught from the 60 random plants sampled.

	n	**Mean**	**Std Error**	**Minimum**	**Maximum**
Sweep net (only) insects/plant	60	0.47	0.06	0.00	2.00
Total insects/plant	60	1.04	0.11	0.00	3.83

To determine the required number of plants to be sampled in the study, randomly generated samples of 6, 12, 15, 20, 25, 28, 36 and 44 plants were used. The mean number of insects per plant for each sample size was calculated. The estimated mean total of insects per plant converged to the true mean total of insects per plant when samples of 15 or more plants per site were sampled (Fig. 2.5). The mean of 1.04, calculated above (Table 2.2), was derived from Monte Carlo procedures based on five scouting techniques and was quite consistent with that obtained from the actual field values incorporating all six scouting techniques (Fig. 2.5). Variability in means between 1.04 and 1.08 (reached when 15 plants were sampled), is not significantly different. The decision to scout 15 plants per site was based on this analysis.

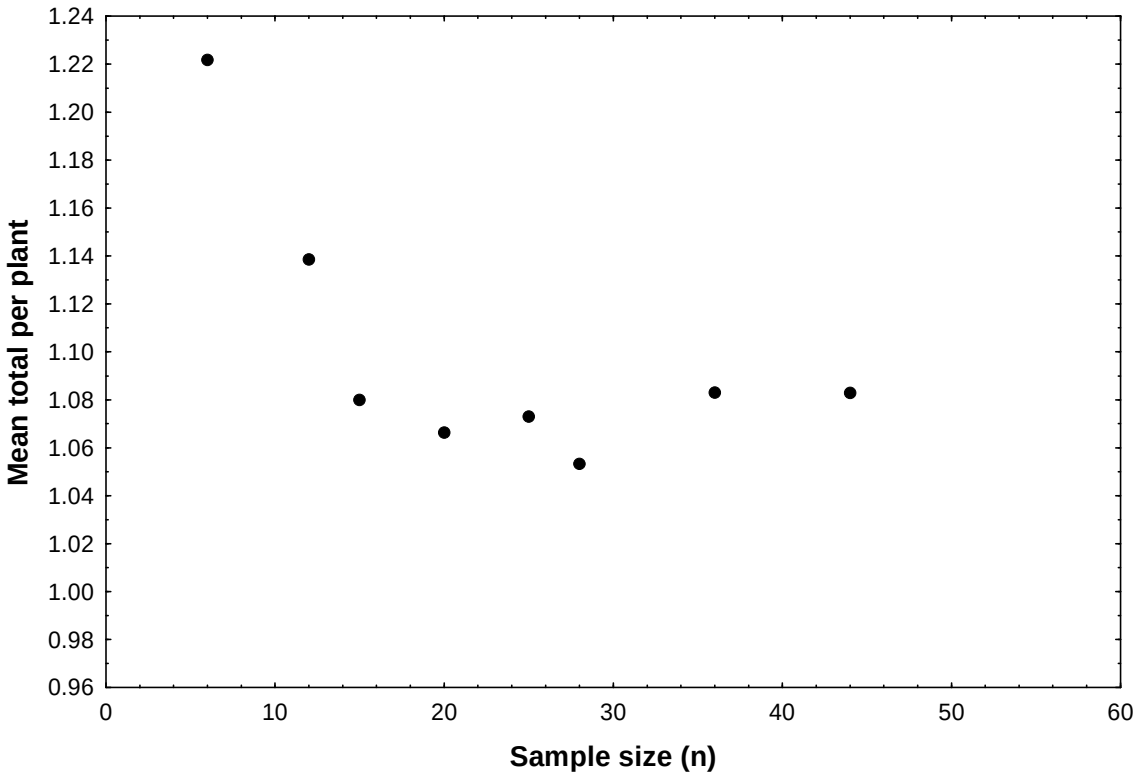


Figure 2.5 The mean total of insects per plant versus sample size (n = 60) showing convergence to the true mean for samples of at least 15 plants per site.

2.3 Monitoring

In developing a monitoring system, certain objectives need to be met. The pests causing damage to the crop have to be identified; methods need to be devised on how to combat pest presence; and strengths or limitations these methods may have need to be assessed (Wall 1990). In designing a species-specific monitoring trap system, Wall (1990) defines three objectives; detection of the pest, assessing whether control measures need to be applied and determining the timing of control measures.

Data are gathered using a sensitive trapping method to detect the presence or absence of a pest species. Quantitative information is required to calculate timing of control measures, and this would include: a) specific biological information (i.e. key factor analysis); b) meteorological and temperature data records should be kept as both affect insect

development; c) seasonal cycles; and d) records of the time of day when the samples are collected. A quantified correlation between trap catch and population density, or the amount of any further damage that may occur, needs to be determined to do a risk assessment (Wall 1990, Higley & Peterson 1994, Pedigo & Rice 2006).

Monitoring is a valuable tool used to confirm predictions of pest presence from timing approaches. All pest management activities rely on the interactive relationship between the pest, its host and environmental factors. Resources and expenditure used to develop and operate pest sampling and monitoring programmes are usually directly linked to the economic value of the crop (Higley & Peterson 1994).

Active traps used to lure and capture insect pests use various means of attraction: light, colour, bait, kairomones and pheromones (Higley & Peterson 1994). Traps should be easy to assemble and manage, of standard construction (in size and quality), easily obtainable and cost-effective (Wall 1990, Higley & Peterson 1994). Variation in design may have an effect on the sampling range and close range behaviour, resulting in variation in the quality of the trap data. Traps should be deployed at a consistent height relative to the canopy of the crop, and monitoring traps placed in a comparable position within each of the study sites throughout the study period.

2.3.1 The use of pheromones

The behavioral activities of many insects, for example dispersal, migration, mating, aggregation and alarm signaling, and even fecundity, are influenced by chemical cues (van Emden & Service 2004). Pheromones, the natural chemicals used to convey information to individuals within or between species, have been reproduced by man, either synthetically or by chemical replication, and used as a control method for pests. These synthetic pheromones are particularly useful in pest control as they are mostly species-specific, do not have any impact on the environment (i.e. residues), and are required in minute quantities (van Emden & Service 2004).

Pheromones are important tools in pest control and are used in a number of applications: a) to monitor and survey pest populations; b) detecting the presence of pests in new areas; c) for attract and kill programmes; d) pheromone confusion/distruption technique; e) as an oviposition deterrent; f) as an alarm pheromone; and g) to manipulate natural enemy behaviour (Silverstein 1981, Wall 1990, van Emden & Service, 2004).

Sex pheromones were first identified in Lepidoptera (van Emden & Service 2004), and were initially thought to be unique to this order, but many attractant volatiles have now been identified from other orders. Mating attractant pheromones are most widely used in pest control and these are generally derived from females. Only sex pheromones from females have been field tested because, although males may also produce pheromones, these are not as effective over long distances (van Emden & Service 2004). Most lepidopteran species mate at dusk, and females of different species 'call' in different time-windows. There is also an optimum pheromone release rate for different species, so halving or doubling the release rate using a pheromone based trap may significantly reduce the number of males caught.

Pheromone traps are used to detect the presence of specific insect pests, as early-warning devices for emergence from overwintering sites, immigration or migration from other areas, in surveys and quarantine work. To determine the timing of control measures, calculation of a threshold catch is required. This threshold usually indicates either an initial onset or the significant emergence of the pest. It is used to facilitate decision-making as to the need for either further observation, focusing on the developmental stages of the insect, or the instigation of active control. The threshold catch is also used to determine whether the economic threshold is likely to be exceeded. When the threshold has been reached, the application of active control measures can commence (Wall 1990, van Emden & Service 2004).

A consistent quantitative correlation between the trap catch and population density is required to estimate the size of the pest population, thereby making risk assessment more accurate. These estimates can be applied to track population trends and dispersal of the

pest within the habitat, and to determine the effectiveness of control measures (Wall 1990, van Emden & Service 2004). Depending on the type of pheromone used, these tend to be gender-specific and predominantly for males so that trap catches will be biased and may be difficult to relate to the population density. Therefore the sex ratio between males and females of a species needs to be taken into account. Using a male pheromone attractant, the relationship between trap catch and population density will not be linear as females releasing natural pheromones will compete with the pheromone-based traps as the population increases, and the relative proportion of males caught will decrease (van Emden & Service 2004). The concept of using pheromone traps to 'trap-out' males at the beginning of a season to inhibit pest populations may seem feasible, but mathematical models have shown that 90% of the males would have to be destroyed before any reduction would be seen in the next generation (van Emden & Service 2004), especially if males mate more than once.

Wall (1990) determined numerous advantages of using pheromone traps as a tool for monitoring; traps are sensitive, are usually species-specific, do not require any energy source to operate once they are set up, need minimal maintenance, are not labour-intensive and can be operated by people who have little, if any, training in entomology. Wall (1990) also identified some disadvantages of using pheromone traps: a) the interpretation of catches; b) how the sampling area may be affected over time; c) climatic effects on trap-catch; d) the efficiency of traps as catches accumulate; e) possible competition with wild females; and f) adult insects may be separated in time from the damaging stage, leading to difficulty in relating trap-catch to the actual population density.

Using a pheromone-based monitoring system, the basic components are the trap, an attractant or lure and knowledge of the biology of the pest insect to be able to interpret the catch. Because pheromone traps are usually species-specific, they are the most sensitive of the sampling techniques and substantial confidence can therefore be placed on negative results for the active area of the trap (Wall 1990). The biology of the insect monitored can affect the efficiency of the monitoring system. For example, by using

pheromone traps to monitor population fluctuations of a multivoltine insect, the application will be somewhat limited. Pheromone traps in this instance could be used to monitor the commencement of flight of adult populations that are separated in time from preceding flights or generations in the area (Wall 1990).

Traps should not be too closely positioned as this may lead to the pheromones or baits interacting, distorting individual trap catches and resulting in a reduction in the number of insects caught. If a number of the same pheromone-based traps are used, (i.e. as a means of controlling pest populations), it is essential that the sampling range of the trap is calculated as it would be practically impossible to usefully interpret the trap-catch without doing this (Wall 1990). To establish trapping density using a multi-trap method, one trap is initially set up within a study site for a predetermined period of time and the number of insects counted. Additional traps are then set up at different space and time intervals, and the insects from these are counted and the data analysed. This was, however, not applicable to this study as only single monitoring traps were placed in each of the lands.

Other factors regarding sampling range that ought to be considered are the distance over which the insects are attracted and the distance they may have travelled before being attracted through, for example, migratory or appetitive behaviour (Wall & Perry 1987, cited in Wall 1990). Traps deployed in a site, even if standardized trap spacing is employed, will attract more insects if they are positioned upwind, thereby altering trap catches depending on wind direction (Wall & Perry 1978, cited in Wall 1990). Positioning of the traps must be carefully planned as insects from surrounding vegetation may be attracted to the trap and indicate false-positive catches (Wall 1990).

2.3.2 Selection of monitoring traps

Traps chosen for the monitoring programme were carefully selected, taking into account information obtained about the phytophagous insects occurring in New Mexico and South Africa (Tables 1.3 and 1.5). Depending on the biology of the pest, a decision needs to be

made as to what type of trap will be most effective. Details of the monitoring traps, pheromone-based lures and baits used in this study are detailed below in Table 2.3.

Table 2.3 Details of the five traps placed in each of the study sites to monitor insect activity.

Trap	Lure, Bait or Pheromone	Active Ingredient and Application	Insects
Yellow Delta Trap	EGO Pherolure™	Ampoule dispensing proprietary volatiles used with YDT sticky liner	Mediterranean and Natal Fruit Fly (Male)
Yellow Delta Trap	Lorelei®	Ampoule dispensing (E)-7-dodecenyl acetate, (E)-8-dodecenyl acetate and (Z)-8-dodecenyl acetate used with YDT sticky liner	False Coddling Moth (Male)
Sensus Trap	Questlure®	Dispenser with sponge impregnated with protein hydrolysate and alpha-cypermethrin with one Dichlorvos/Vapona block	Mediterranean and Natal Fruit Fly (Female)
Yellow Bucket Funnel Trap	Texas Volitile™	Ampoule dispensing phenylacetaldehyde, methyl-2-methoxybenzoate, methyl salicylate, and optionally 2-phenylethanol and/or limonene, used with two Dichlorvos/Vapona blocks	African Bollworm, looper, cutworm and stemborer
Yellow Card Trap	Plantex™	Polybutene gum. Applied to both sides of Yellow Card	Thrips, aphids, leafminers and white fly

Throughout the study period of one year, trap catches were collected and a scouting regime undertaken on a weekly basis, providing an extensive sampling strategy and a representative sample of insects.

2.3.2.1 African Bollworm (Helicoverpa armigera) *and other noctuid species*

A number of species of noctuids are serious pests of cultivated crops. The species that seems to be most damaging to *Capsicum* grown in Tzaneen is *Helicoverpa armigera* (African bollworm). To determine which families of Lepidoptera were the most abundant, a Yellow Bucket Funnel Trap (Fig. 2.6D) with a Texas Volatile™ attractant and two Dichlorvos pastilles to kill the catch, were used in this study. The trap, bait and poison were all produced by Insect Science (Pty) Ltd, Nelspruit, South Africa. Funnel traps using pheromone lures are significantly more effective than sticky traps for monitoring *H. armigera* populations (Kant *et al*. 1999).

2.3.2.2 False Codling Moth (Thaumatotibia leucotreta)

Monitoring traps for *T. leucotreta* adults were set up as this moth has been associated with *Capsicum* cultivated in Tzaneen. A Yellow Delta Trap (Insect Science (Pty) Ltd, Nelspruit, South Africa) (Figs. 2.6A&B), with a Lorelei® sex pheromone attractant (Citrus Research International (Pty) Ltd, Citrusdal, South Africa) was placed in each of the study sites. The Lorelei® attractant is contained in an ampoule-like dispenser with a polyethylene tube which regulates a constant rate of release of the pheromone. Under normal climatic conditions, the Lorelei® attractant is effective for approximately 7 months. The pheromone-based traps used for monitoring Lepidoptera were not placed on the same trap stand; this reduced possible interference between pheromone lures.

2.3.2.3 Fruit fly (Ceratitis *species*)

During the 2004-2005 growing season, some of the growers set up Yellow Delta Traps with pheromone-based lures (Chempac Fruit Fly Lure®, Chempac (Pty) Ltd, Suider Paarl, South Africa) in their lands to monitor fruit fly activity. The trap liners collected from these traps gave a clear indication that *Ceratitis capitata* (Mediterranean Fruit Fly) was present in large numbers within this crop. This information, coupled with the fact that *Ceratitis capitata* (Mediterranean Fruit Fly), *C. cosyra* (Marula Fruit fly), and *C. rosa* (Natal Fruit Fly) occur in Tzaneen, prompted the decision to use a Yellow Delta Trap

with an EGO PheroLure™ (Insect Science (Pty) Ltd, Nelspruit, South Africa), to monitor fruit fly presence in *C. baccatum* lands (Fig. 2.6A&B).

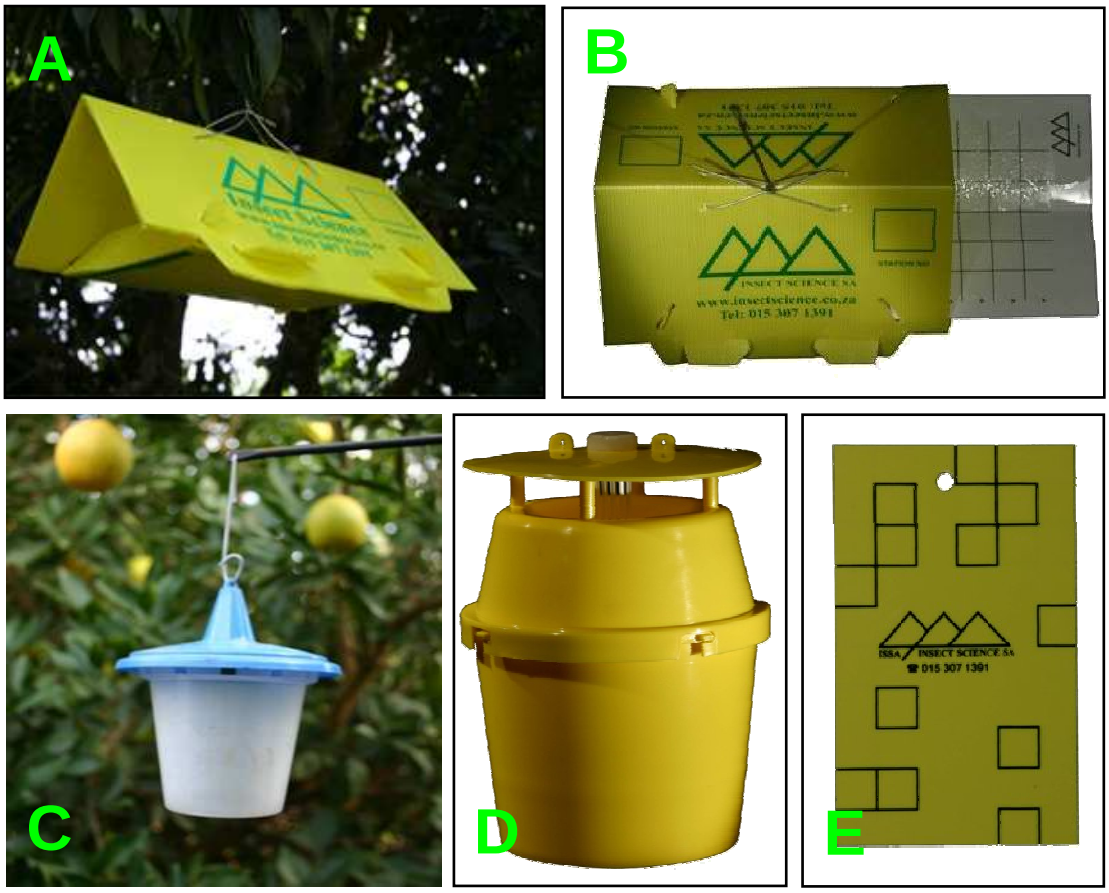
Sensus Traps (Quest Developments CC, Brits, South Africa) (Fig. 2.6C) were also selected to monitor fruit flies, to enable comparisons to be made of the relative efficacy of the Sensus Trap and the Yellow Delta Trap used with a fruit fly pheromone lure. Sensus traps were set up with Questlure® (Quest Developments CC, Brits, South Africa), a protein hydrolysate bait and alpha-cypermethrin insecticide that are impregnated in a sponge encased by a hard, green, plastic dispenser. A Dichlorvos (Vapona) pastille (Insect Science (Pty) Ltd, Nelspruit, South Africa), was also placed in the lid of the trap to kill the trap catch. Depending on weather conditions, the bait is effective for approximately 6-8 weeks.

2.3.2.4 Thrips species

Several species of thrips are damaging to *Capsicum* and infestations usually involve more than one species. Two of the most injurious species are Western Flower Thrips, *Frankliniella occidentalis* and Onion Thrips, *Thrips tabaci*. However, there are a number of species that prey on other thrips and mites (e.g. *Haplothrips bedfordi* preys on *Thrips tabaci* (Hartwig 1985)).

Yellow Card Traps are used for monitoring populations of small insects such as aphids (Hemiptera: Aphididae), thrips (Thysanoptera), leafminers (Diptera: Agromyzidae) and whiteflies (Hemiptera: Aleyrodidae). Yellow Card 'Plastic' Traps measuring 125 x 77 mm, were made of hard plastic with pre-marked census squares on either side, and produced by Insect Science (Pty) Ltd, Nelspruit, South Africa (Fig. 2.6E). The pre-marked squares, each measuring 13 mm², account for 21% of the total surface area. Pests caught in the squares on both sides are counted and then multiplied by 5. Catch values are interpreted, for example, for thrips on Macadamia: between 0-10 = low; 11-20 = medium and 21-500 = high (Insect Science (Pty) Ltd, Nelspruit, South Africa).

As these Yellow Card Traps were to be removed weekly from the study sites and analysed at a later stage, and to reduce costs, yellow corrugated plastic card was cut to the same specifications and substituted for the Yellow Card Plastic Traps. Templates were made out of hard plastic to facilitate drawing of the pre-marked squares on the yellow corrugated plastic cards with a fibertipped, waterproof permanent marker. The cards were also marked with the site name and date the trap was set out. A tacky substance, Plantex™ (Chempack (Pty) Ltd, Suider Paarl, South Africa), was applied to both sides, at a thickness of about 1-2 mm, with a paint scraper. The card was then hung on the same trap stand from which the Sensus and False Codling Moth traps were hung.



Figures 2.6A-E. Traps used to monitor insect populations in *Capsicum baccatum* fields. **A & B.** Yellow Delta Traps. **C**. Sensus Trap. **D.** Yellow Bucket Funnel Trap. **E.** Yellow Card Plastic Trap. (Photo Credits: Insect Science (Pty) Ltd).

2.3.3 Trap deployment

Once the lands to be used for the study were chosen, each was measured and its rows counted to give an approximation of its size (Table 2.4). The size and shape of each land was recorded, and its centre calculated. Two monitoring trap stands were positioned 3m apart in the approximate centre of each land (Fig. 2.7). Traps were deployed at a height just above the canopy of the crop, and trap stands placed in a comparable position within each of the study sites where they remained throughout the study period.

Table 2.4 Calculation for the positioning and placement of the monitoring trap stands in each of the eight study sites.

Farm Name and Land	**Length**	**Width**	**Trap placement**	
			Across	**In**
Varnam Seedlings 1	140 m	80 rows	139 m	40 rows
Varnam Seedlings 2	300 m	44 rows	149 m	22 rows
Varnam Ratooned	322 m	100 rows	160 m	50 rows
Imjabulo Seedlings	159 m	56 rows	78 m	28 rows
Imjabulo Ratooned	159 m	82 rows	78 m	41 rows
Lower Melrose Seedlings*****	60 m	78 rows	29 m	35 rows
Brenthoek Seedlings*****	173 m	72 rows	85 m	31 rows
Brenthoek Ratooned	203 m	100 rows	100 m	50 rows

* Land was unevenly shaped and an approximation of the ‘centre’ was made.

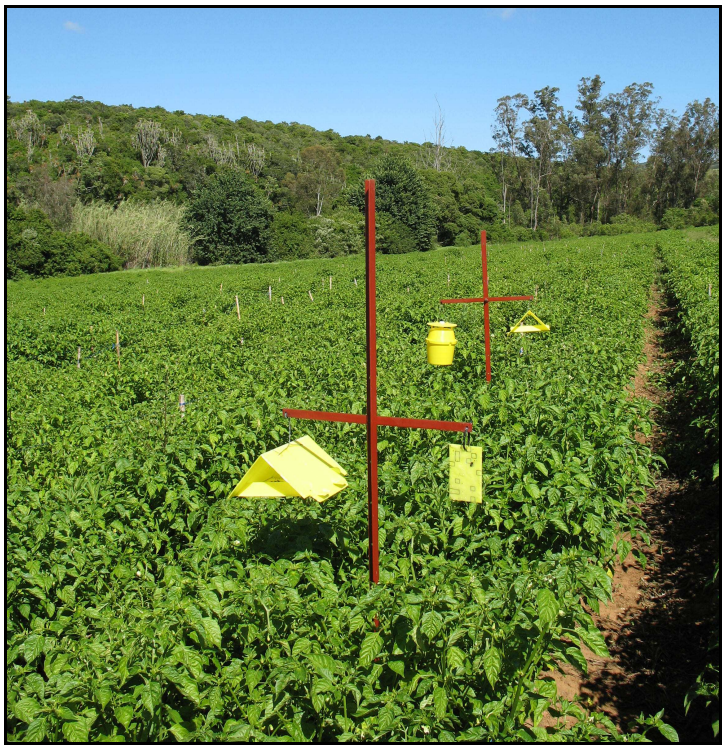


Figure 2.7 Monitoring trap stands positioned in the Varnam Seedling 2 *Capsicum baccatum* field.

Due to tractors and machinery requiring access to the fields for spraying, cultivating or overhead irrigation, it was necessary for the trap stands to be easily demountable and replacable in their original positions. The stands were a 50 cm crossbar of flat-bar and a 2 m-tall upright of angle iron (Figs. 2.7 and 2.8). Crossarm attachment holes were drilled 96 cm from the bottom of the upright and thereafter every 10 cm to enable the crossarm to be moved higher as the crop grew, or lowered as the plants died back or were ratooned, ensuring that the traps were always positioned just above the plant canopy. The crossarm had three holes drilled in it; one in the middle, the other two on either side. A bolt inserted through the middle hole was used to attach the crossarm to the upright using a spring washer and nut. A plastic cable tie or wire was threaded through the holes on each side of the 'arm' to affix the traps to the stand.

Because of their weight, the stands needed to be positioned at a suitable depth to prevent them toppling. The bottom of the stand was cut off at 45º to enable proper purchase in the

soil. Holes were dug 50 cm deep with a soil auger and lined with a 50 cm length of 50 mm PVC piping as a sleeve for the stand. About 4 cm of PVC piping was left projecting above the surface of the soil to provide a visual aid when replacing the stand. This facilitated the easy removal and remounting of the trap stands.

Figure 2.8 Trap stands positioned in the Brenthoek Ratooned *Capsicum baccatum* field.

2.4 Weekly sampling programme

As it was not possible to scout and collect traps from each of the sites in one day, they were split into two groups. The first group comprised the Brenthoek and Imjabulo sites, which were scouted and the monitoring trap catches collected every Monday, for the duration of the 52-week survey. The second group was made up of the Varnam and Lower Melrose sites, surveyed each Tuesday for the same 52 weeks. The sites in each group were scouted on a rotating basis to moderate the variable of time of day when the lands were scouted (e.g. diurnal insects tend to be more mobile towards mid-day than early in the morning).

2.4.1 Scouting

Scouting of the 15 plants was undertaken first. If the previous scouting visit was started from the western corner of the land, the next week the scouting would begin with the eastern corner, on a rotation basis, to ensure that data would be collected throughout the lands. Scouting commenced by counting ten rows along the edge of the field and ten paces into the field where a plant was sampled. This was repeated until a total of fifteen plants had been scouted. The same six techniques as in the pilot trial were employed. Any eggs or larvae encountered were collected for rearing and identification. Any live adult insects collected were killed in a killing-jar, using ethyl acetate, and placed in plastic vials marked with the plant number (which plant out of the fifteen plants sampled) and the site name.

Scouting data for the first nine weeks (21 & 22 of November 2005 to 16 & 17 of January 2006) were captured and analysed to evaluate whether the number of scouting techniques could be reduced. This would evaluate whether some of the techniques were in fact redundant when compared to actual insect community composition. It was established that most insects (79.8%) were collected using just two techniques: (i) manually working through the plant from the top down, checking both sides of the leaves for eggs and larvae which were recorded and collected in separately marked vials; and (ii) recording damage to the plant (i.e. thrips damage to leaves, number of pods stung, eaten or housing larvae), significantly more than were collected using a sweep net (14.1%), observation and picking off plant (3.9%), collecting from soil beneath plant (1.2%) and shaking plant over sheet (1.0%) ($\chi^2 = 1570.9$, 1 df, $p < 0.0001$). Thus, a modified scouting system was implemented from the 23rd of January 2006 using just the two most productive techniques.

Thrips damage was recorded and scored for each of the plants scouted throughout the study period. The extent of thrips damage caused to the leaves was assessed as a percentage and placed in one of four categories: No damage (0%); Low damage (<15%); Medium damage (<40%); and High damage (>40%).

At the beginning of April until the end of July 2006, bird damage to pods was noted and recorded. The birds were identified as Cape Canaries, *Serinus crithagra canicollis* Swainson, and were observed eating pods on *Capsicum* plants in the lands. *Serinus crithagra canicollis* feed on seeds taken directly from plants, particularly soft green seeds, and also eat fruits and some insects. They often occur in flocks of up to 500 when not breeding (Hockey *et al.* 2006). Damaged pods remained attached to the plant and no feeding on fallen fruit on the ground was observed (Fig. 2.9). The pods eaten by the birds showed no evidence of other damage (i.e. larvae or fungus). Pods were damaged at various stages, starting at when the pod was developed to full size but still green, through to when ripe and red, as long as the fruit was firm. Although this study deals with insects associated with *Capsicum*, it was decided that a record of the damage caused by these birds be kept as a comparison to check whether insects were indeed the main cause of damage to this crop.

Figure 2.9 Bird damage to *Capsicum baccatum* pods.

2.4.2 Trapping

After each scouting session, monitoring trap catches were collected and the traps refurbished as necessary. The sticky liners and Yellow Card Traps were placed in polythene bags and sealed. All samples were then taken to the laboratory for identification, recording and data capture.

Dispensers were replaced as soon as the level of the pheromone decreased substantially and only a small amount remained in the plastic dispenser. Dispensers were never ‘dry’ when removed; there was always a minimum residue present. Even though manufacturers advise that the efficacy of certain pheromone lures or baits last a certain period before replacement is required, in practice this is sometimes unrealistically long. Scouts should be trained, not only maintain and service the traps, but to also make informed decisions as to whether or not the baits need replacing. During the study, when some dispensers needed replacing, all of those ‘type’ of dispenser were replaced in each of the eight study sites (Appendix 3). The longest lasting dispenser throughout the study was the Lorelei® product. The design of the dispenser, where the release of the pheromone is through the wall of a polyethylene tube (PE-tube), ensures a constant rate of release as long as there is liquid in the tube. All pheromone dispensers were kept in a refrigerator before deployment in the sites.

III

RESULTS

Although the full catalogue of insects recovered from the various traps is given in Appendix 4, more detailed analyses were restricted to those insects shown to be phytophagous on *Capsicum* in the lands studied. These insects include the four principal pests: African Bollworm, False Codling Moth, Mediterranean Fruit Fly and thrips species which were consistently observed to cause damage to the fruit and leaves during the course of the year-long study. Likewise, these same species or their close relatives have previously been documented as pests of *Capsicum* in both the USA and particularly in north-eastern South Africa.

3.1 Comparison of the presence or absence of pest species caught using different trap types

The general log-linear analysis procedure is a method used to study the relationship between categorical variables. The procedure analyses the frequency counts of observations that fall into the cross-classification categories in a cross-tabulation or contingency table (Quinn & Keough 2002). Log-linear analyses were performed using STATISTICA 7.0 software to assess the presence or absence of each pest species among the different trap types and between ratooned and seedling lands. The response variable was the presence and absence of insects over 52 weeks, and trap type (1-5) was used as a factor for all eight lands. Therefore presence or absence was measured for 416 events (52 x 8) for each of the five traps, bringing the total to 2080 observations.

3.2 Comparison of the numbers of insects caught among the different trap types in the lands

The presence or absence and observed frequencies of the four main insect pests are shown together with percentages (cf. Tables 3.2, 3.3, 3.6, 3.7, 3.10, 3.11, 3.14 and 3.15). Log-linear analyses were conducted to test for differences in the numbers of insects caught among the different trap types and between all eight lands. The response variable was the number of insects caught over 52 weeks, and all eight lands and three traps were the two factors.

3.2.1 Total number of insect pests per trap

Figure 3.1 shows the total number of African Bollworm, False Codling Moth, Mediterranean Fruit Fly and thrips recovered from the traps during the course of the year for each land separately. It is apparent from the scale on the y-axis that African Bollworm occurred at a very low frequency in all eight lands, and similarly for False Codling Moth in five of the eight lands. Mediterranean Fruit Fly and thrips emerge as the most prevalent insects across all lands.

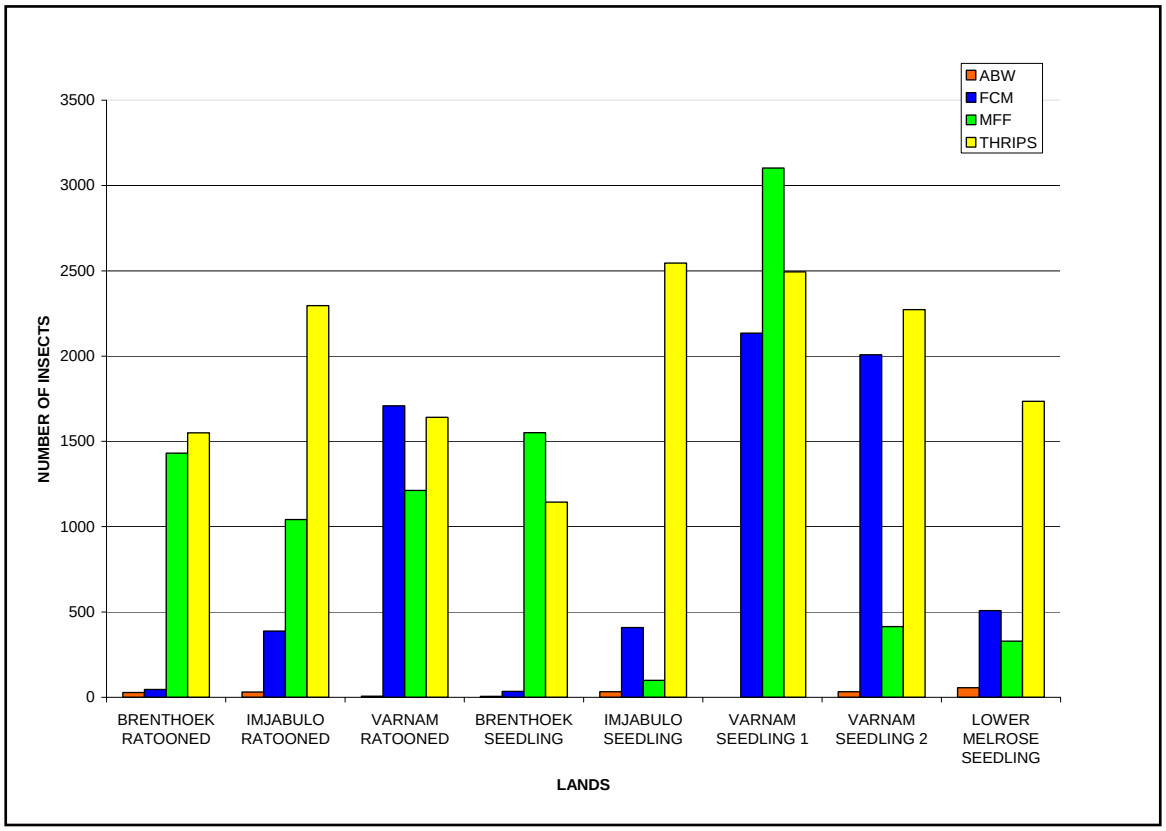


Figure 3.1 Total number of African Bollworm, False Codling Moth, Mediterranean Fruit Fly and thrips recovered from traps throughout the study period for all eight lands.

The study period of 52 weeks was divided up into 4 equal periods, which correspond to the farming cycle of planting, pod formation and harvest, each period consisting of 13 weeks. The periods were: 1) 21/11/05-19/2/06; 2) 20/2/06-21/5/06; 3) 22/5/06-20/8/06; and 4) 21/8/06-19/11/06. Means and standard errors of the number of insects caught during each period were calculated for each of the four pest insects over each of the eight lands (cf. Tables 3.4, 3.8, 3.12 and 3.16). Bar graphs plotting the means and standard errors of each insect pest per land for each of the eight lands are presented in Appendix 5.

3.3 Comparison of the numbers of insects caught among the different trap types by ratooned and seedling lands

Given the patterns in the frequency of occurrence of the four insect pests across all lands, it is of possible agronomic significance to sub-divide the lands into groups of ratooned

and seedling lands. Log-linear analyses were conducted to test for differences in the numbers of insects caught among the different trap types and between the ratooned and seedling lands.

3.3.1 Mean total number of the four insect species

The seasonal occurrence of all four insect species, African Bollworm, False Codling Moth, Mediterranean Fruit Fly was calculated as the mean number of adults per week, and the total number of thrips caught was used, for all lands throughout the 52 week study period (Fig. 3.2).

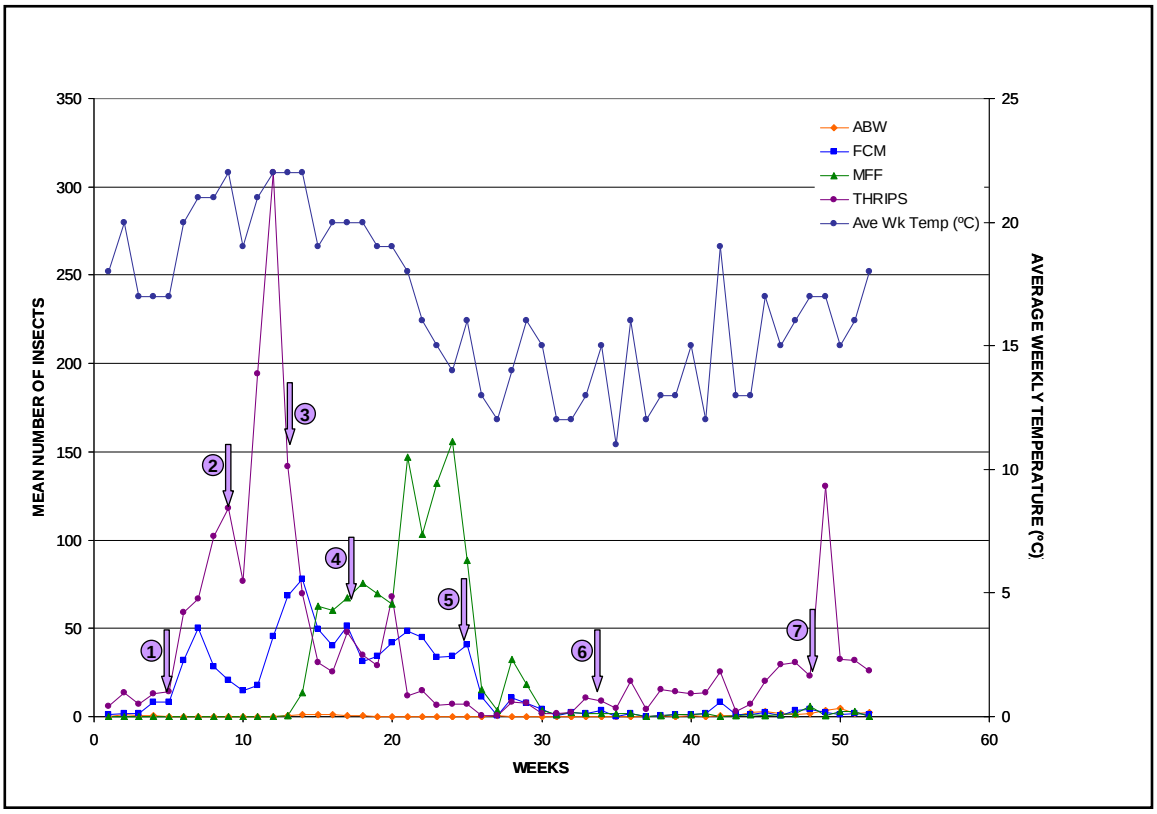


Figure 3.2 Weekly mean total number of adult insect pests for all eight lands. (Events: 1 = Pods mature in ratooned lands (19-25 December); 2 = Beginning of harvest in ratooned lands (16-22 January); 3 = Pods mature in seedling lands (13-19 February); 4 = Beginning of harvest in seedling lands (13-19 March); 5 = End of harvest in ratooned lands (8-14 May); 6 = End of harvest in seedling lands (3-9 July); 7 = Plants start flowering in ratooned lands (17-22 October)).

The mean number of thrips and False Codling Moth began increasing around Week 5 (19-25 December 2005). This occurrence was expected with regard to thrips populations, as temperatures increased and host plant matter became available (i.e. buds, blossoms, terminal growth with young leaves). It was surprising however that False Codling Moth occurred at this time as there was no ripening or suitably sized pods for oviposition. Mediterranean Fruit Fly numbers only began increasing during Week 14 (20-26/2/2006). Fruit changed colour towards the end of January and by the 20th of February ripe fruit started to appear. During the fruiting period, when pods ripen, seems to be the prime time at which Mediterranean Fruit Fly populations cause damage in *Capsicum* lands. Throughout the study period the mean number of adult African Bollworm was nominal (range of mean 0.00-4.75; Fig. 3.2).

The larval mean frequencies were calculated for African Bollworm, False Codling Moth and Mediterranean Fruit Fly, and are shown in Fig. 3.3. The bulk of the harvest was collected from the end of February through to May. Fruit production and harvesting was reduced towards mid-June around Week 30 (12-18 June 2006), as the growing season ended.

At the end of the season, growers either ploughed in their lands (Varnam Ratooned: Week 19; Brenthoek Seedling: Week 39) or ratooned their crops (Brenthoek Ratooned: Week 39; Varnam Seedling 1, Imjabulo Ratooned and Seedling: Week 35; Varnam Seedling 2: Week 36; and Lower Melrose Seedling: Week 38).

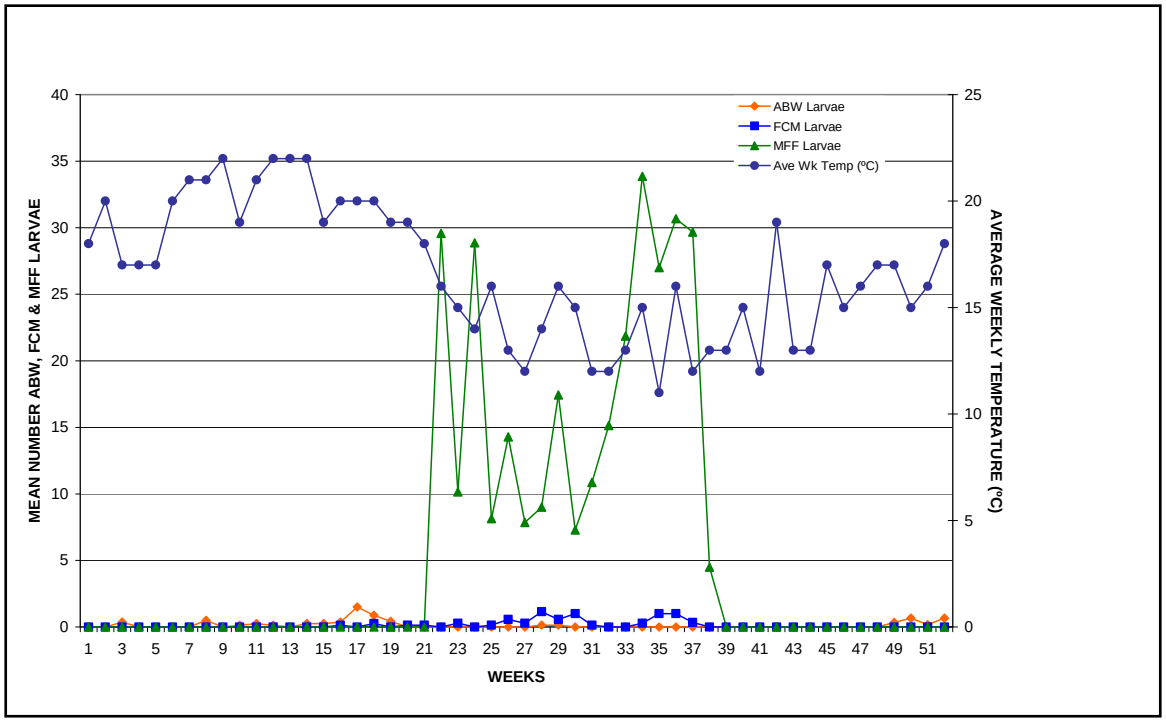


Figure 3.3 Weekly mean number of African Bollworm, False Codling Moth and Mediterranean Fruit Fly larvae for all eight lands.

3.4 Comparison of the numbers of pods damaged in the lands by insects, secondary damage and birds

The scouting of 15 plants per land was undertaken on a weekly basis throughout the study period and records were kept of all damage to pods (Table 3.1). The number of pods damaged per land by insects, secondary damage (i.e. fungi and bacteria) and birds was analysed using a Chi-Square analysis (Fig. 3.4).

Table 3.1 Total number of pods damaged on 15 plants per land for all lands over the 52 week study period.

LAND	Insects	Microbes	Birds	Total Damage
Brenthoek Ratooned	718	811	51	1580
Imjabulo Ratooned	1188	87	129	1404
Varnam Ratooned	242	83	0	325
Brenthoek Seedling	940	114	270	1324
Imjabulo Seedling	362	26	61	449
Varnam Seedling 1	958	97	1011	2066
Varnam Seedling 2	511	68	836	1415
Lower Melrose Seedling	960	107	314	1381
Total	**5879**	**1393**	**2672**	**9944**
Percentage	**59.1%**	**14%**	**26.9%**	**100%**

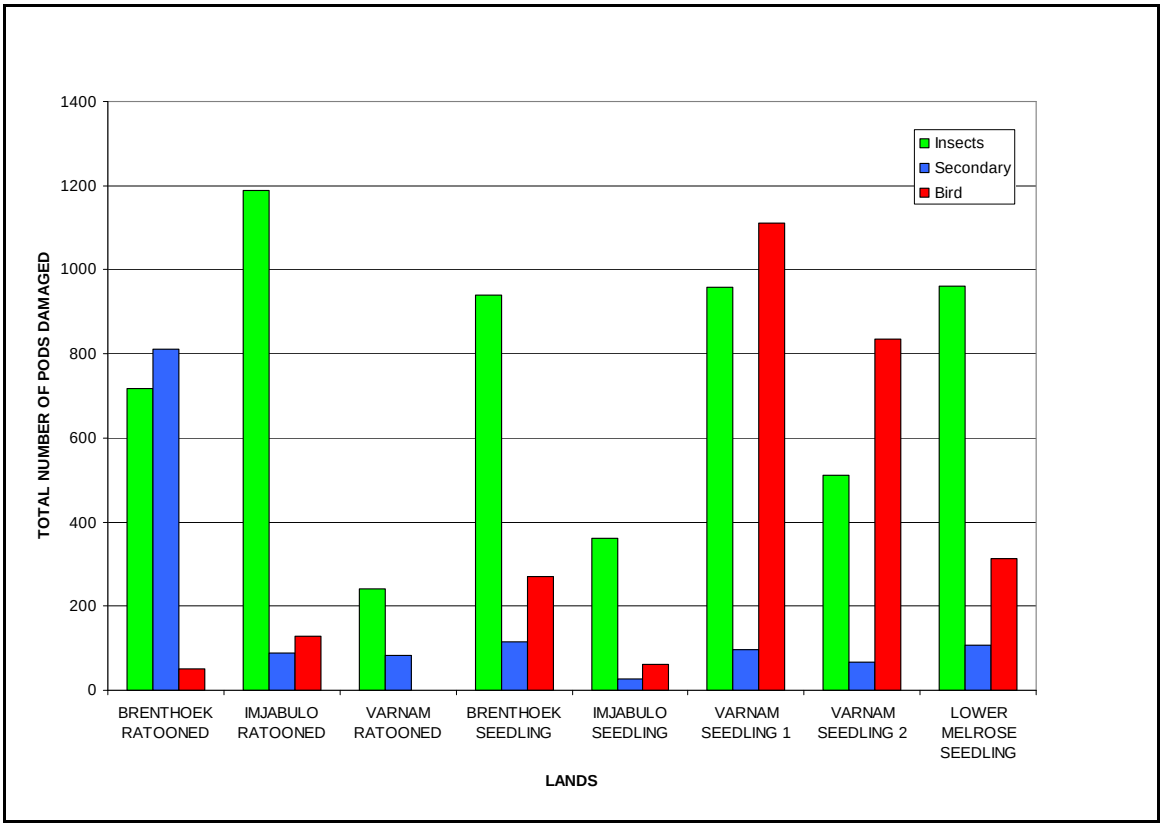


Figure 3.4 Total number of pods damaged on 15 plants per week by insects, secondary damage and birds for all lands over the 52 week study period.

3.4.1 Insect damage

There were significant differences among the lands in the numbers of pods with insect damage (χ^2 = 1061.7, 7 df, p = < 0.001). The Varnam Ratooned and Imjabulo Seedling lands had significantly fewer pods damaged by insects, and Imjabulo Ratooned had significantly more pods damaged than the other lands. A contributing factor to the low number of pods damaged in the Varnam Ratooned land has to do with the land being ploughed in after Week 19.

3.4.2 Secondary damage

Significant differences among the lands were also noted in the numbers of pods with secondary damage (χ^2 = 2692.2, 7 df, p = < 0.001). Brenthoek Ratooned had significantly more pods damaged by fungi and bacteria than any of the other lands and Imjabulo Seedlings had significantly fewer pods damaged.

3.4.3 Bird damage

There were significant differences among the lands for pods damaged by birds (χ^2 = 3062.9, 7 df, p = < 0.001). The lands Brenthoek Ratooned, Varnam Ratooned and Imjabulo Seedlings had significantly fewer damaged pods due to birds; the Varnam Ratooned having been ploughed in. Varnam Seedling 1 and Varnam Seedling 2 lands however had significantly more pods damaged.

3.4.4 Overall damage

The distribution of damage on pods caused by insects, secondary damage and birds significantly differed among the lands (χ^2 = 4016.0, 14 df, p = < 0.001). In terms of total damage, 59.1% is attributable to insects, 26.9% to birds and 14.0% to secondary damage.

3.5 African Bollworm *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae)

3.5.1 Introduction

Helicoverpa armigera is a cosmopolitan pest that damages a wide range of plants including fibre, fodder, food, horticultural and oilseed crops grown for agricultural purposes. It is an economically significant pest (Annecke & Moran 1982, Fitt 1989, APHIS 2007a) and was ranked top agricultural pest out of 101 of the most important phytophagous insects on cultivated crops in South Africa (Moran 1983). Bell & McGeoch (1996) confirmed the status of *H. armigera* as the most important lepidopteran pest in South Africa. Suitable hosts belong to both the dicotyledon and monocotyledon groups of plants and include fruit, grain, vegetables, cultivated crops, garden ornamentals, a wide variety of garden flowers and a number of indigenous and invasive plants (Annecke & Moran 1982, Abate *et al*. 2000, CAB 2004).

The success of *Helicoverpa* species as polyphagous pests stems from a number of physiological, behavioural and ecological characteristics. Populations are able to exploit unfavourable habitats through their wide range of host plants and larvae are able to adapt physiologically to various secondary metabolites produced by the plants. Other factors by which they adjust to the seasonality of their habitat include the extreme mobility of adults, high fecundity and the ability to undergo facultative diapause in the event of low temperatures or drought (Fitt 1989). The incidence and severity of *H. armigera* damage varies on a temporal scale and between crops and regions, making it an unpredictable pest (Cherry *et al*. 2003).

African Bollworm are the most injurious of insect pests in agricultural systems in South Africa, therefore the nominal occurrence of both adults and larvae during this study was somewhat unexpected.

3.5.2 Results

3.5.2.1 Comparison of the presence or absence of pest species caught using different trap types

There was a significant trap effect for the number of African Bollworm (χ^2 = 405.2, 4 df, p < 0.001). Considerably more African Bollworm were observed using the Yellow Bucket Funnel Trap, which can be attributed to the fact that this trap was used with a volatile lure dispenser (Table 3.2).

Table 3.2 Log-linear analysis for African Bollworm (ABW) observed frequency: presence or absence by traps.

	Yellow Card	**Yellow Delta Traps**		**Sensus Trap**	**YBF Trap**	**Total**
		MFF	**FCM**			
Absent	415	411	412	416	307	1961
Present	1	5	4	0	109	119
Total	416	416	416	416	416	2080

Adult African Bollworms were present 109 times in the Yellow Bucket Funnel Trap out of 416 observations.

3.5.2.2 Comparison of the numbers of insects caught among the different trap types in the lands

The Yellow Card and Sensus traps caught too few African Bollworm adults to be included in the analysis. In all eight lands the percentage occurrence of African Bollworm was greater than 90% in the YBF Traps, indicating that the frequency distributions of African Bollworm among the lands were not significantly different (χ^2 = 12.9, 14 df, p = 0.54, Table 3.3, Fig. 3.5). However, significantly more African Bollworm adults were caught in YBF Traps on VR and LMS lands than on the other six lands (χ^2 = 115.1, 7 df, p < 0.001).

Table 3.3 African Bollworm observed frequency and percentages for traps by lands.

LAND	Yellow Delta Traps		YBF Trap	Total # Insects	Row Totals
	MFF	FCM			
BR	0	0	27	27	
Row %	0.0	0.0	100.0		100%
Column %	**0.0**	**0.0**	**10.7**		
IR	2	0	28	30	
Row %	6.7	0.0	93.3		100%
Column %	**40.0**	**0.0**	**11.1**		
VR	0	0	6	6	
Row %	0.0	0.0	100.0		100%
Column %	**0.0**	**0.0**	**2.4**		
BS	0	0	5	5	
Row %	0.0	0.0	100.0		100%
Column %	**0.0**	**0.0**	**2.0**		
IS	0	0	32	32	
Row %	0.0	0.0	100.0		100%
Column %	**0.0**	**0.0**	**12.6**		
VS 1	1	1	72	74	
Row %	1.4	1.4	97.2		100%
Column %	**20.0**	**25.0**	**28.4**		
VS 2	1	0	31	32	
Row %	3.1	0.0	96.9		100%
Column %	**20.0**	**0.0**	**12.2**		
LMS	1	3	52	56	
Row %	1.8	5.3	92.9		100%
Column %	**20.0**	**75.0**	**20.6**		
Column Totals	5	4	253	262	
Column %	**100%**	**100%**	**100%**		

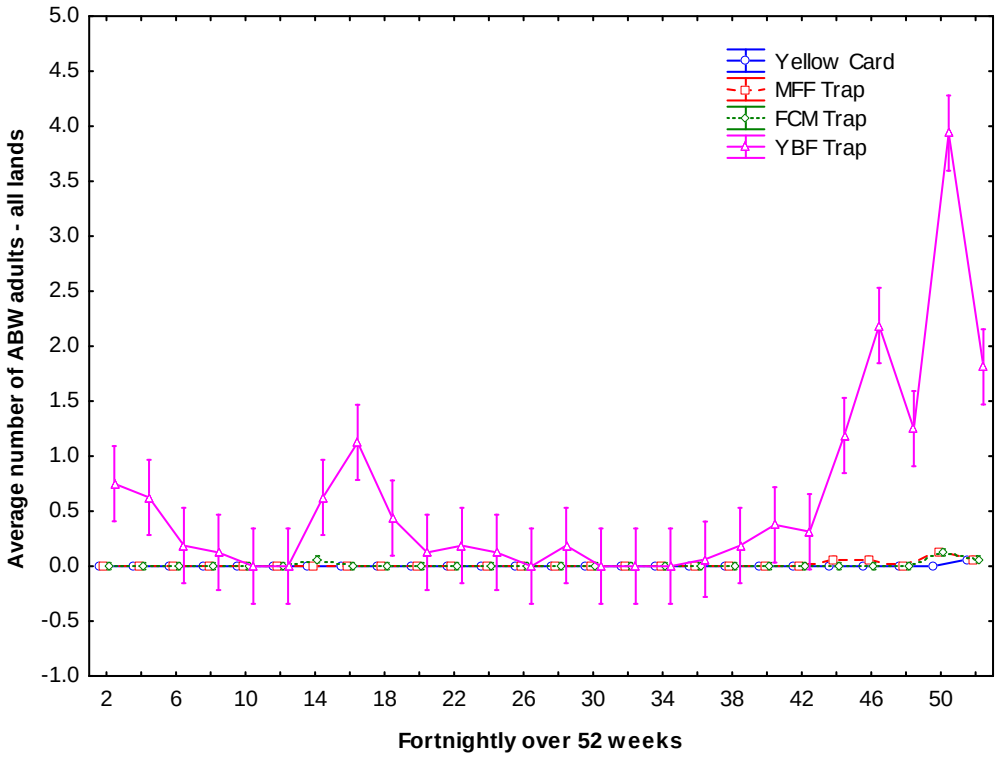


Figure 3.5 Mean number of African Bollworm caught for all eight lands throughout the study period, showing trap effect.

3.5.2.3 Total number of African Bollworm

The total number of African Bollworm recovered from the traps during the course of the year, for each of the eight lands, is shown in Fig. 3.6.

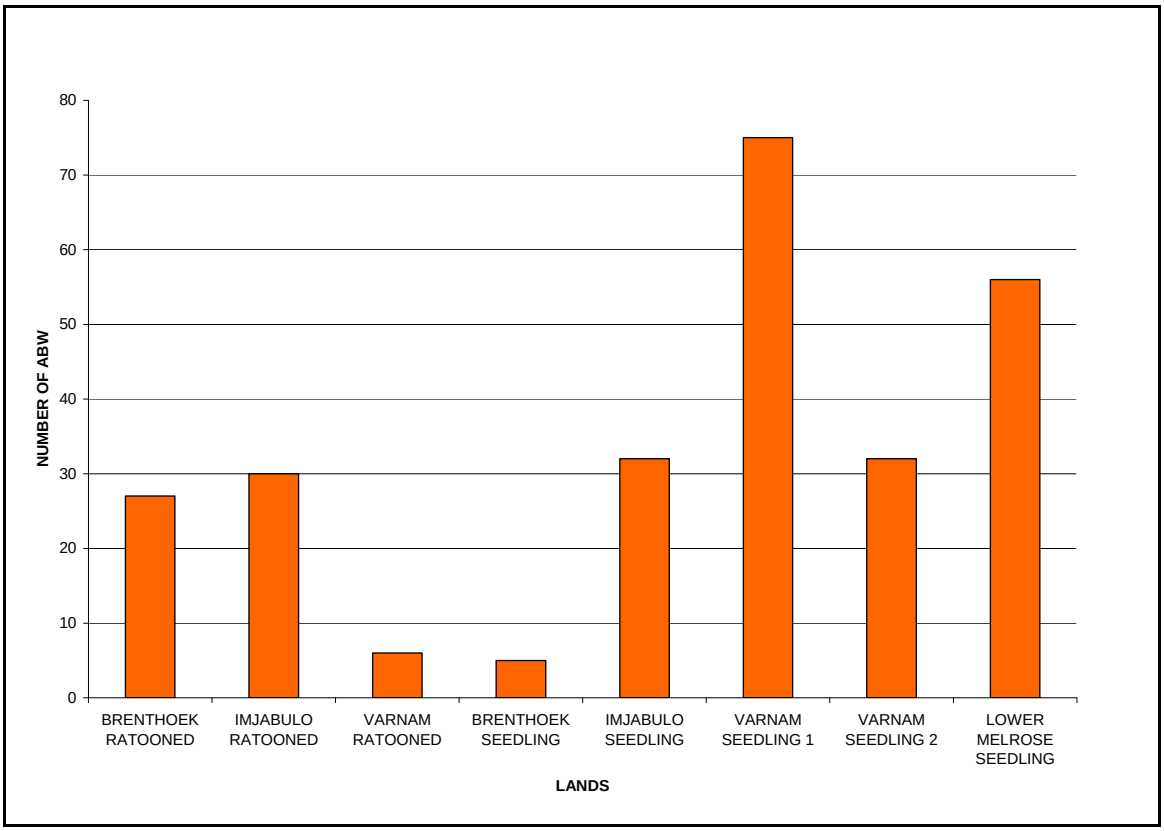


Figure 3.6 Total number of African Bollworm adults recovered from traps throughout the study period for all eight lands.

The study period of 52 weeks was divided up into 4 equal periods (c.f. Section 3.2). Means and standard errors of the number of African Bollworm moths caught during each period were calculated over each of the eight lands (Table 3.4). Bar graphs plotting the means and standard errors of each insect pest per land for each of the eight lands are given in Appendix 5.

Table 3.4 African Bollworm means and standard errors over four periods for all lands.

	BR		IR		VR		BS		IS		VS 1		VS 2		LMS	
Period	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
1	0.38	0.21	0.38	0.18	0.15	0.10	0.08	0.08	0.46	0.24	0.31	0.17	0.15	0.15	0.38	0.18
2	0.31	0.17	0.15	0.10	0.31	0.13	0.31	0.13	0.38	0.27	0.92	0.43	0.38	0.18	0.31	0.13
3	0.31	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.10	0.15	0.10	0.08	0.08
4	1.08	0.49	1.77	0.57	0.00	0.00	0.00	0.00	1.62	0.51	4.38	0.90	1.77	0.47	3.54	1.03

Period 1 = 21/11/05-19/2/06; 2 = 20/2/06-21/5/06; 3 = 22/5/06-20/8/06; 4 = 21/8/06-19/11/06.

3.5.2.4 Comparison of the numbers of insects caught among the different trap types by ratooned and seedling lands

The Mediterranean Fruit Fly, False Codling Moth and Yellow Bucket Funnel traps were included in the analysis. The log-linear analysis results revealed that the frequency distributions of African Bollworm between the ratooned and seedling lands were not significantly different (χ^2 = 2.0, 2 df, p = 0.375, Table 3.5). However, significantly more African Bollworm adults were caught in the three traps on seedling lands than on ratooned lands (χ^2 = 70.6, 1 df, p < 0.001). African Bollworm was approximately three times as abundant in seedling lands compared to ratooned lands.

Table 3.5 African Bollworm observed frequency and percentage for traps by type of land.

LAND	**Yellow Delta Traps**		**YBF Trap**	**Total # Insects**	**Row Totals**
	MFF	**FCM**			
Ratooned	2	0	61	63	
Row %	3.2	0.0	96.8		100%
Column %	**40.0**	**0.0**	**24.1**		
Seedling	3	4	192	199	
Row %	1.5	2.0	96.0		100%
Column %	**60.0**	**100.0**	**75.9**		
Column Totals	5	4	253	262	
Column %	**100%**	**100%**	**100%**		

3.5.2.5 Mean total number of African Bollworm for all lands over the study period

To convert weeks to calendar dates, refer to Appendix 6.

The seasonal occurrence of adult African Bollworm was calculated as the mean number of adults per week for all of the eight lands throughout the 52 week study period (Fig. 3.7). Adult numbers were extremely low with a total of 262 individuals caught throughout the year. Four minor 'peaks' occurred: 1) Week 2 (28 November-4

December); 2) Week 15 (27 February-5 March); 3) Week 45 (25 September-1 October); and 4) Week 50 (30 October-5 November).

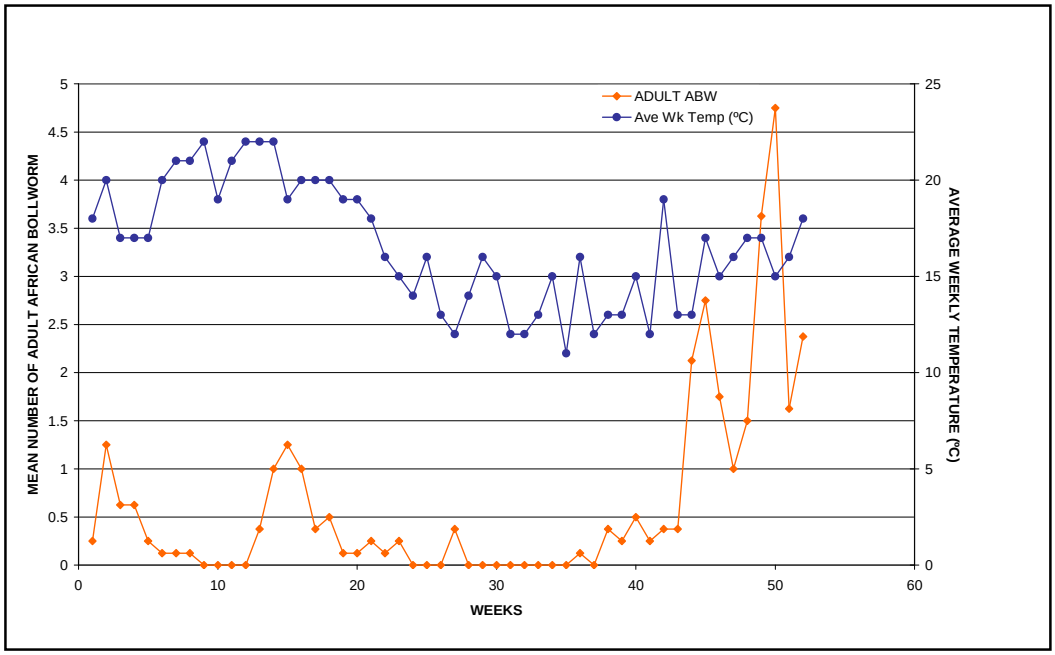


Figure 3.7 Weekly mean number of adult African Bollworm for all eight lands.

The temporal occurrence of the four 'peaks' is not entirely consistent with the African Bollworm life cycle (cf. Section 3.5.3). This may have been caused by the extremely low number of African Bollworm and that there were in fact no 'peaks'. Data from the ratooned and seedling lands were combined which perhaps caused the length of life cycles to be extended due to an overlap.

3.5.2.6 Mean total number of African Bollworm larvae observed through scouting for all lands over the study period

Scouting results show a total number of 53 African Bollworm larvae observed throughout the study period (Fig. 3.8).

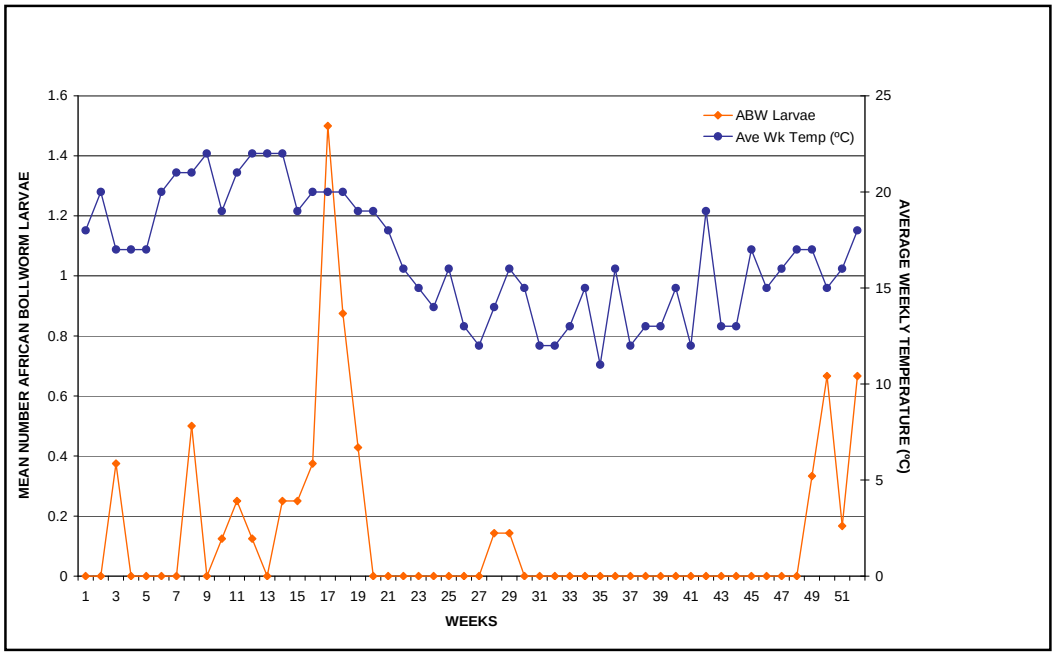


Figure 3.8 Weekly mean number of African Bollworm larvae for all eight lands.

3.5.3 Discussion

Adults are able to migrate over vast distances to locate food resources as and when host plants become available. Movement within and between cropping systems and wild hosts situated in close proximity is also important because this provides *H. armigera* with a constant supply of sites for oviposition and feeding (Fitt 1989). Most flight activity occurs at night and on the first night after eclosion short flights of less than 200m are made for feeding (and perhaps orientation to resources), before the adults settle again, usually within the same habitat (Lingren *et al.* 1988). Subsequent flights usually commence at dusk and last 1-2 hours, during which time adults disperse locally, feed, mate and oviposit. There is no further activity until around midnight when males take flight to mate, which period lasts until 03h00-04h00. During this time females are sedentary, releasing their pheromone plumes from near the top of plants so that wind currents can disperse them (Lingren *et al.* 1982, Topper 1987, Fitt 1989).

Three distinct types of flight by *Helicoverpa* species were described by Farrow & Daly (1987): short-range, long-range and migratory flights, which involve different behavioural patterns and play a significant role in the exploitation and colonization of

agroecosystems (Fitt 1989). Short-range flights take place shortly after dusk, just above the host plant canopy, and facilitate mating, oviposition, feeding and seeking shelter. Distances covered within the habitat are 100-1000m. For long-range movement adults fly about 10m above canopy height and make use of prevailing winds for dispersal for distances of 1-10 km (Farrow & Daley 1987). These flights occur when the population moves between crops to find alternative feeding and oviposition sites. Migratory flights occur above the normal flight boundary layer at altitudes of up to 1-2 km. The migratory population benefits from synoptic-scale wind systems which can carry them for several hours and transmigrations of hundreds of kilometres can occur (Drake *et al*. 1981, Drake & Farrow 1985). A distinct feature indicative of migratory behaviour is the suppression of feeding responses to external stimuli which would otherwise be attractive (Kennedy 1986, Fitt 1989).

The high fecundity of many noctuids is an important factor contributing to their pest status. This, combined with a short generation time, enables the rapid growth of populations. Fecundity is influenced by temperature and humidity as well as adequate larval and adult nutrition. Laboratory studies estimate that a female lays between 1000 and 1500 eggs in her reproductive lifetime of about 8-10 days (Fye & McAda 1972). However, according to Fitt (1989), it is not obvious how relevant laboratory estimates are as there are no estimates of realised fecundity in the field. Computer simulation models have put fecundity in the field to be from 500 to 3000 eggs per female, depending on temperature and host plant availability (Knipling & Stadelbacher 1983).

Facultative diapause enables *H. armigera* to adapt to environmental conditions and thereby extend their geographic range. The prevalence of *H. armigera* undergoing diapause increases with increasing latitude (Fitt 1989). In subtropical and temperate regions most individuals, but not all, undergo diapause, and tropical populations breed continuously but only a small proportion of pupae may diapause (Reed 1965, Hackett & Gatehouse 1982).

Females lay their eggs singly on various plant structures (van den Berg & Cock 1993). Larvae are carnivorous and cannibalistic, which may explain singly-laid eggs (van den Berg & Cock 1993). Eggs are spherical with diameters of approximately 0.43 mm. When newly-laid, they are whitish in colour, changing to dark brown just before they

hatch, which takes between 3-4 days at optimal temperatures (Vermeulen & Bedford 1998) (Fig. 3.9A).

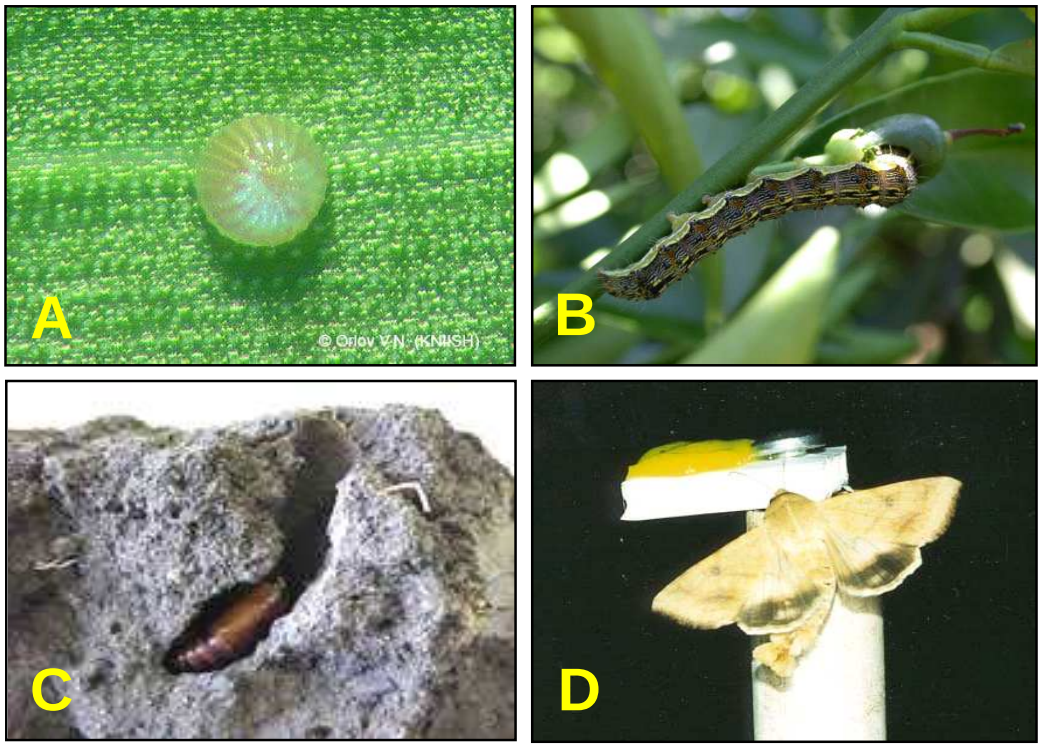
Neonate larvae usually consume the eggshell, except for the base, which is left on the substrate, before searching for a flower or bud on which to feed. Larvae pass through six, sometimes seven, instars. The first two instars are yellow to reddish-brown. Later instars acquire their characteristic pattern of three longitudinal dark bands interspersed with lighter stripes. The variation in pigmentation is however quite diverse, ranging from shades of green, reddish-yellow, reddish-brown to a dark blackish. Larvae take 2-3 weeks to develop and the final instar grows to about 40 mm long. Larvae drop to the ground and enter a pre-pupal stage which lasts about 3 days, during which they burrow to a depth of 170-180 mm in the soil and spin a delicate cocoon (van den Berg 2001) (Fig. 3.9B).

Pupae are dark brown and take 12-23 days to reach eclosion, depending on ambient temperature. In early winter the pupal stage will usually be protracted by diapause (Parry-Jones 1936, cited in Bedford *et al*. 1989; Reed 1965, Hackett & Gatehouse 1982, Fitt 1989) (Fig. 3.9C).

There is a difference in colouration between male and female adults. Males have a pale olive-grey head and reddish-brown antennae, and the thorax and forewings are a dark olive-grey. Forewings have a brown apical tinge with a small dark spot half-way along the discal cell and a larger dark brown spot at the apex of the discal cell. An irregular light brown band extends across the apical third of the wing. The hind wing is white with a dark brown band on the apical border. Females are generally darker and their thorax and forewings are brown tinged with red. The markings on their wings are also darker and more distinct. Adult wing spans measure 35-40 mm, their bodies are stout, broad at the thorax and then tapering and 14-18 mm long (Vermeulen & Bedford 1998, van den Berg 2001) (Fig. 3.9D).

Field populations of *H. armigera* adults emerge in large numbers in spring, coinciding with the time at which most of their host plants flower. After eclosion, adults feed on nectar. Females require a nectar meal before oviposition. Females in a field environment can lay on average anywhere between 730-1000 eggs during a lifetime.

Oviposition occurs between 20h00-23h00 and eggs are usually laid on the top two-thirds of a plant. If oviposition takes place on a leaf, the egg is usually laid on the upper surface. Adults are short-lived and survive for a period of between 2-3 weeks. In areas with mild winter temperatures, *H. armigera* can produce 2-8 generations per year depending on temperature, host sequence and host suitability. A high percentage of *Helicoverpa armigera* populations do not undergo diapause in tropical regions of Africa (Annecke & Moran 1982, APHIS 2007a).



Figures 3.9A-D. A. Egg; **B.** Larva feeding on citrus; **C.** Pupa in burrow; **D.** Male adult at trap. (Photo Credits: **A.** V.N. Orlov (KNIISH); **B.** D. Papacek (www.bugsforbugs.com.au). **C.** Queensland Government, Australia. **D.** D. Britton, University of New England, Australia).

3.6 False Codling Moth *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae)

3.6.1 Introduction

The distribution of *T. leucotreta* extends across both tropical and southern temperate Africa: Senegal, Burkina Faso, Ivory Coast, Togo, Ethiopia, Uganda, Zimbabwe, Mozambique, South Africa, Swaziland, Mauritius and Madagascar (Reed 1974, Hill 1975, Catling & Aschenborn 1978). It has been regarded as a major pest of economic importance in South African citrus and other fruit for a century (Fuller 1901, cited by van den Berg 2001; Howard 1909, cited by van den Berg 2001). *Thaumatotibia leucotreta* was first reported as a pest on citrus in KwaZulu-Natal by Fuller (1901, cited by van den Berg 2001), and subsequently from other parts of South Africa by Howard (1909, cited by van den Berg 2001). A study on its biology, ecology and control on citrus and other hosts was conducted as early as 1921 by Gunn. In an extensive survey of the most important phytophagous pests in South Africa, Moran (1983) ranked *T. leucotreta* as 33rd in pest status and 14th in lepidopteran pest status. However, later research conducted by Bell & McGeoch (1996) place *T. leucotreta* in 9th position in lepidopteran pest ratings.

Thaumatotibia leucotreta has a wide range of indigenous host plants that act as reservoirs or refuges from which it is able to invade cultivated crops (Catling & Aschenborn 1978). Pearson & Maxwell-Darling (1958, cited in van den Berg 2001) identified 12 indigenous and eight exotic plants as *T. leucotreta* hosts in central Africa. Similarly, Schwartz (1981, cited in van den Berg 2001) recorded 21 cultivated and 14 indigenous host plants for *T. leucotreta* in South Africa. Although *T. leucotreta* has become a major pest on cotton in equatorial Africa (Angelini & Labonne 1970, cited in van den berg 2001, Reed 1974), Catling & Aschenborn (1978) reported that there was no record of *T. leucotreta* on cotton grown in South Africa. However, by 1982 it is a minor sporadic pest on cotton (Annecke & Moran 1982).

Extensive research on tropical, subtropical and some temperate *T. leucotreta* host plants have been conducted by Gunn (1921), Daiber (1976), Catling & Aschenborn (1978), Schwartz (1981, cited in van den Berg 2001), Annecke & Moran (1982), De

Villiers *et al*. (1987a) and Kroon (1999). *Thaumatotibia leucotreta* also attacks acorns (Annecke & Moran 1982), so that oak trees can be significant refuges for populations when preferred host plants are otherwise out of season.

A high number of adult False Codling Moth were attracted to the pheromone-based traps in the lands, but when compared to larval data collected by scouting, this proved to be a false-positive result.

3.6.2 Results

3.6.2.1 Comparison of the presence or absence of pest species caught using different trap types

There was a significant trap effect for the number of False Codling Moth (χ^2 = 1215.4, 4 df, $p < 0.001$). Significantly more occurrences of False Codling Moth were observed using the False Codling Moth Trap with a False Codling Moth pheromone-based lure (Table 3.6).

Table 3.6 Log-linear analysis for False Codling Moth observed frequency: presence or absence by traps.

	Yellow Card	**Yellow Delta Traps**		**Sensus Trap**	**YBF Trap**	**Total**
		MFF	**FCM**			
Absent	416	409	143	416	416	1800
Present	0	7	273	0	0	280
Total	416	416	416	416	416	2080

False Codling Moth adults were present 273 times in the False Codling Moth Trap out of 416 observations.

3.6.2.2 Comparison of the numbers of insects caught among the different trap types in the lands

Only the Mediterranean Fruit Fly and False Codling Moth traps were included in the analysis. No False Codling Moth adults were caught in the other traps (Yellow Card,

Sensus and Yellow Bucket Funnel traps). The frequency distributions of False Codling Moth across the lands were significantly different ($\chi^2 = 24.6$, 7 df, $p < 0.001$, Fig. 3.10). Significantly more False Codling Moth were caught in the False Codling Moth traps on VR, VS 1 and VS 2 lands than on the other lands (Table 3.7).

Table 3.7 False Codling Moth observed frequency and percentages for traps by lands.

LAND	**Yellow Delta Traps**		**Total # Insects**	**Row Totals**
	MFF	**FCM**		
BR	1	45	46	
Row %	2.2	97.8		100%
Column %	**12.5**	**0.6**		
IR	1	387	388	
Row %	0.3	99.7		100%
Column %	**12.5**	**5.3**		
VR	1	1708	1709	
Row %	0.1	99.9		100%
Column %	**12.5**	**23.6**		
BS	2	32	34	
Row %	5.9	94.1		100%
Column %	**25.0**	**0.4**		
IS	0	409	409	
Row %	0.0	100.0		100%
Column %	**0.0**	**5.7**		
VS 1	2	2132	2134	
Row %	0.1	99.9		100%
Column %	**25.0**	**29.5**		
VS 2	0	2008	2008	
Row %	0.0	100.0		100%
Column %	**0.0**	**27.8**		
LMS	1	508	509	
Row %	0.2	99.8		100%
Column %	**12.5**	**7.0**		
Column Totals	8	7229	7237	
Column %	**100%**	**100%**		

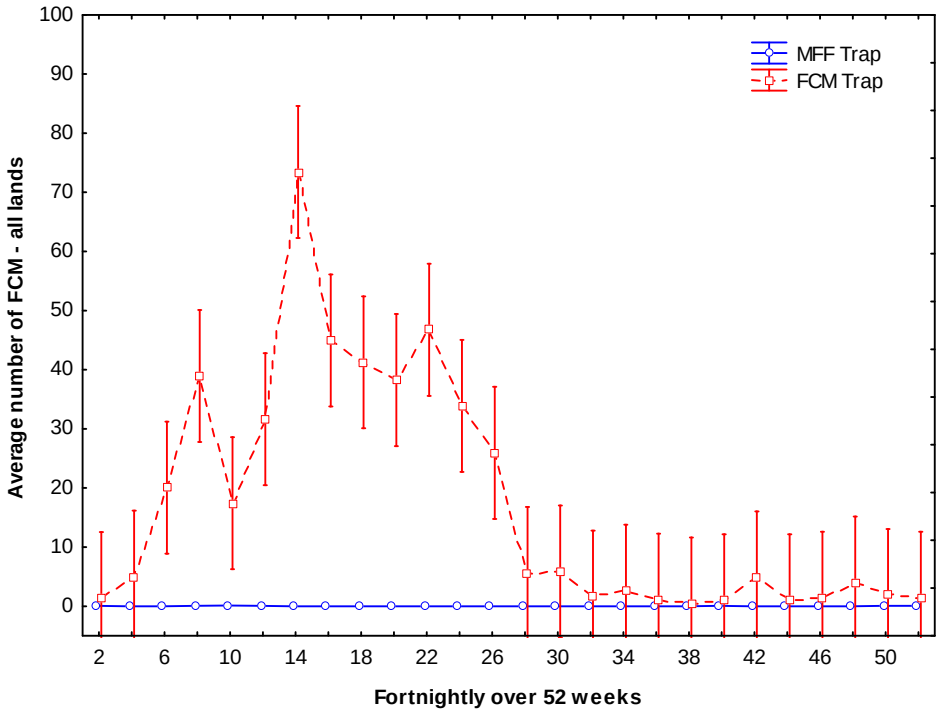


Figure 3.10 Mean number of False Codling Moth caught for all eight lands throughout the study period, showing trap effect.

3.6.2.3 Total number of False Codling Moth

The total number of False Codling Moth recovered from the traps during the course of the year, for each of the eight lands, is shown in Fig. 3.11.

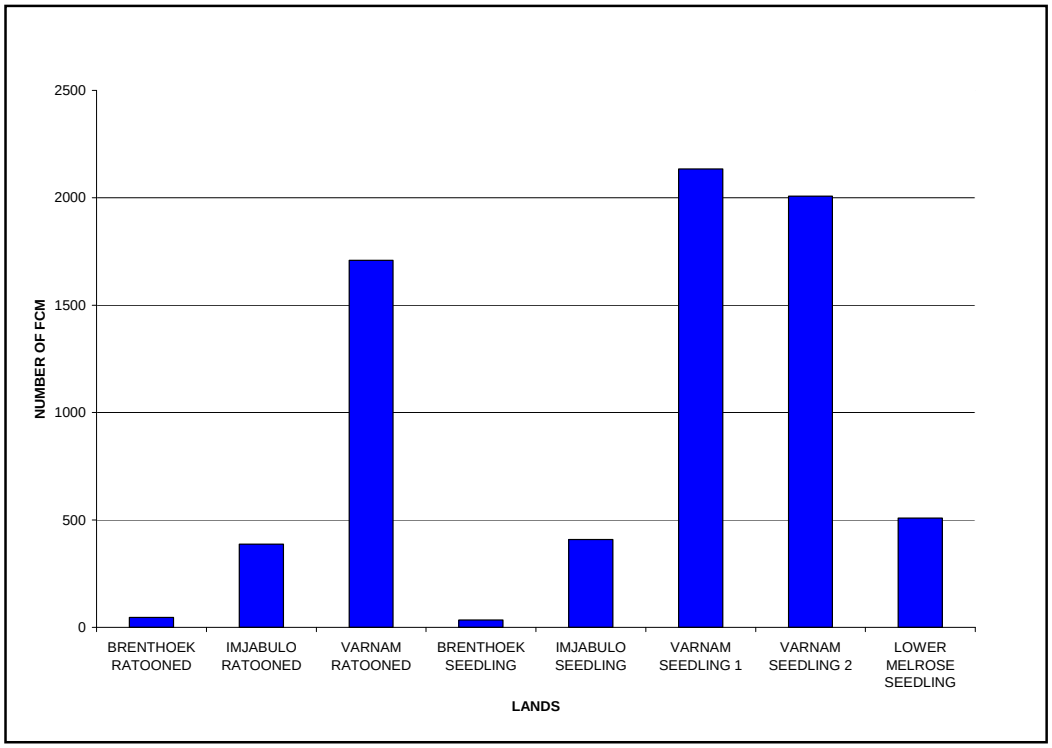


Figure 3.11 Total number of False Codling Moth recovered from traps throughout the study period for all eight lands.

The study period of 52 weeks was divided up into 4 equal periods (cf. Section 3.2). Means and standard errors of the number of False Codling Moth caught during each period were calculated over each of the eight lands (Table 3.8). Bar graphs plotting the means and standard errors of each insect pest per land for each of the eight lands are given in Appendix 5.

Table 3.8 False Codling Moth means and standard errors over four periods for all lands.

	BR		IR		VR		BS		IS		VS 1		VS 2		LMS	
Period	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
1	0.77	0.21	8.62	2.39	77.38	21.46	0.62	0.17	9.62	2.67	30.46	8.45	40.92	11.35	15.15	4.20
2	1.31	0.36	18.85	5.23	54.08	15.00	1.46	0.41	19.85	5.50	115.08	31.92	101.31	28.10	20.46	5.68
3	0.69	0.19	1.54	0.43	0.00	0.00	0.54	0.15	1.46	0.41	9.08	2.52	6.62	1.83	2.00	0.55
4	0.77	0.21	0.85	0.23	0.00	0.00	0.00	0.00	0.54	0.15	9.54	2.65	5.62	1.56	1.54	0.43

Period 1 = 21/11/05-19/2/06; 2 = 20/2/06-21/5/06; 3 = 22/5/06-20/8/06; 4 = 21/8/06-19/11/06

3.6.2.4 Comparison of the numbers of insects caught among the different trap types by ratooned and seedling lands

Trap catches for False Codling Moth were only recorded in the Mediterranean Fruit Fly and False Codling Moth traps, the data from which were included in this analysis. In both the ratooned and seedling groups the percentage occurrence of False Codling Moth was almost 100% in the False Codling Moth Traps indicating that the frequency distributions of False Codling Moth between the ratooned and seedling lands were not significantly different ($\chi^2 = 0.24$, 1 df, $p = 0.625$, Table 3.9). However, approximately 2.5 times more False Codling Moth adults were caught in False Codling Moth Traps on seedling lands than on ratooned lands ($\chi^2 = 1201.7$, 1 df, $p < 0.001$). The ratio of False Codling Moth was approximately 30:70 ratooned to seedling lands.

Table 3.9 False Codling Moth observed frequency and percentage for traps by type of land.

LAND	**Yellow Delta Traps**		**Total # Insects**	**Row Totals**
	MFF	**FCM**		
Ratooned	3	2140	2143	
Row %	0.14	99.86		100%
Column %	**37.5**	**29.6**		
Seedling	5	5089	5094	
Row %	0.09	99.90		100%
Column %	**62.5**	**70.4**		
Column Totals	8	7229	7237	
Column %	**100%**	**100%**		

3.6.2.5 Mean total number of False Codling Moth for all lands over the study period

To convert weeks to calendar dates, refer to Appendix 6.

The seasonal occurrence of adult False Codling Moth was calculated as the mean number of adults per week for all of the eight lands throughout the 52 week study

period (Fig. 3.12). Adult numbers were particularly high with a total of 7237 individuals caught throughout the year. Five peaks occurred: 1) Week 7 (2-8 January); 2) Week 14 (20-26 February); 3) Week 17 (13-19 March); 4) Week 21 (10-17 April) and Week 25 (8-14 May). Of these five peaks, two seem to be double peaks, those at Weeks 17 and 25. This may have been caused by pooling the data from the ratooned and seedling lands, or by climatic conditions that introduce variation into the same major peak. The temporal occurrence of the five peaks is not consistent with the False Codling Moth life cycle. When combining larval occurrence from the scouting data (Fig. 3.13) to adult presence, larval frequency was extremely low (47 individuals in all), and this led to the conclusion that the pheromone-based traps were presenting a false-positive result. Thus adult peaks would not coincide with the False Codling Moth life cycle as adults were being attracted into the lands.

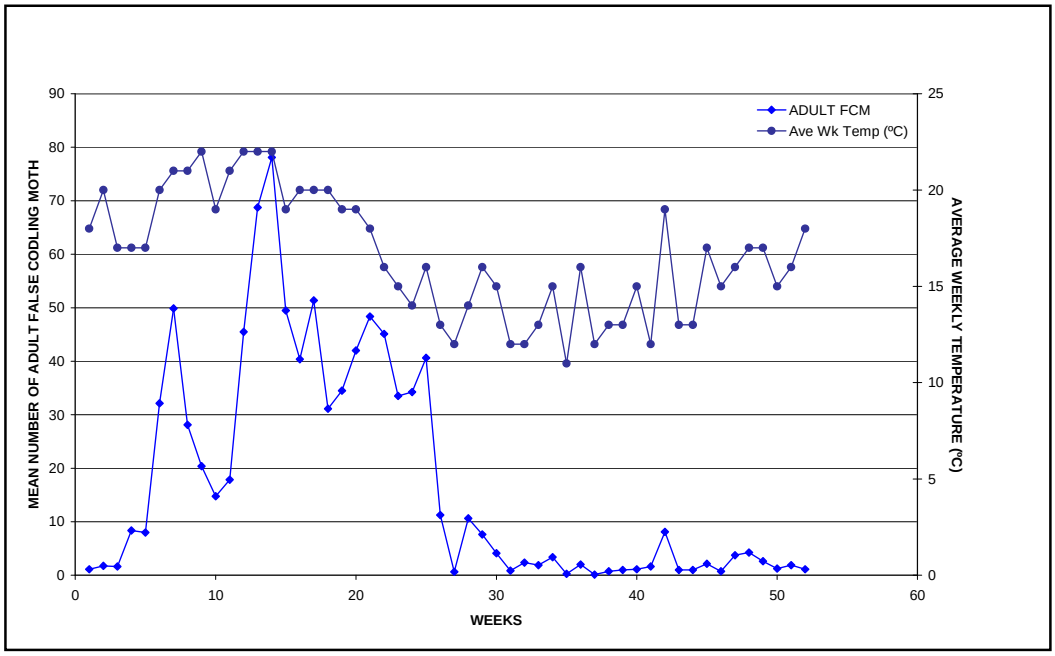


Figure 3.12 Weekly mean number of adult False Codling Moth for all lands.

The False Codling Moth life cycle varies from 19.9 to 26.7 weeks (cf. Section 3.6.3). Calculations in this study were based on an average life cycle of 23.3 weeks. False Codling Moth does not undergo a quiescent period or diapause, thus ensuring continual year-round populations although densities will be lower at certain periods (van den Berg 2001). Annecke & Moran (1982) recorded that developmental time is

extended during winter.

Because False Codling Moth occur year-round and their development is closely linked to ambient temperature, correlations between field populations and natural history could be modelled on a spreadsheet using thermal accumulation models were data for several years available.

3.6.2.6 Mean total number of False Codling Moth larvae observed through scouting for all lands over the study period

Scouting results show a total number of 47 False Codling Moth larvae observed throughout the study period (Fig. 3.13).

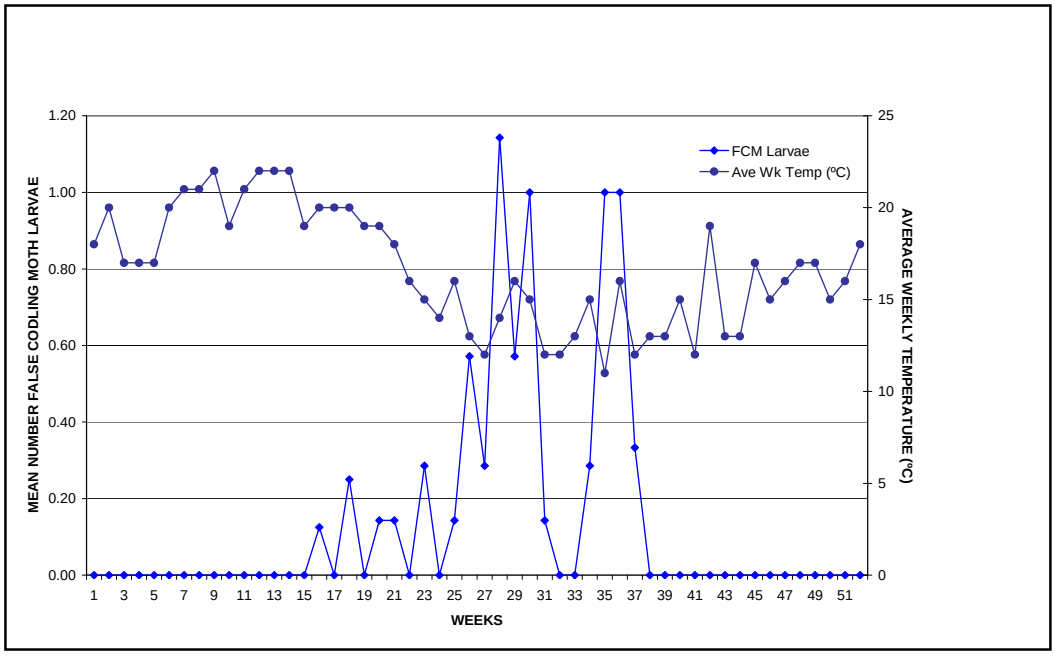


Figure 3.13 Weekly mean number of False Codling Moth larvae for all eight lands.

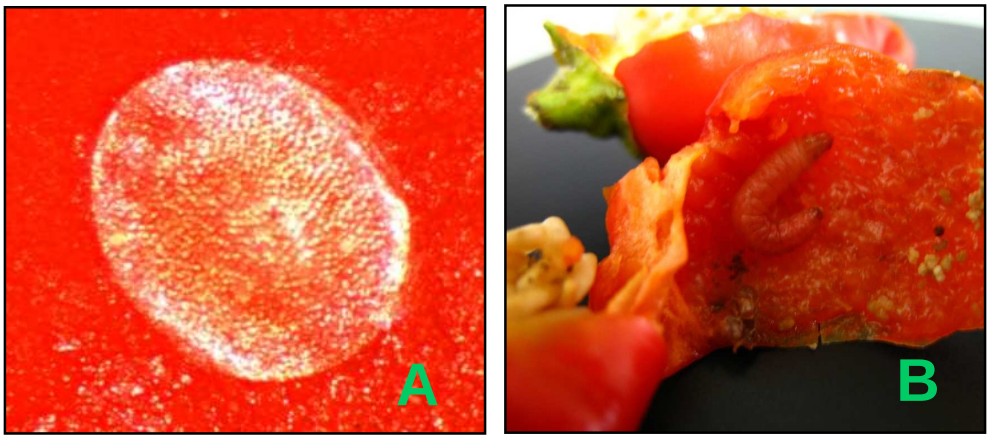
3.6.3 Discussion

In most areas of its distribution *T. leucotreta* is a year-round threat to cultivated crops due to it being a generalist feeder with broad range of host plants, especially in regions with mild tropical and subtropical winters. *Thaumatotibia leucotreta* do not undergo diapause or a quiescent period, which means that populations are continuous

year-round pests. Population fluctuations are greatly affected by the composition and succession of alternative host plants, whether cultivated or indigenous (Newton 1998). According to Ullyett & Bishop (1938, cited in van den Berg 2001), adult moths moving into a cultivated crop from indigenous hosts give rise to heavy infestations at the beginning of the season. Alternative hosts in close proximity to crop hosts are likely to have an impact on the size of the population (Newton 1988).

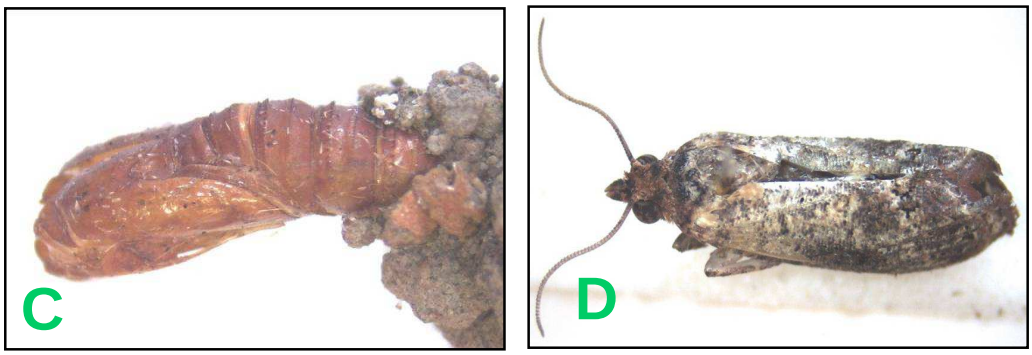
Females lay their eggs singly on or near to the fruit. The average egg measures about 0.77 x 0.60 mm, is oval and flat, and the exposed surface has a shiny, granulated finish (Fig. 3.14A). Newly laid eggs are pearl-white and translucent, changing to a reddish colour with a black spot (the head capsule) shortly before hatching (Daiber 1979, van den Berg 2001).

Thaumatotibia leucotreta larvae have five instars: the first instar measures up to 1.5 mm long, is cream-white with a dark brown head, and the final instar is 12-15 mm long, pinkish-red with a brown head (Fig. 3.14B) (Daiber 1979). There is high neonate mortality (Newton 1998) and cannibalism occurs among young larvae and usually only one larva will mature within in a single fruit (Catling & Aschenborn 1978, Annecke & Moran 1982, Newton 1998).



Figures 3.14A. *Thaumatotibia leucotreta* egg showing detailed 'pitting' on exposed surface; and **B.** *Thaumatotibia leucotreta* final instar, both on *Capsicum baccatum* pods.

Capsicum fruit that is infected will abscise, which is called pod drop, and at this stage growers should collect and destroy any fallen fruit in their fields to prevent larvae emerging from the fruit and pupating in the soil, on the surface of the soil, in debris or fallen fruit, thus continuing their life cycle. Larvae spin a loose silken cocoon in which they pupate (Fig. 3.14C).



Figures 3.14C. *Thaumatotibia leucotreta* pupa with soil attached; and **D**. adult.

Adults are relatively unremarkable in colouration being a mottled dark grey (Fig. 3.14 D). Their wingspan is 16-20 mm and the hind wings are paler than the forewings and fringed with hairs. Males are smaller than females and possess an anal tuft of scales, the hind tibia is densely covered with elongated scales, and a scent organ is present near the anal angle on each hind wing (Newton 1998, van den Berg 2001).

Newton (1998) states the sex ratio is close to unity in field populations, and adult longevity is 2-3 weeks (Ripley et al. 1939, cited in van den Berg 2001). Females mate shortly after eclosion, and pre-oviposition is 5-6 days in field observations and 1-2 days under laboratory conditions. Schwartz (1981, cited in van den Berg 2001) recorded multiple mating in both sexes. Daiber (1980) reported an average fecundity of 456 eggs per female at a constant temperature of 25°C, and 87 eggs per female at a constant temperature of 15°C. Five days after emergence, females kept at a temperature of 20°C, achieved peak egg laying of 29 eggs per female per day (Daiber 1980).

In a field study conducted in an unsprayed citrus orchard, peak flight activity occurred in November and again from February to March (Schwartz 1981, cited in van den

Berg 2001). In Tswane, Gauteng Province, South Africa, the *T. leucotreta* life cycle on guavas commences in January or February and takes an average of 152 days. Eggs have an incubation period of between 11 and 14 days, larval development takes 59 to 71 days, there is a pre-pupal stage of 21 to 30 days and the pupal stage lasts 43-66 days (Gunn 1921).

3.7 Mediterranean Fruit Fly *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae)

3.7.1 Introduction

The family Tephritidae is among the larger families of Diptera and comprises about 500 genera and approximately 4000 species. The genus *Ceratitis* MacLeay includes about 65 species. Native to tropical Africa, *Ceratitis* species have become established through adventive introductions in all continents except Asia (White & Elson-Harris 1992).

Natal Fruit Fly, Ceratitis rosa *Karsch (Diptera: Tephritidae)*

Ceratitis rosa is an economically important tephritid, widespread throughout Africa and the islands of Mauritius and Réunion. Its distribution in South Africa is limited mostly to the subtropical regions of the Northern Province, Mpumalanga and KwaZulu-Natal and along the coastal regions of the Western and Eastern Cape (Kok & Georgala 1978; Barnes 1983; Grové 2001). *Ceratitis rosa* and *C. capitata* are sympatric although *C. rosa* is generally more abundant in the northern regions and *C. capitata* in the south (Annecke & Moran 1982). Because the distributions are similar and both species are extremely polyphagous, monitoring for both *C. capitata* and *C. rosa* was undertaken during this study. However, the number of *C. rosa* which occurred in *Capsicum baccatum* fields was nominal; only seven individuals were caught throughout the entire study period.

Mediterranean Fruit Fly, Ceratitis capitata *(Wiedemann) (Diptera: Tephritidae)*

Ceratitis capitata is one of the most economically damaging tephritid pest species of economic importance (Grové 2001). It is highly polyphagous on tropical, subtropical

and deciduous fruits (Annecke & Moran 1982), and its distribution extends to almost all tropical and warm temperate regions of the world (White & Elson-Harris 1992). One of the main reasons it is so widely spread is due to its broad range of hosts, both cultivated and wild, from a variety of plant families (White & Elson-Harris 1992, Copeland *et al*. 2002). Thomas *et al*. (2001) recorded more than 260 host plants which include flowers, fruit, nuts and vegetables. Damage to commercial fruit by *C. capitata* is frequently high and may reach up to 100% (Fimiani 1989, Fischer-Colbrei & Buschen-Petersen 1989, Thomas *et al*. 2001). *Capsicum annuum* was recorded by Fimiani (1989) as a host plant in the Mediterranean area, and *Capsicum frutescens* in Réunion by Étienne (1972, cited by White & Elson-Harris 1992). In a study conducted on *C. capitata* host plants in Kenya, Copeland *et al*. (2002) found plants belonging of the genus *Solanum* to be the most heavily infested. In South Africa, *C. capitata* occurs throughout the year and attacks most cultivated crops and wild fruits (Annecke & Moran 1982, Grové 2001). Thomas *et al*. (2001) compiled a comprehensive list of world-wide host species grouped according to importance, host species which have become infested under laboratory conditions and hosts of unknown importance. Numerous other host plants have been recorded by Clausen *et al.* (1965), Williers (1979), Annecke & Moran (1982), Hancock (1987, 1989), White & Elson-Harris (1992), APHIS (2007b).

Mediterranean Fruit Fly proved to be the most damaging of the insects occurring in *C. baccatum* lands during the study period.

3.7.2 Results

3.7.2.1 Comparison of the presence or absence of pest species caught using different trap types

There was a significant trap effect for the number of Mediterranean Fruit Fly (χ^2 = 176.2, 4 df, $p < 0.001$). Significantly more occurrences of Mediterranean Fruit Flies were observed using the Mediterranean Fruit Fly Trap with a female Mediterranean Fruit Fly pheromone-based dispenser (Table 3.10).

Table 3.10 Log-linear analysis for Mediterranean Fruit Fly observed frequency: presence or absence by traps.

	Yellow Card	Yellow Delta Traps		Sensus Trap	YBF Trap	Total
		MFF	FCM			
Absent	354	270	395	351	385	1755
Present	62	146	21	65	31	325
Total	416	416	416	416	416	2080

Mediterranean Fruit Fly adults were present 146 times in the Mediterranean Fruit Fly Trap out of 416 observations.

3.7.2.2 Comparison of the numbers of insects caught among the different trap types in the lands

The frequency distributions of Mediterranean Fruit Fly across the lands were significantly different (χ^2 = 664.9, 28 df, $p < 0.001$, Fig. 3.15). Significantly more Mediterranean Fruit Fly were caught in Mediterranean Fruit Fly Traps on VS 1 land and significantly fewer on IS land than on the other lands (Table 3.11).

Table 3.11 Mediterranean Fruit Fly observed frequency and percentages for traps by lands.

LAND	Yellow Card	Yellow Delta Traps		Sensus Trap	YBF Trap	Total # Insects	Row Totals
		MFF	FCM				
BR	6	1394	9	17	6	1432	
Row %	0.4	97.4	0.6	1.2	0.4		100%
Column %	**5.2**	**16.0**	**36.0**	**5.5**	**18.8**		
IR	28	981	5	24	4	1042	
Row %	2.7	94.1	0.5	2.3	0.4		100%
Column %	**24.3**	**11.3**	**20.0**	**7.7**	**12.5**		
VR	18	1045	1	147	1	1212	
Row %	1.5	86.2	0.1	12.1	0.1		100%

Column %	**15.7**	**12.0**	**4.0**	**47.4**	**3.1**		
BS	15	1506	3	23	4	1551	
Row %	1.0	97.1	0.2	1.5	0.2		100%
Column %	**13.0**	**17.3**	**12.0**	**7.4**	**12.5**		
IS	12	69	1	16	1	99	
Row %	12.1	69.7	1.0	16.2	1.0		100%
Column %	**10.4**	**0.8**	**4.0**	**5.2**	**3.1**		
VS 1	19	3032	1	46	4	3102	
Row %	0.7	97.8	0.0	1.5	0.0		100%
Column %	**16.5**	**34.8**	**4.0**	**14.8**	**12.5**		
VS 2	5	389	3	14	3	414	
Row %	1.2	94.0	0.7	3.4	0.7		100%
Column %	**4.3**	**4.5**	**12.0**	**4.5**	**9.4**		
LMS	12	283	2	23	9	329	
Row %	3.7	86.0	0.6	7.0	2.7		100%
Column %	**10.4**	**3.3**	**8.0**	**7.4**	**28.1**		
Column Totals	115	8699	25	310	32	9181	
Column %	**100%**	**100%**	**100%**	**100%**	**100%**		

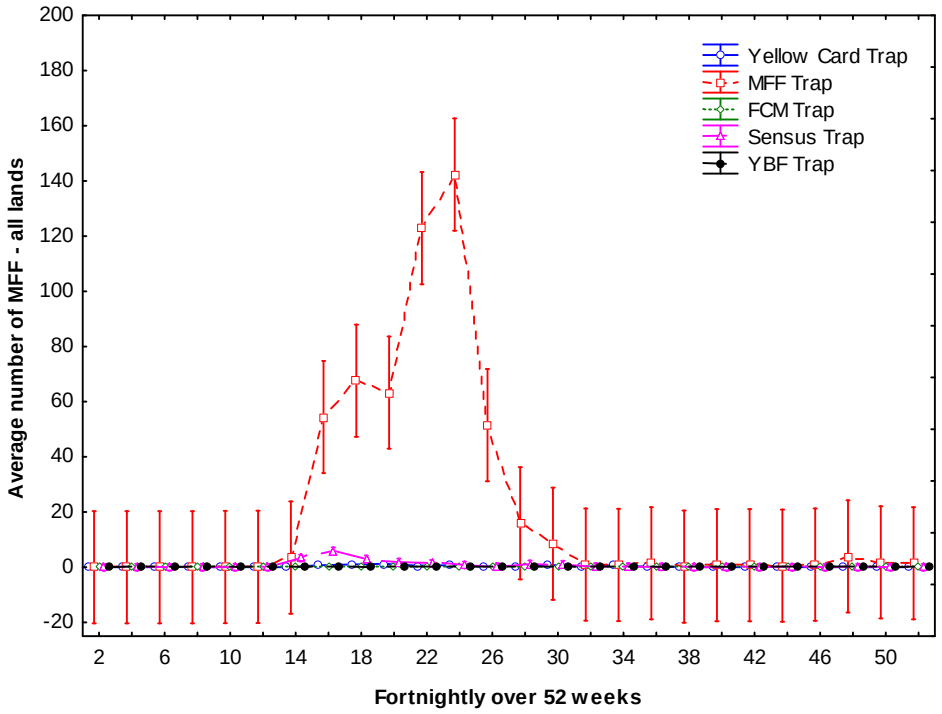


Figure 3.15 Mean number of Mediterranean Fruit Fly caught for all eight lands throughout the study period, showing trap effect.

3.7.2.3 Total number of Mediterranean Fruit Fly

The total number of Mediterranean Fruit Fly recovered from the traps during the course of the year, for each of the eight lands, is shown in Fig. 3.16.

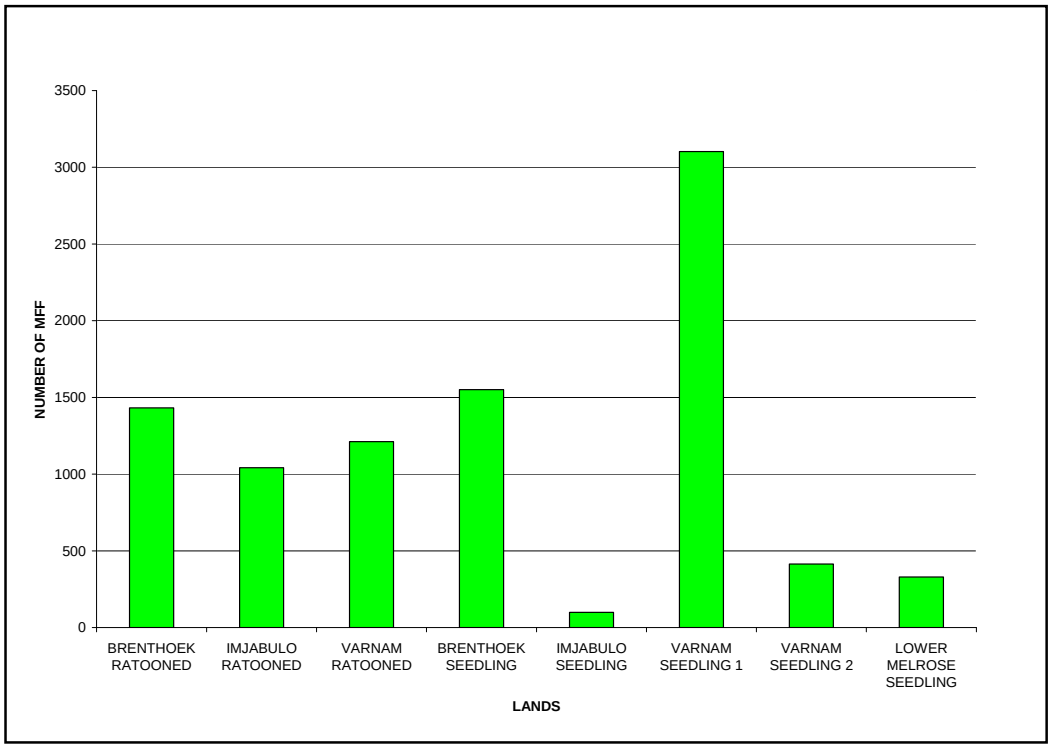


Figure 3.16 Total number of Mediterranean Fruit Fly recovered from traps throughout the study period for all eight lands.

The study period of 52 weeks was divided up into 4 equal periods (cf. Section 3.2). Means and standard errors of the number of Mediterranean Fruit Fly caught during each period were calculated over each of the eight lands (Table 3.12). Bar graphs plotting the means and standard errors of each insect pest per land for each of the eight lands are given in Appendix 5.

Table 3.12 Mediterranean Fruit Fly means and standard errors over four periods for all lands.

	BR		IR		VR		BS		IS		VS 1		VS 2		LMS	
Period	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
1	0.00	0.00	0.15	0.04	0.31	0.09	0.00	0.00	0.00	0.00	0.08	0.02	0.08	0.02	0.00	0.00
2	102.85	28.52	77.62	21.53	92.92	25.77	115.62	32.07	5.62	1.56	209.23	58.03	29.00	8.04	16.62	4.61
3	7.00	1.94	2.23	0.62	0.00	0.00	3.69	1.02	2.00	0.55	17.69	4.91	2.38	0.66	8.38	2.33
4	0.31	0.09	0.15	0.04	0.00	0.00	0.00	0.00	0.00	0.00	11.62	3.22	0.38	0.11	0.31	0.09

Period 1 = 21/11/05-19/2/06; 2 = 20/2/06-21/5/06; 3 = 22/5/06-20/8/06; 4 = 21/8/06-19/11/06

3.7.2.4 Comparison of the numbers of insects caught among the different trap types by ratooned and seedling lands

The frequency distributions of Mediterranean Fruit Fly between the ratooned and seedling lands were significantly different (χ^2 = 66.3, 4 df, p = < 0.001, Table 3.13). It is evident that, in both the ratooned and seedling groups, significantly more Mediterranean Fruit Fly were caught in the Mediterranean Fruit Fly Traps. A significantly higher number of Mediterranean Fruit Fly were caught in the traps in the seedling lands than in the ratooned lands (χ^2 = 356.4, 1 df, p < 0.001). The ratio of Mediterranean Fruit Fly was approximately 40:60 ratooned to seedling lands.

Table 3.13 Mediterranean Fruit Fly observed frequency and percentage for traps by type of land.

LAND	Yellow Card	Yellow Delta Traps		Sensus Trap	YBF Trap	Total # Insects	Row Totals
		MFF	FCM				
Ratooned	52	3420	15	188	11	3686	
Row %	1.4	92.8	0.4	5.1	0.3		100%
Column %	**45.2**	**39.3**	**60.0**	**60.6**	**34.4**		
Seedling	63	5279	10	122	21	5495	
Row %	1.1	96.1	0.2	2.2	0.4		100%
Column %	**54.8**	**60.7**	**40.0**	**39.4**	**65.6**		
Column Totals	115	8699	25	310	32	9181	
Column %	**100%**	**100%**	**100%**	**100%**	**100%**		

3.7.2.5 Mean total number of the four insect pests for all lands over the study period

To convert weeks to calendar dates, refer to Appendix 6.

The seasonal occurrence of adult Mediterranean Fruit Fly was calculated as the mean number of adults per week for all of the eight lands throughout the 52 week study period (Fig. 3.17). A total of 9181 adults were caught throughout the year. Four peaks

occurred: 1) Week 18 (20-26 March); 2) Week 21 (10-17 April); 3) Week 23 (24-30 April); and 4) Week 27 (22-28 May). Of these four peaks, those taking place at Weeks 21 and 23 seem to be a double peak as they occur within a short period of each other. This too may have been caused by combining the data from the ratooned and seedling lands, or by climatic variation within a single major peak. The temporal occurrence of the four peaks is not consistent with the Mediterranean Fruit Fly life cycle. Mediterranean Fruit Fly adults were absent except when fruit was present and there was some evidence of generations within the crop.

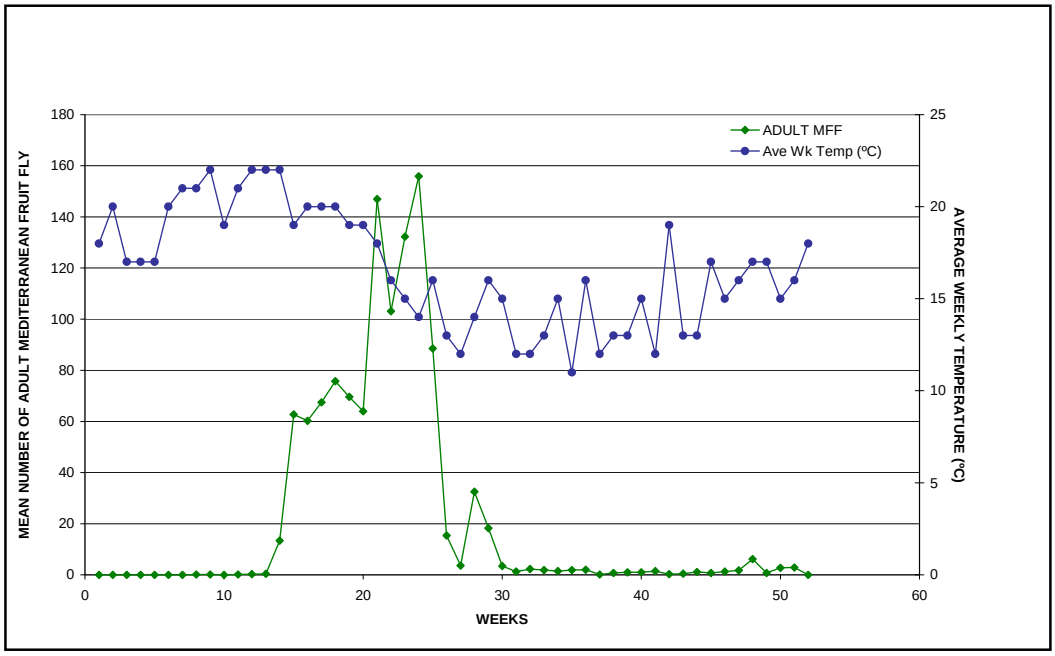


Figure 3.17 Weekly mean number of adult Mediterranean Fruit Fly for all lands.

In interpreting the seasonal phenology of Mediterranean Fruit Fly it must be taken into account that this phytophagous pest occurs year-round with a reduction in population density particularly over cooler periods, although spraying, harvesting, migration, lengthening of the life cycle, higher mortality or reduced fecundity due to limited food for adults have to be taken into account. Mediterranean Fruit Fly adult presence was detected at very low numbers from Weeks 8 (9-15 January)-13 (13-19 February), which suggests that wild populations of Mediterranean Fruit Fly invaded the *Capsicum* lands from surrounding vegetation or other cultivated lands in the area once the *Capsicum* pods had begun to ripen in mid-February, providing alternative

oviposition sites and resources. Thereafter adult numbers continued to increase rapidly and only declined at Week 30 (12-18 June). A mean total of 1.00 fly for all lands at week 40 suggests that Mediterranean Fruit Fly populations were no longer present in the *Capsicum* lands or in the surrounding areas. This could be of major importance to farmers as ploughing in or ratooning the crop soon after harvesting has finished would promote field hygiene and could have some impact on subsequent Mediterranean Fruit Fly populations. The rapid expansion of Mediterranean Fruit Fly strongly suggests that they are not derived solely from within the crop system.

The life cycle of Mediterranean Fruit Fly varies from 10.6 to 16.6 weeks (cf. Section 3.7.3). Calculations in this study were based on an average life cycle of 13.6 weeks unless otherwise stated. Mediterranean Fruit Fly do not undergo diapause and populations therefore are continuously present throughout the year. This, together with its wide range of agricultural and wild host plants, makes Mediterranean Fruit Fly a highly successful phytophagous insect of major economic importance.

3.7.2.6 Mean number of pods damaged observed through scouting for all lands over the study period

A cumulative total of 5511 damaged pods were collected throughout the study period. Damage was categorized as follows: a) Mediterranean Fruit Fly larvae (larval instars large enough to be positively identified as Mediterranean Fruit Fly larvae); b) Diptera larvae (larval instars too small to positively identified) present in pods; c) pods with diptera damage (pods apparently damaged by diptera larvae); d) pods stung or with marks on the skin (exocarp pierced); e) pods which were rotten (may have been caused due to exocarp being pierced); and f) pods infected with fungus (also may have been caused by exocarp being punctured) (Figs. 3.18-3.23).

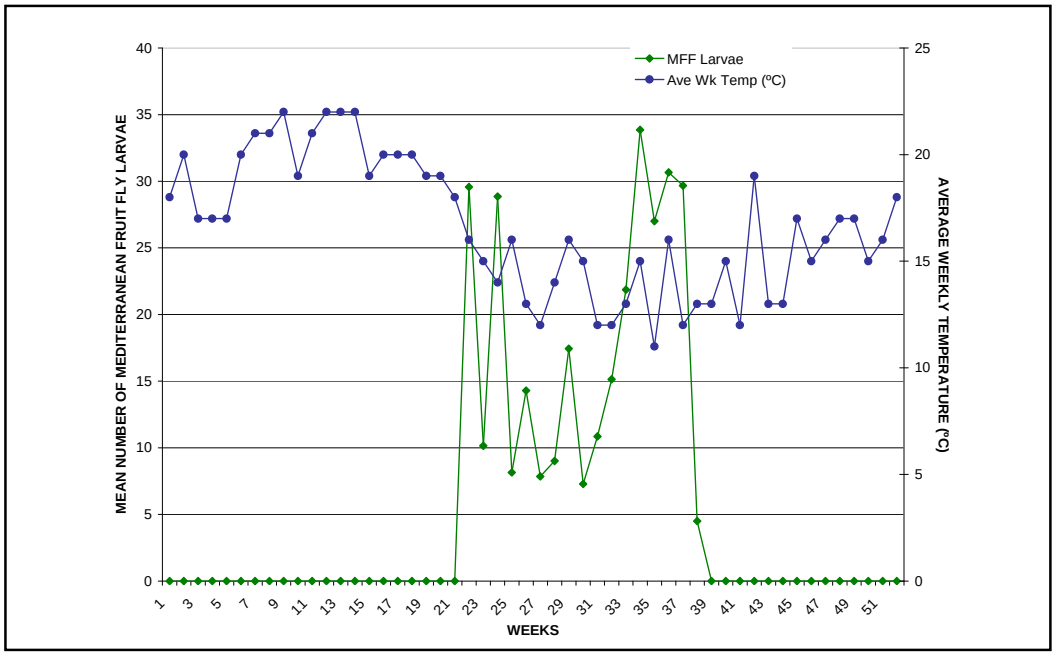


Figure 3.18 Weekly mean number of Mediterranean Fruit Fly larvae present in pods (total = 1879) for all eight lands.

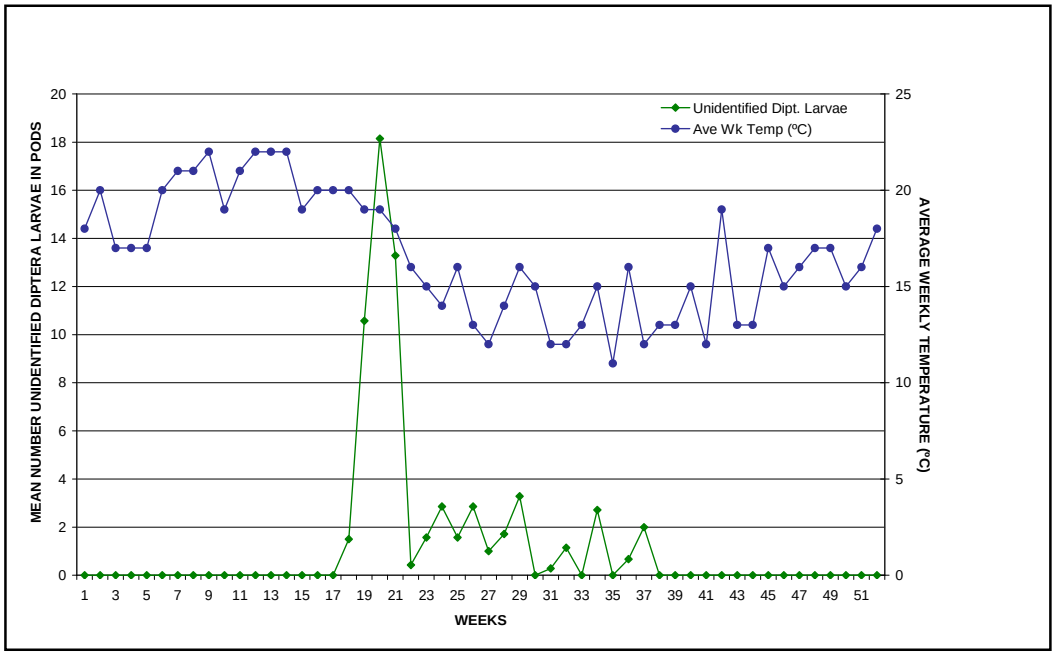


Figure 3.19 Weekly mean number of unidentified Diptera larvae present in pods (total = 450) for all eight lands.

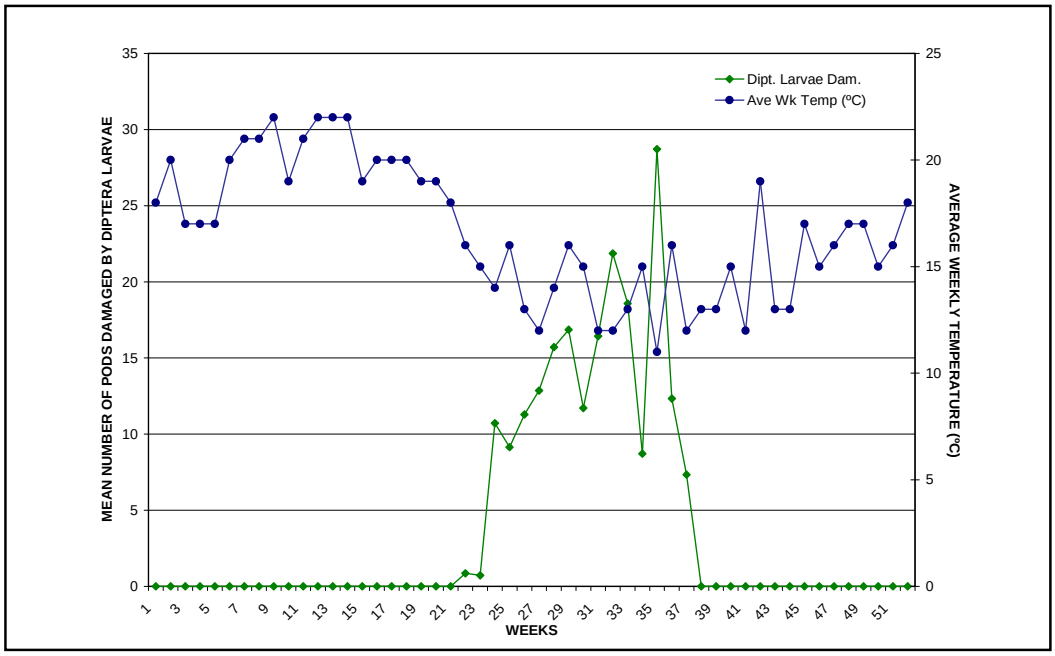


Figure 3.20 Weekly mean number of pods (total = 1348) damaged by Diptera larvae for all eight lands.

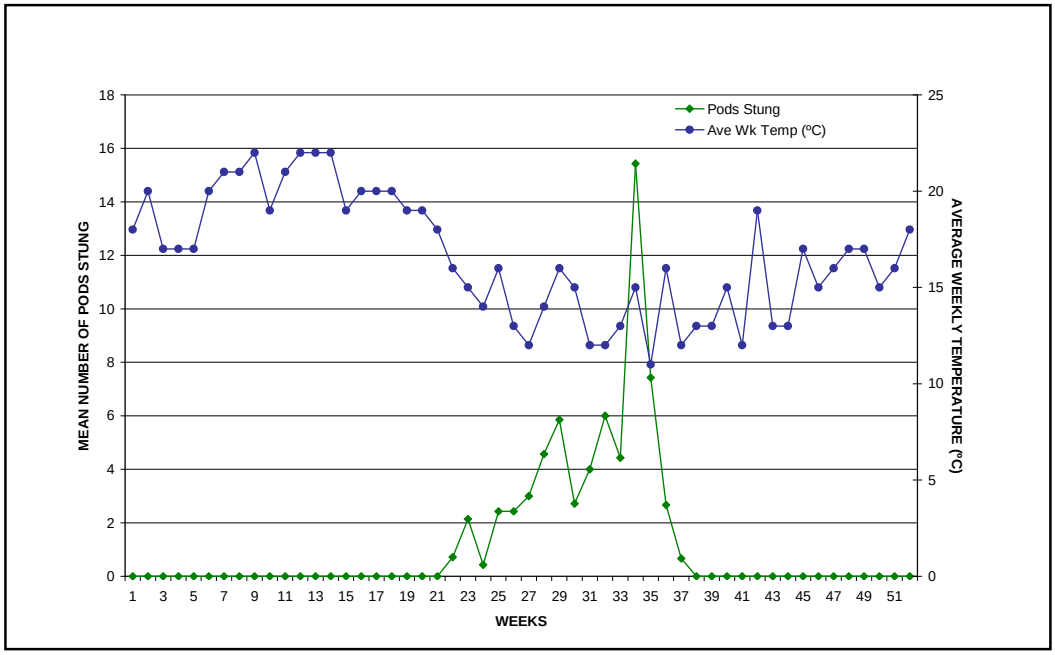


Figure 3.21 Weekly mean number of pods (total = 441) damaged (stung or marked) for all eight lands.

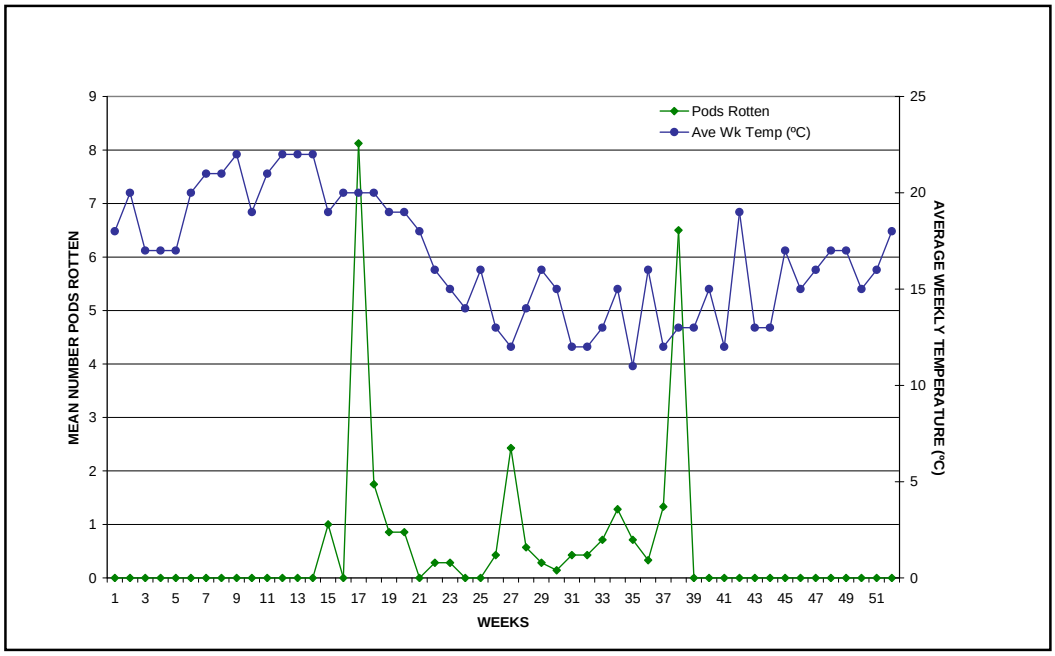


Figure 3.22 Weekly mean number of pods (total = 173) rotten for all eight lands.

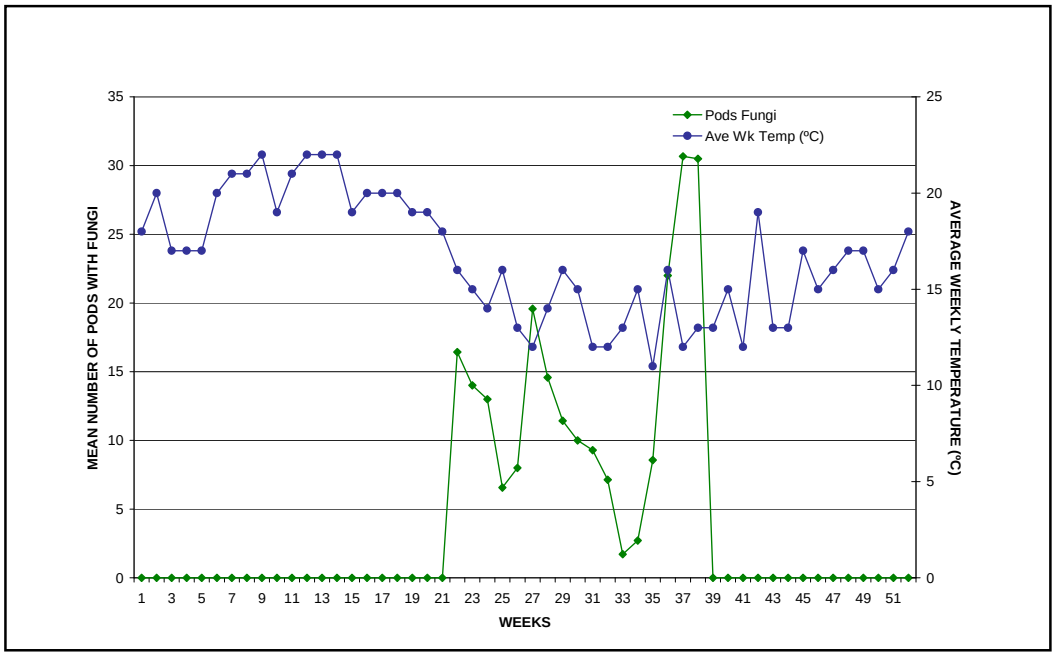


Figure 3.23 Weekly mean number of pods (total = 1220) damaged by fungi for all eight lands.

3.7.3 Discussion

Some tephritid species have preferred host plants and this may become ambiguous when reading a list that records host plants for a particular species. Host choice is dependent upon a number of variables; stage of host development, availability of fruit or flowers, variety of fruit and competition with other pests. Competition between different pests may lead to assumptions regarding preferred hosts. For example, shortly after *Bactrocera dorsalis* was found in Hawaii in 1945, *C. capitata* populations were displaced throughout most of its range and restricted to higher elevation localities and cooler climes (Christenson & Foote 1960, Vargas *et al*. 1983, Nishida *et al.* 1985). Therefore apparent host preferences may be influenced by competition from other phytophagous pests.

The successful distribution of *C. capitata* is also due to its remarkable ability for physiological adaptation. *Ceratitis capitata* is able to expand it host range by modulating two behavioural characteristics; (i) oviposition preference, and (ii) larval feeding tendency. Females tend to oviposit indiscriminately and, should larvae have the ability to adapt to the plant physiologically and genetically, the host range becomes extended. This was shown by Krainacker *et al*. (1987) when almost all hosts presented to *C. capitata* were utilized.

Fruit fly damage can be separated into two categories; (i) primary damage, caused by oviposition and subsequent larval feeding on the fruit; and (ii) secondary infection caused by fungi or bacteria as a result of damage to the skin or rind by oviposition. *Ceratitis capitata* may also transmit fruit-rotting fungi (APHIS 2007b).

Ceratitis capitata females lay clusters of about 10 eggs in the tissue just beneath the rind or skin of the fruit (Fig. 3.24A). Hard or semiripe fruit are often preferred for oviposition as fully ripened fruit are generally more succulent and this leads to a high mortality of eggs and young larvae (Christenson & Foote 1960, Thomas *et al*. 2001). Eggs take from 2-4 days to hatch. The larvae pass through three instars which total 6-11 days (Fig. 3.24B). Another cause of larval mortality is the hardening of host fruit or vegetable skins which prevent larvae exiting to pupate (i.e. pumpkins). Third instar larvae drop to the ground and move into the soil where they form puparia. A common

feature of *Ceratitis* spp. larvae is that, through a series of contractions of their abdominal muscles, they can spring for a distance of about 10 cm at a time along a substrate to find suitable pupariation sites. This is useful characteristic for larval identification at species level. Most fruit fly species pupate in soil to a depth of not more than 5 cm (Christenson & Foote 1960, Hodgson *et al*. 1998). The pupal stage also lasts 6-11 days (Fig. 3.24C).

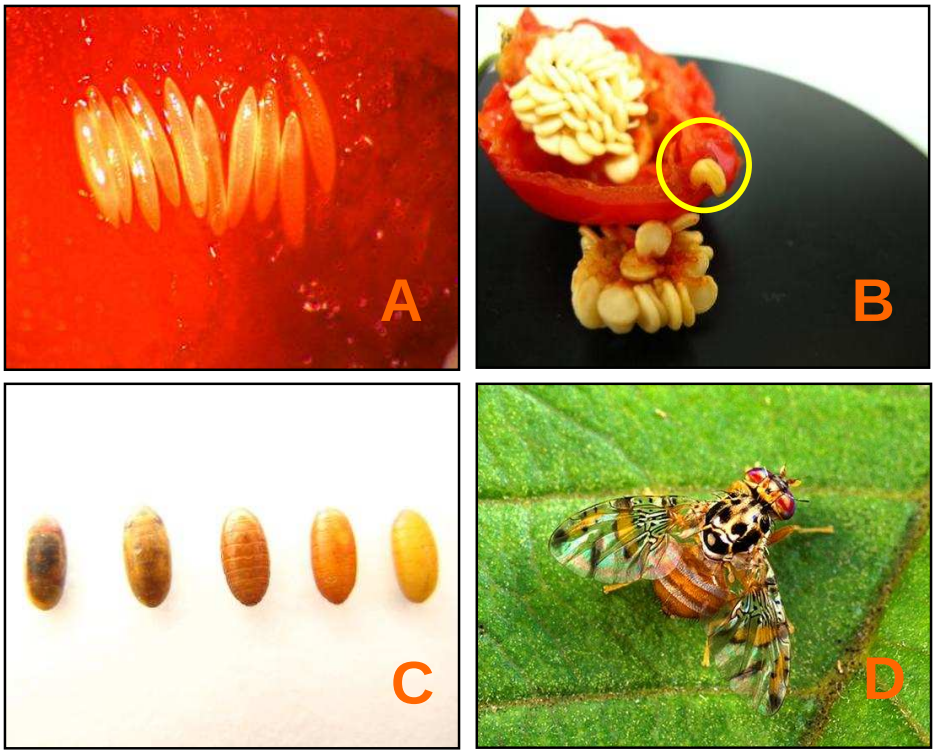
Newly emerged adult fruit fly are not sexually mature; males become active four days after emergence, and females between six and eight days (Thomas *et al*. 2001). Adults are sexually active throughout the day. Larger numbers of adults appear early in the morning during warm weather and only sporadically during cooler temperatures. Tephritids are generally inactive at night and during periods of moderate to heavy rainfall. Major mass population movement is caused by ripening and fruiting of host plants while minor movement is attributed as a response to irregular distribution of honeydew as a food source (Ripley *et al*. 1940).

Upon emergence, adults require essential nutrients and a protein meal that promotes egg maturation in females (Christenson & Foote 1960, Hendrichs *et al*. 1991). Protein baits release volatile chemicals, one of which is ammonia, that provide feeding cues to foraging females (Epsky & Heath 1998). Reproductive females require a substantial and varied diet to achieve peak fecundity and meals containing minerals, vitamins and sterols are required to promote daily oviposition and egg maturation (Hendrichs *et al*. 1991). Both male and females feed on damaged fruit caused by birds, other insects or vertebrates, and honeydew produced by some insects and plants. Hendrichs *et al*. (1991) reported that females also feed on bird faeces, a source of nutrients and nitrogen for the female, in addition to their normal diet. Hendrichs *et al*. (1991) showed that in *C. capitata* fecundity was significantly increased when, in addition to fruit, bird faeces was included in their diet. Fletcher (1987) reported that most fruit tissue is a poor source of protein and showed that bacteria provide essential nutrients. Studies have shown that an important source of nutrients come from bacteria on the plant surface (Drew 1989, Drew & Lloyd 1989, Lloyd 1991). In some *Bactrocera* spp., these bacteria are probably spread by mature females feeding on fruit surfaces; and the same range of bacteria species are found in the gut contents and in stung fruit (Drew & Lloyd 1989). Females feed more than males and forage for considerable

periods off the primary host plant. Oviposition takes place mainly in the afternoon. Males do not often forage off the primary host; they feed mainly during the later part of the afternoon and their longevity is not increased on a more diverse diet.

Many tephritids are predisposed to lek behaviour; this is when males congregate and defend a mating territory, a lek, whilst releasing 'call' pheromones to receptive females. Hendrichs & Hendrichs (1990) proposed that the origin of the lek mating system may be attributed to predation pressure on frugivorous tropical tephritids, which has since been supported by Papaj *et al.* (1989, cited in White & Elson-Harris 1992) and Hendrichs *et al*. (2001). *Ceratitis capitata* has a dual mating strategy: a) in the mornings males are usually found at the lek mating sites; and b) in the afternoon they move onto the host fruit in an attempt to intercept and mate with ovipositing females (Prokopy & Hendrichs 1979, Hendrichs *et al*. 1991). *Ceratitis capitata* usually mate on or near host plants.

Longevity of adults is 2-3 months depending on the season (Fig. 3.24D). A female can lay approximately 300 eggs during her lifetime (Grové 2001). Under favourable conditions, the life cycle is considerably shortened and adults may survive up to six months (Du Toit 1998, Thomas *et al*. 2001). According to Du Toit (1998) *C. capitata* populations can produce up to 15 generations per year depending on the availability of host plants and suitable climatic conditions. *Ceratitis capitata* overwinter as adults in evergreen shrubs and trees (Ripley & Hepburn 1930; Annecke & Moran 1982) and during this period, oviposition is suspended (Grové 2001).



Figures 3.24A-D. A. Eggs; **B.** Larva feeding on *Capsicum*; **C.** Pupae at different developmental stages; **D.** Adult male. (Photo Credits: **D.** Scott Bauer, USDA).

A characteristic feature of female tephritids is their long, extendible ovipositor. Species associated with fruit deposit their eggs just under the outer skin or rind of the fruit (Annecke & Moran 1982; Grové 2001). If the skin of the fruit is thin, oviposition is relatively quick and easy; whereas if the skin of the fruit is thick (i.e. citrus), oviposition is more problematical (Sivinski 1996). It has been shown that *C. capitata* will selectively choose pre-stung fruit in which to oviposit, sometimes using pre-existing oviposition holes, thus reducing the female's exposure time to predators and decreasing mortality rate (Papaj *et al.* 1989, cited in White & Elson-Harris 1992; Hendrichs *et al*. 2001). European yellowjacket wasps, *Vespula germanica* (Fabricius), have been reported preying on *C. capitata* females whilst the fruit fly's ovipositor was inserted in fruit (Hendrichs *et al*. 2001). By making use of pre-existing oviposition punctures and fruit wounds, *C. capitata* are able to exploit a broad range of fruits, nuts and vegetables. The female's ovipositor is not extensively developed as that of specialist species, and the ability to deposit eggs in a variety of hardened substrates is as a result of an evolved behavioural trait (using pre-existing wounds or punctures),

and not of having evolved a highly developed ovipositor (Papaj *et al*. 1989, cited in White & Elson-Harris 1992).

Ceratitis capitata and several *Anastrepha* and *Rhagoletis* species have been reported to use a post-oviposition deterrent or host-marking pheromone to discourage other females of the same species laying in the same fruit (Averill & Prokopy 1989) and has been suggested as a possible potential fruit fly management tool (Papaj *et al*. 1989, cited in White & Elson-Harris 1992).

Many host plants fruit intermittently under natural conditions, providing fruit at various stages of development simultaneously and supplying food resources for successive generations of multivoltine insects. Under monoculture conditions fruit fly foraging becomes somewhat more predictable. With the knowledge that *C. capitata* females require a wide variety of food resources and often leave the primary host plant to forage, setting up food-baited interception traps and the application of bait sprays along the perimeter may help to control populations (Hendrichs *et al*. 2001).

Most tephritids associated with fruit are attracted to substances which release ammonia, (e.g. hydrolysed or autolysed proteins) (Christenson & Foote 1960, Sivinski & Calkins 1986). Lures based on bacterial odours as attractants are being manufactured (Sivinski & Calkins 1986), and the importance of odours associated with host plants has also been recognised (Boller & Prokopy 1976, Drew 1989). *Ceratitis* spp. males are attracted to chemicals known as male lures or parapheromones (White & Elson-Harris 1992).

3.8 Thrips (Thysanoptera)

3.8.1 Introduction

The order Thysanoptera is divided into two suborders, Terebrantia and Tubulifera. A total of eight families are made up of an estimated 8 000 extant species (Lewis 1997), with more than 5 500 species described. Approximately 50% of the described species feed on fungi, 40% on dicotyledonous plants or grasses and the remainder exploit mosses, ferns, gymnosperms, cycads or are predatory (Mound 1997, Mound & Teulon

1995, Izzo *et al*. 2002), while scarcely 1% have been identified as serious pests (Morse & Hoddle 2006). The four thrips species which have been principally identified in the literature as being the most economically damaging are Onion thrips, *Thrips tabaci* (Lindeman, 1888), Western Flower thrips, *Frankliniella occidentalis* (Pergande, 1895), Chillie thrips, *Scirtothrips dorsalis* Hood and Melon thrips, *Thrips palmi* Karny (Mound & Teulon 1995, Mound 2002).

Thrips are highly successful insect invaders and are able to adapt to a wide range of environments (Morse & Hoddle 2006). Thrips populations are particularly abundant in their area of origin and are predisposed to an invasive lifestyle due to their small size, cryptic habits, catholic tastes and ability to adapt to new habitats, all of which help facilitate relocation. After introduction to a new region, populations have the ability to synchronize life cycle characteristics to fit in to recently colonised ecosystems (Morse & Hoddle 2006). Thrips are easily adaptable and biotypes of some species, such as *Frankliniella occidentalis*, can exist as monophagous and polyphagous strains in regions where they have become established (Mound 1997).

Many cultivated plants are severely affected by thrips throughout the world causing plant damage and a reduction in crop yields (Morse & Hoddle 2006). Thrips damage also impacts on the cosmetic quality of commodities (i.e. fresh fruit and vegetables, flowers and indoor plants), causing further economic loss (Childers & Achor 1995, Childers 1997, Lewis 1997). Quarantine inspections are made routinely for thrips when importing produce world wide, and presence of these pests can have a huge negative impact on international trade markets (Morse & Hodder 2006).

Thrips are vectors of numerous microbial pathogens (Ullman *et al*. 1997). Thrips also transmit viruses from at least four virus groups: ilarviruses, sobemoviruses and carmoviruses (which are pollen-borne), and tospoviruses (where virus and vector share a close biological relationship which involves leaf-to-leaf transmission) (Ullman *et al*. 2002, Whitfield *et al*. 2005). Tospoviruses impact negatively on the production of a wide range of horticultural crops. The tomato spotted wilt *Tospovirus* has a known host range of 1090 species from 85 plant families (Peters *et al*. 1995, Parrella *et al*. 2003, Campbell *et al*. 2004).

A complete list of thrips species caught throughout the study period is listed in Appendix 4. Natural history notes on four of the species identified are detailed below.

Western Flower Thrips, *Frankliniella occidentalis* (Pergande, 1895) (Thripidae)
Frankliniella occidentalis are omnivorous, primarily feeding on pollen and plant tissue and supplementing their diet with high-protein sources such as other small herbivores, thrips larvae (van Rijn *et al.* 1995) and spider mite eggs (Trichilo & Leigh 1986). In California, *Frankliniella occidentalis* on cotton seedlings are considered as beneficial insects as they prey on spider mites. *Frankliniella occidentalis* are vectors of tospoviruses.

Onion Thrips, *Thrips tabaci* (Lindeman, 1888) (Thripidae)
Thrips tabaci is cosmopolitan and is an economically important pest on a number of cultivated plants (Annecke & Moran 1982). *Thrips tabaci* is a vector of plant viruses (i.e. yellow spot virus on pineapple) and diseases that infest a wide range of cultivated plants and weeds (Annecke & Moran 1982, de Villiers *et al*. 1987b).

Kromnek Thrips/Cotton Bud Thrips/Blossom Thrips, *Frankliniella schultzei* (Trybom, 1910) (Thripidae)
Frankliniella schultzei has a wide range of host plants and are primarily flower feeders. This species is a significant vector of Kromnek disease of tobacco and tomato plants, caused by the same virus, tomato spotted wilt *Tospovirus*, and yellow spot virus on pineapple (de Villiers *et al*. 1987b, Petty 2001).

Aeolothrips brevicornis (Bagnall, 1915) (Aeolothripidae)
Aeolothrips spp. are commonly known as banded-wing thrips. The *Aeolothrips*, which make up approximately half the species in the family Aeolothripidae, are beneficial, predatory thrips preying on pest mites and other thrips species. Adults and larvae are usually found in flowers, and the larvae drop off the plant to pupate on the soil.

Species from the families Aeolothripidae, Phlaeothripidae and Thripidae are predominantly beneficial predatory thrips. Prey includes pest mites, other thrips species, scale insects (Hemiptera: Coccidae) and lace bugs (Hempitera: Tingididae).

Although thrips causing the most damage to *C. baccatum* plants was not assigned to any particular species, the scouting data showed that quite a considerable amount of quantifiable damage occurred.

3.8.2 Results

3.8.2.1 Comparison of the presence or absence of pest species caught using different trap types

The thrips catch from the Yellow Bucket Funnel Trap was excluded from all analyses because it was impossible to count individuals with any accuracy as some of the trap catches had become wet during rains. After collecting and drying the catches in petri dishes in an incubator, thrips adhered to other insects, most especially the more pubescent Hymenoptera, Coleoptera and Lepidoptera. There were also many loose scales from the Lepidoptera in the catch, making the counting of individual thrips virtually impossible.

Therefore presence or absence of insects was measured for 416 events (52 x 8) for each of the traps (x 4) bringing the total to 1664 observations. Significantly fewer occurrences of thrips were observed using the Sensus Trap as compared to the Yellow Card, Mediterranean Fruit Fly and False Codling Moth traps ($\chi^2 = 369.4$, 3 df, $p < 0.001$) (Table 3.14).

Table 3.14 Log-linear analysis for thrips observed frequency: presence or absence by traps.

	Yellow Card	**Yellow Delta Traps**		**Sensus Trap**	**Total**
		MFF	**FCM**		
Absent	78	105	98	309	590
Present	338	311	318	107	1074
Total	416	416	416	416	1664

Thrips were only present 107 times in the Sensus Trap out of 416 observations.

3.8.2.2 Comparison of the numbers of insects caught among the different trap types in the lands

As mentioned earlier in this chapter, the Yellow Bucket Funnel thrips trap catch was excluded from all analyses. The frequency distributions of thrips across the lands were significantly different (χ^2 = 1004.1, 21 df, $p < 0.001$, Fig. 3.25). Significantly more thrips were caught in Yellow Card Traps on IR, IS, VS 1 and VS 2 than on the other lands (Table 3.15). It is also evident that across all lands significantly fewer thrips were caught in the Sensus Traps.

Table 3.15 Thrips observation frequency and percentages for traps by lands.

LAND	Yellow Card	Yellow Delta Traps		Sensus Trap	Total # Insects	Row Totals
		MFF	FCM			
BR	759	396	341	54	1550	
Row %	49.0	25.5	22.0	3.5		100%
Column %	**9.2**	**11.3**	**11.4**	**5.6**		
IR	1381	336	384	195	2296	
Row %	60.2	14.6	16.7	8.5		100%
Column %	**16.8**	**9.6**	**12.9**	**20.2**		
VR	873	454	176	138	1641	
Row %	53.2	27.7	10.7	8.4		100%
Column %	**10.6**	**13.0**	**5.9**	**14.3**		
BS	581	238	307	18	1144	
Row %	50.8	20.8	26.8	1.6		100%
Column %	**7.1**	**6.8**	**10.3**	**1.9**		
IS	1425	515	482	124	2546	
Row %	56.0	20.2	18.9	4.9		100%
Column %	**17.3**	**14.8**	**16.1**	**12.8**		
VS 1	1017	654	445	378	2494	
Row %	40.8	26.2	17.8	15.2		100%
Column %	**12.3**	**18.7**	**14.9**	**39.2**		
VS 2	1118	616	515	23	2272	
Row %	49.2	27.1	22.7	1.0		100%
Column %	**13.6**	**17.7**	**17.3**	**2.4**		

LMS	1085	280	335	35	1735	
Row %	62.5	16.2	19.3	2.0		100%
Column %	**13.2**	**8.0**	**11.2**	**3.6**		
Column Totals	8239	3489	2985	965	15678	
Column %	**100%**	**100%**	**100%**	**100%**		

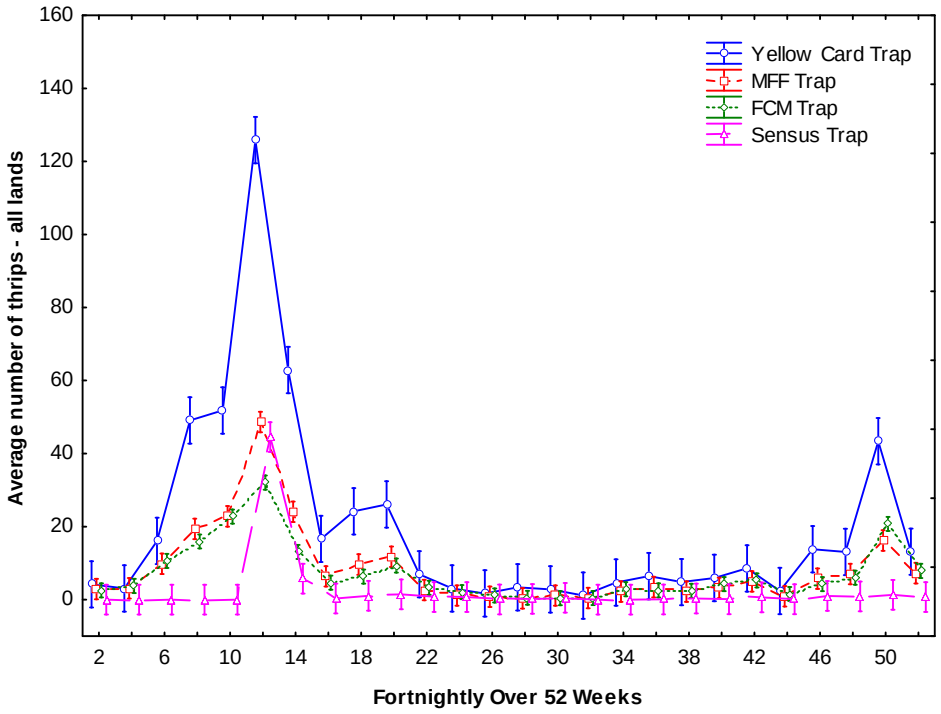


Figure 3.25 Mean number of thrips caught for all eight lands throughout the study period, showing trap effect.

3.8.2.3 Total number of thrips

The total number of thrips (15678 individuals) recovered from the traps during the course of the year, for each of the eight lands, is shown in Fig. 3.26.

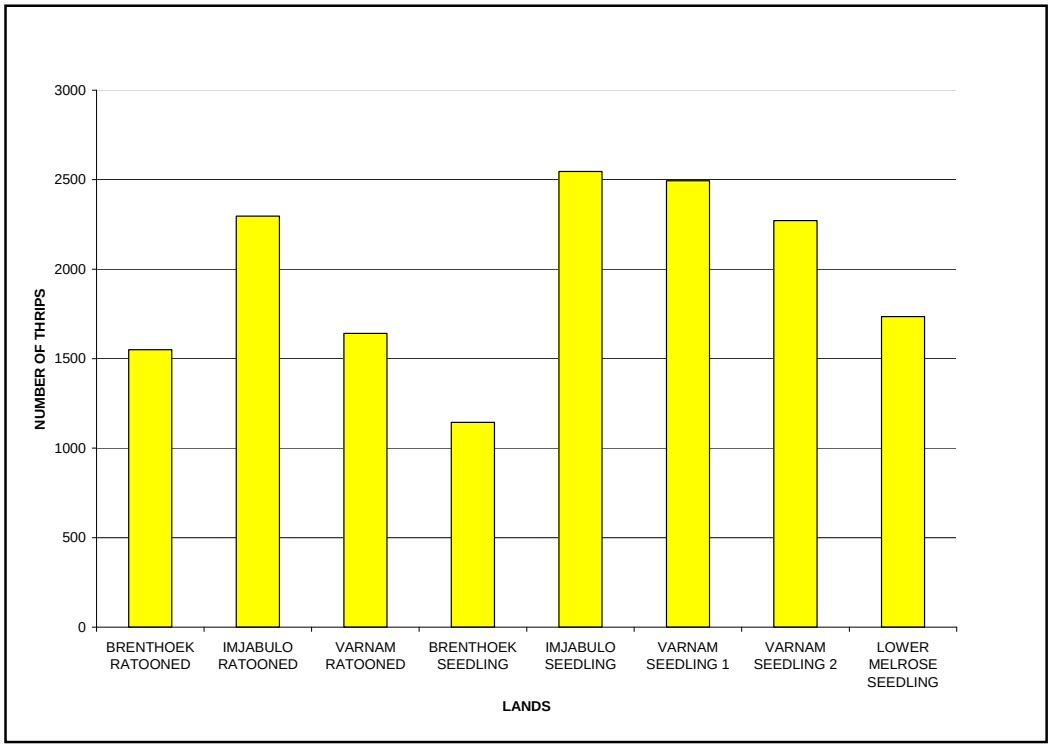


Figure 3.26 Total number of thrips recovered from traps throughout the study period for each land.

The study period of 52 weeks was divided up into 4 equal periods (cf. Section 3.2). Means and standard errors of the number of thrips caught during each period were calculated over each of the eight lands (Table 3.16). Bar graphs plotting the means and standard errors of each insect pest per land for each of the eight lands are given in Appendix 5.

Table 3.16 Thrips means and standard errors over four periods for all lands.

	BR		IR		VR		BS		IS		VS 1		VS 2		LMS	
Period	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
1	60.77	16.85	100.46	27.86	116.23	32.24	49.85	13.82	102.69	28.48	106.54	29.55	85.38	23.68	67.00	18.58
2	19.08	5.29	32.92	9.13	10.00	2.77	27.08	7.51	48.92	13.57	26.31	7.30	30.23	8.38	22.85	6.34
3	10.92	3.03	9.54	2.65	0.00	0.00	11.08	3.07	10.77	2.99	6.92	1.92	8.69	2.41	3.92	1.09
4	28.46	7.89	33.69	9.34	0.00	0.00	0.00	0.00	33.46	9.28	52.08	14.44	50.46	14.00	39.69	11.01

Period 1 = 21/11/05-19/2/06; 2 = 20/2/06-21/5/06; 3 = 22/5/06-20/8/06; 4 = 21/8/06-19/11/06

3.8.2.4 Comparison of the numbers of insects caught among the different trap types by ratooned and seedling lands

The Yellow Card, Mediterranean Fruit Fly, False Codling Moth and Sensus traps were included in the analysis. With respect to their relative percentage occurrence it is evident that in both the ratooned and seedling groups that significantly more thrips were caught on the Yellow Card Traps. The frequency distributions of thrips varied significantly among the ratooned and seedling lands for all traps with significantly more thrips caught using the False Codling Moth Trap in the seedling than the ratooned lands ($\chi^2 = 26.0$, 3 df, $p = < 0.001$, Table 3.17). The ratio of thrips was approximately 35:65 ratooned to seedling lands.

Table 3.17 Thrips observed frequency and percentage for traps by type of land.

LAND	Yellow Card	Yellow Delta Traps		Sensus Trap	Total # Insects	Row Totals
		MFF	FCM			
Ratooned	3013	1186	901	387	5487	
Row %	54.9	21.6	16.4	7.1		100%
Column %	**36.6**	**34.0**	**30.2**	**40.1**		
Seedling	5226	2303	2084	578	10191	
Row %	51.3	22.6	20.4	5.7		100%
Column %	**63.4**	**66.0**	**69.8**	**59.9**		
Column Totals	8239	3489	2985	965	15678	
Column %	**100%**	**100%**	**100%**	**100%**		

3.8.2.5 Mean total number of the four insect pests for all lands over the study period

To convert weeks to calendar dates, refer to Appendix 6.

The eight species of thrips collected during this study belong to three families (Table 3.18).

Table 3.18 Thrips species present in *Capsicum* lands during the study period.

Family	Genus	Species
Aeolothripidae	*Aeolothrips*	*brevicornis*
Phlaeothripidae	*Haplothrips*	*nigricornis*
		callani
		clarisetis
Thripidae	*Frankliniella*	*occidentalis*
		schultzei
	Liothrips	*emulatus* (sp.?)
	Thrips	*tabaci*

Thrips trap catches were not identified to species level due to time and labour constraints. Therefore thrips numbers in this study reflect the total number of individual thrips caught throughout the 52-week study period. Seasonal occurrence was calculated as the mean number of thrips per week for all of the lands throughout the 52 week study period (Fig. 3.27).

In order to interpret the phenological data of Fig. 3.27 it is necessary to briefly describe some details of the life cycle. Thrips species are multivoltine, often lack obligate diapause and are polyphagous or predatory. Thrips exhibit a high fecundity with short generation times depending on ambient temperatures. Many species are wholly or partly parthenogenic (Morse & Hoddle 2006). In interpreting the seasonal phenology of the various thrips species identified during this study, an average duration of a life cycle was calculated from data published by Lewis (1973) based on some nine different species. Thrips species life cycles range from 2.1 to 7.6 weeks. Calculations in this study were based on an average life cycle of 7.2 weeks (cf. Section 3.8.3).

Four peaks occurred: 1) Week 9 (16-22 January); Week 12 (6-12 February); Week 20 (3-9 April); and Week 49 (23-29 October). Of these four peaks, those taking place at Weeks 9 and 12 seem to be a double peak as they occur within a short period of one another. The peak reflected at Week 49 was purely incidental as the lands had been ratooned or

ploughed in and this was probably due to population migrations through the lands to other host plants. The temporal occurrence of the four peaks is not consistent with the average mean life cycle of thrips. Population fluctuations were probably due to the effect weather had on thrips activity which would affect trap catches.

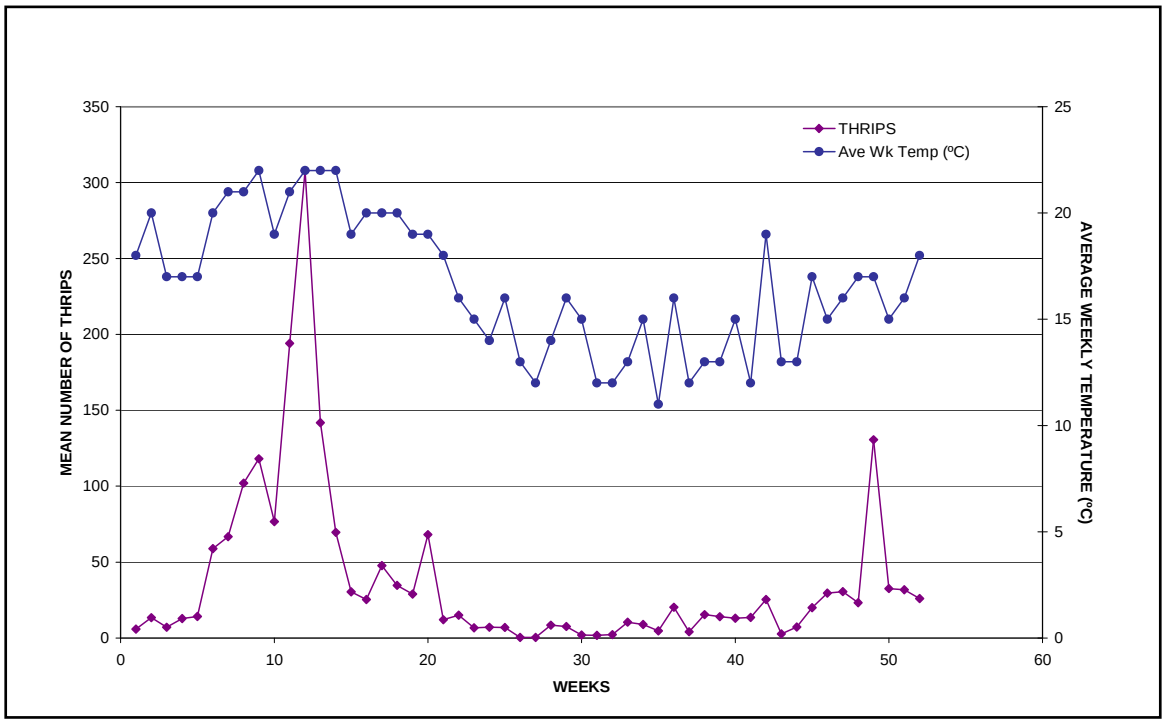


Figure 3.27 Weekly mean number of thrips for all lands.

3.8.2.6 Comparison in the extent of leaf damage by thrips on the lands

Records were kept regarding the extent of thrips damage caused to the leaves of the 15 plants scouted weekly throughout the 52 weeks study period. Damage to the plants was assessed as a percentage of the leaves of new growth, placed in one of four categories: No damage (0%); Low damage (<15%); Medium damage (<40%); and High damage (>40%) (Figs. 3.28-3.35).

A log-linear analysis revealed that the frequency distributions of the extent of leaf damage were significantly different among the lands ($\chi^2 = 175.4$, 21 df, $p < 0.001$, Table

3.19). The percentages of low, medium and high damage observed on Brenthoek Ratooned (56.5%) and Seedling (53.7%) lands and on Lower Melrose Seedling land (53.5%) were significantly higher than those on the other lands.

Table 3.19 Extent of thrips damage (in %) caused to the leaves of the 15 plants scouted weekly throughout the 52 weeks study period.

LAND	No damage %	Low %	Medium %	High %
Brenthoek Ratooned	43.5	17.0	25.0	14.5
Imjabulo Ratooned	63.0	16.5	14.3	6.2
Varnam Ratooned	67.0	18.2	12.6	2.1
Brenthoek Seedling	46.3	18.7	27.3	7.7
Imjabulo Seedling	56.7	16.4	16.9	9.9
Varnam Seedling 1	51.5	24.5	17.2	6.8
Varnam Seedling 2	52.6	18.6	16.9	11.9
Lower Melrose Seedling	46.5	19.0	20.0	14.5
All Lands	52.6	18.6	19.0	9.8

There was a significant difference in the overall distribution of the leaf damage categories (χ^2 = 1991.4, 3 df, p = < 0.001). Significantly more plants had no leaf damage compared to the other damage categories (52.6% no leaf damage, 18.6% low damage, 19.0% medium damage and 9.8% high damage).

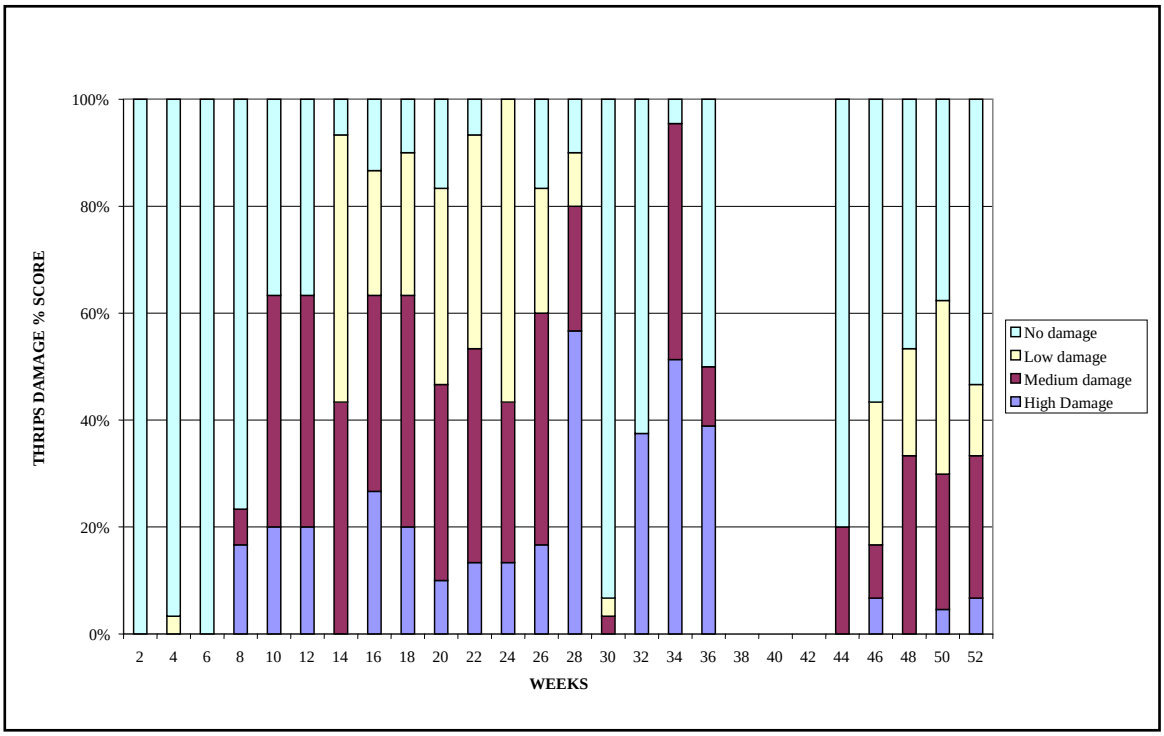


Figure 3.28 Brenthoek Ratooned: fortnightly thrips damage percentage score.

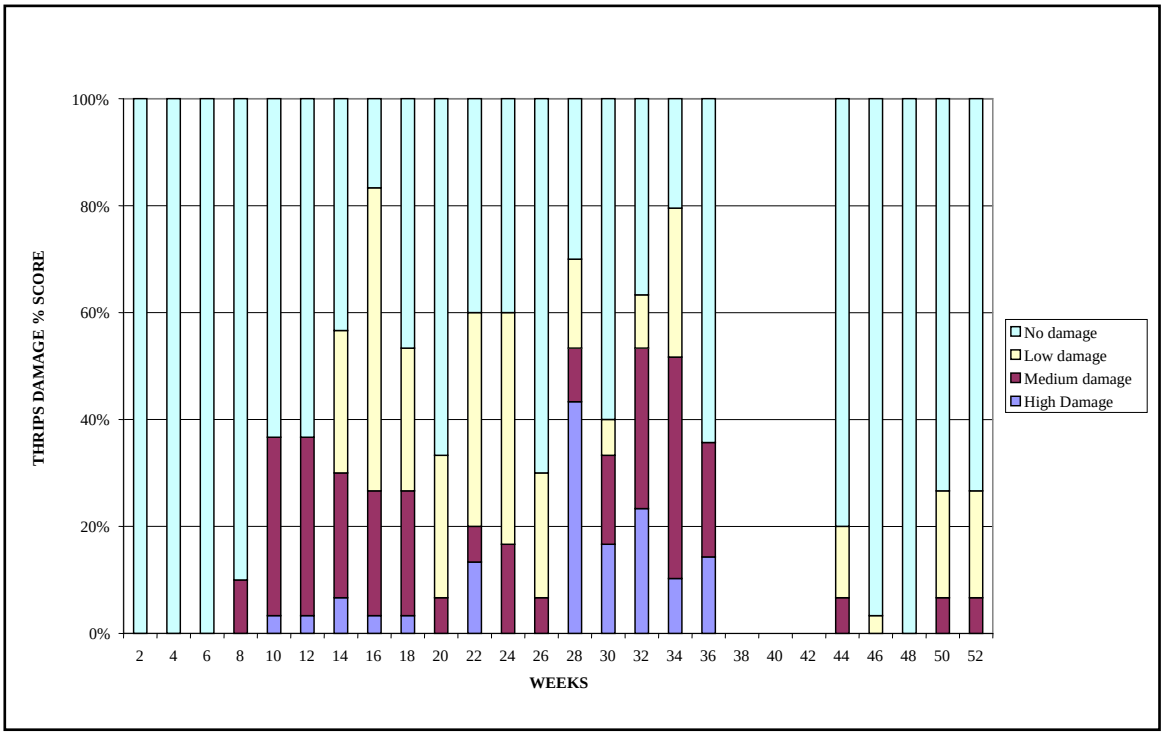


Figure 3.29 Imjabulo Ratooned: fortnightly thrips damage percentage score.

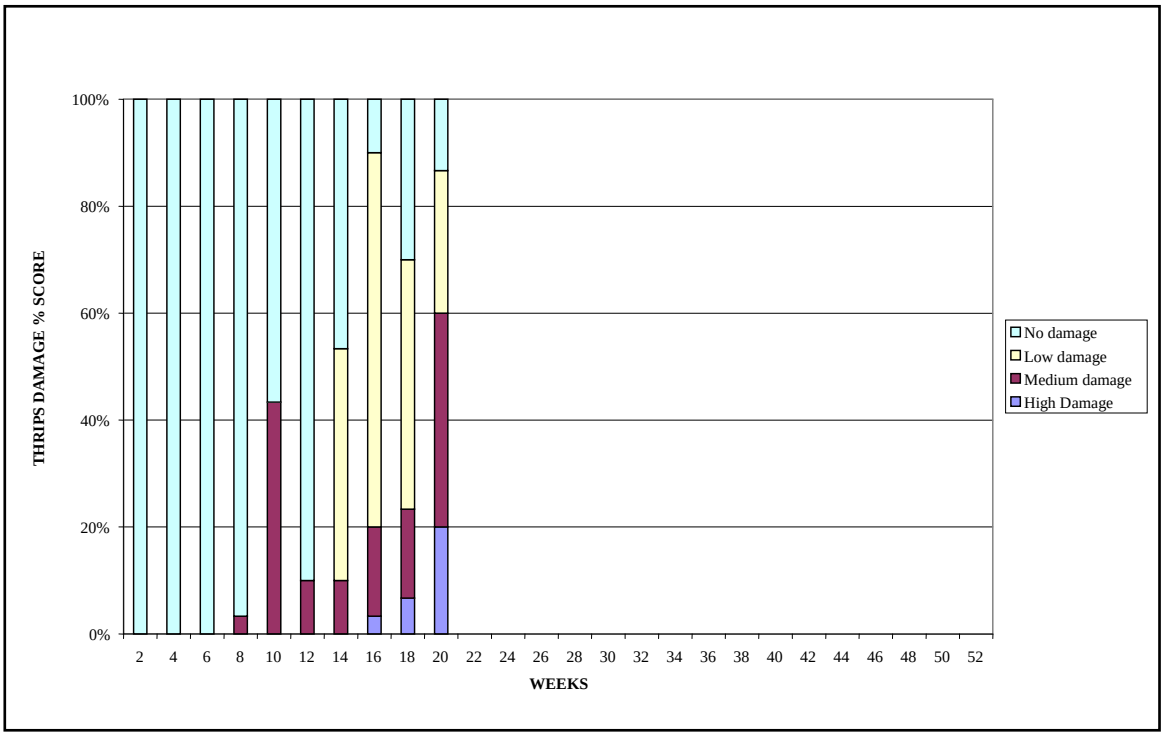


Figure 3.30 Varnam Ratooned: fortnightly thrips damage percentage score.

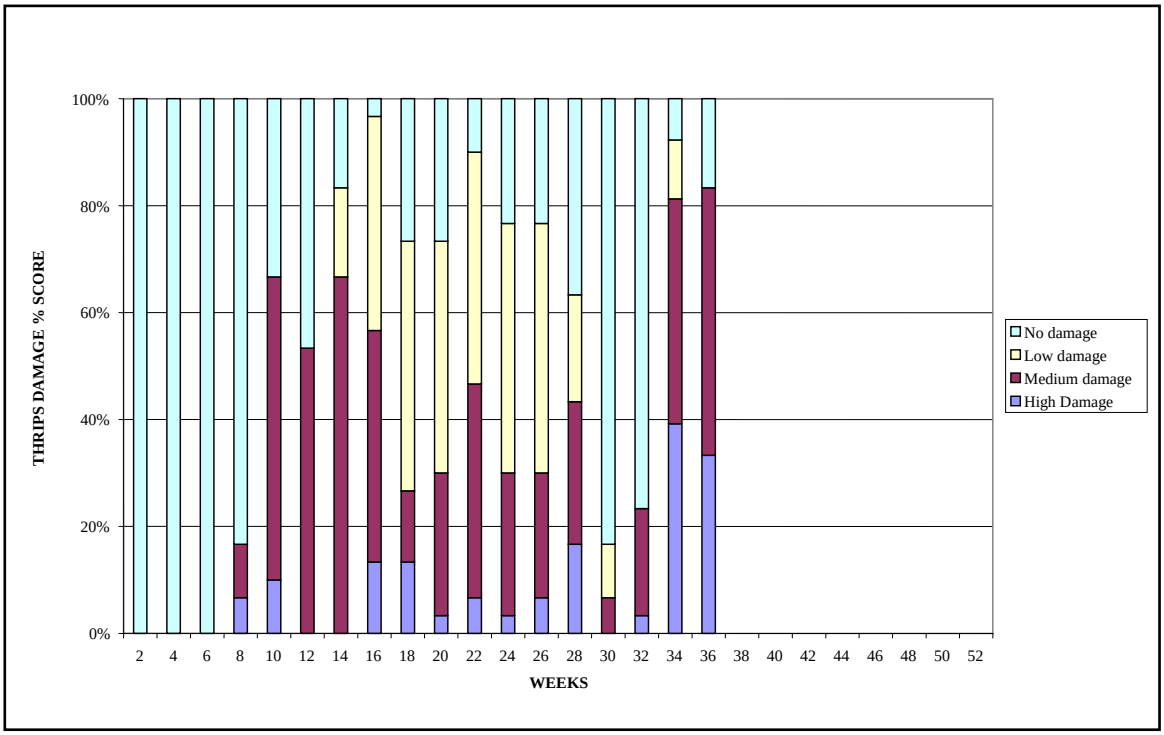


Figure 3.31 Brenthoek Seedling: fortnightly thrips damage percentage score.

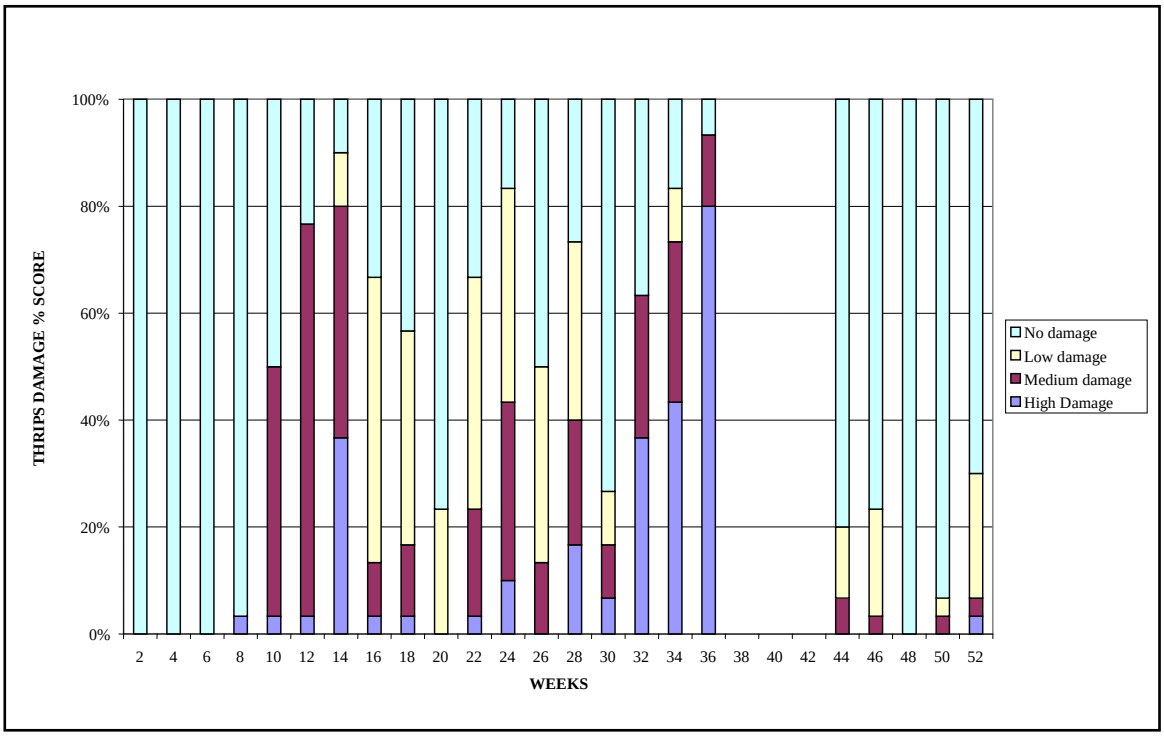


Figure 3.32 Imjabulo Seedling: fortnightly thrips damage percentage score.

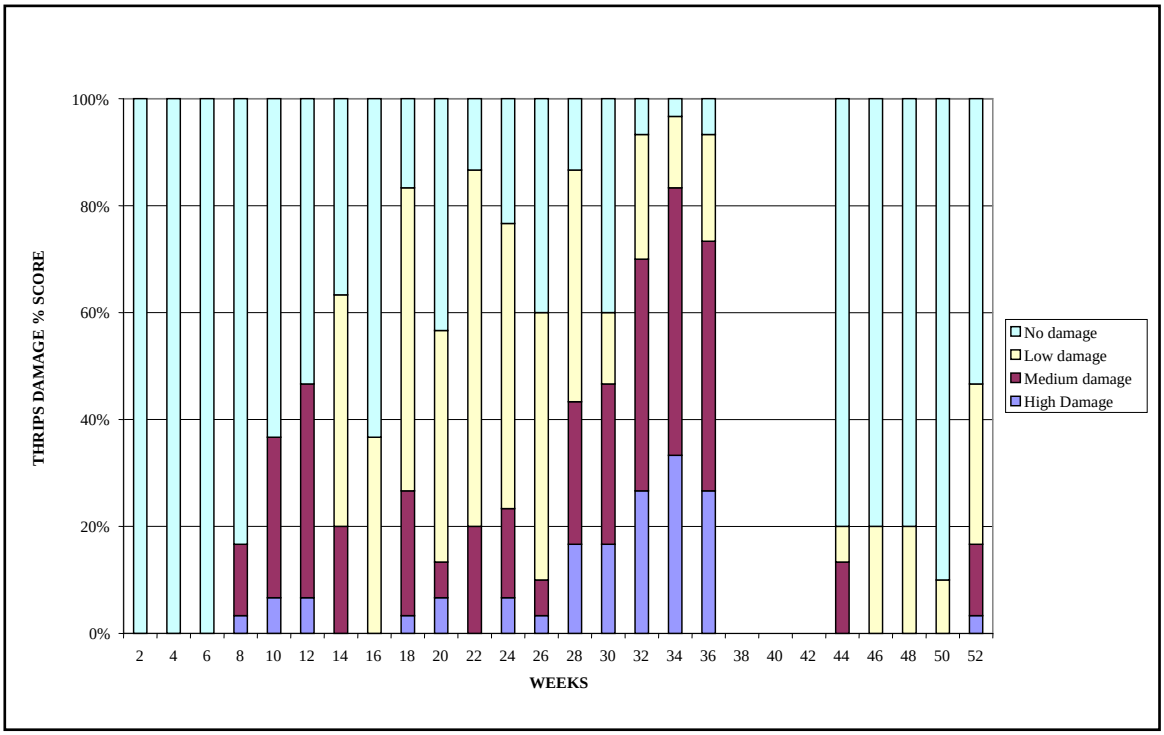


Figure 3.33 Varnam Seedling 1: fortnightly thrips damage percentage score.

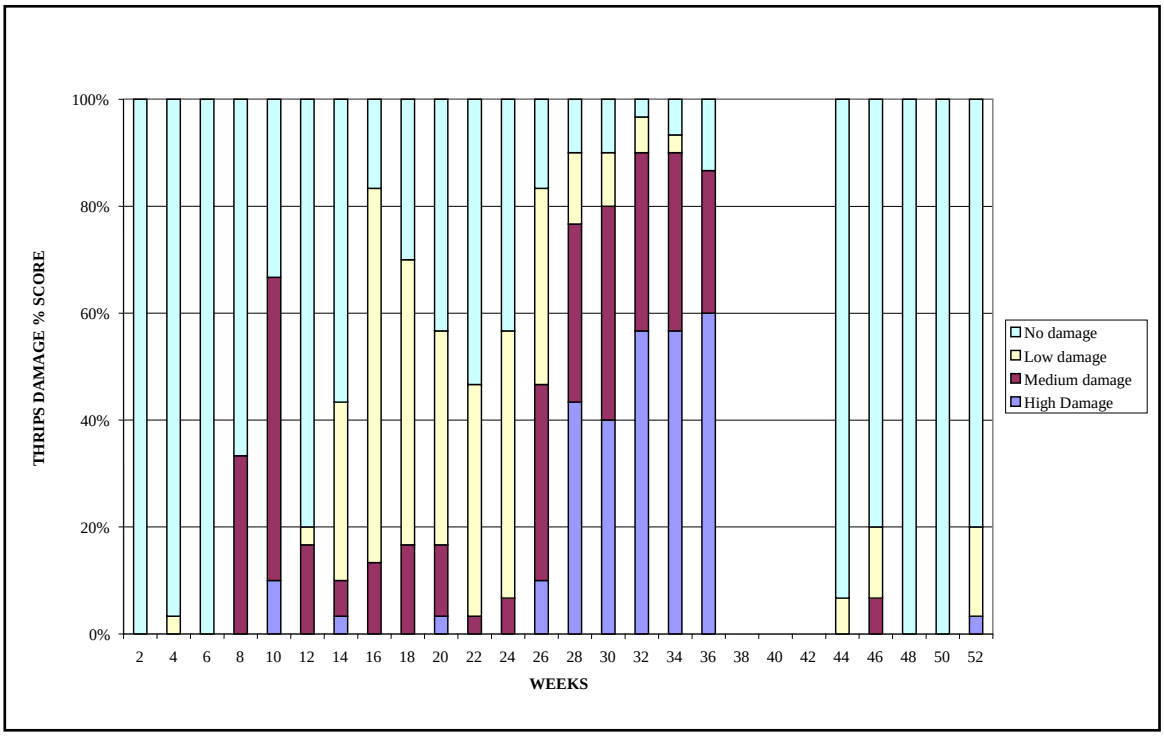


Figure 3.34 Varnam Seedling 2: fortnightly thrips damage percentage score.

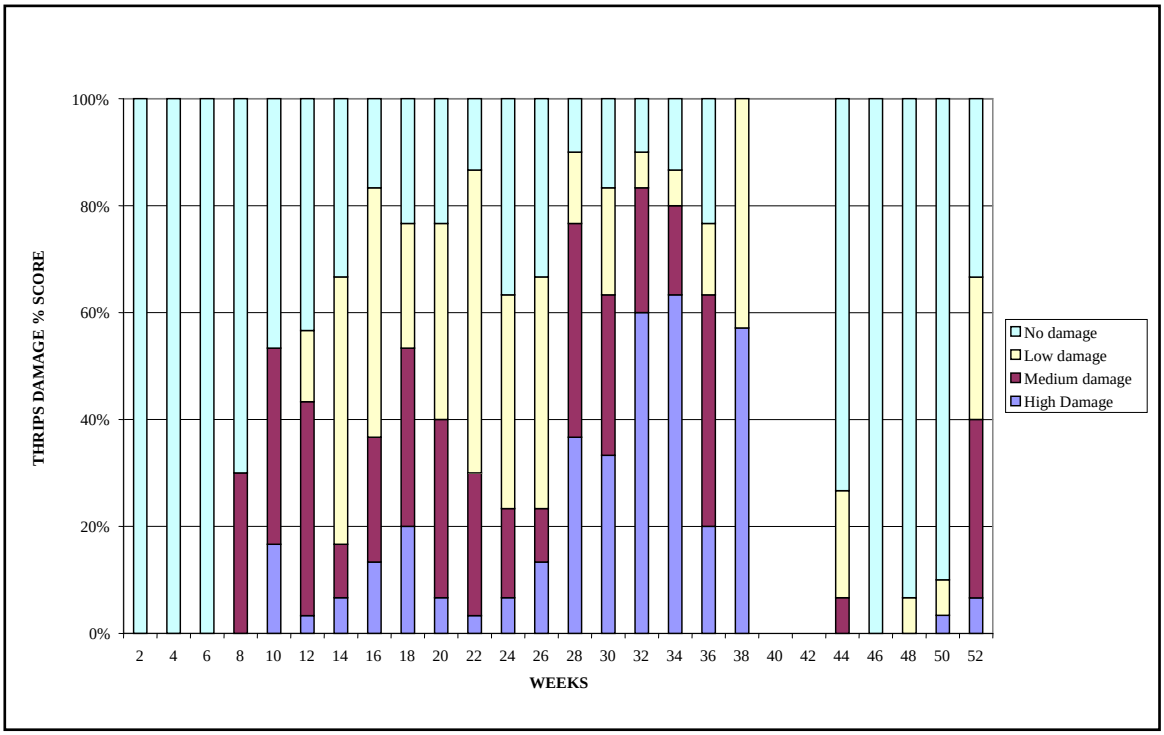


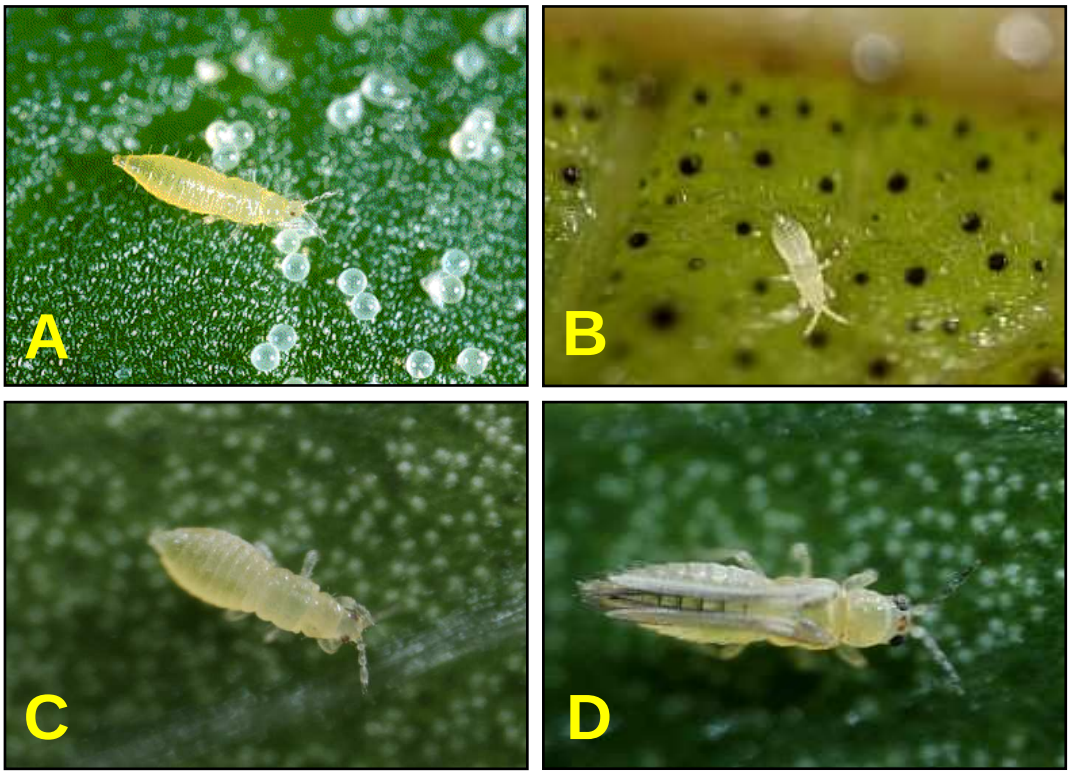
Figure 3.35 Lower Melrose Seedling: fortnightly thrips damage percentage score.

3.8.3 Discussion

Thrips often lack obligate diapause, are multivoltine and polyphagous. They have high fecundity with short generation times and many species are predisposed to parthenogenesis (Mound & Teulon 1995, Mound & Marullo 1996, Mound 1997, Worner 2002, Kirk & Terry 2003, Shelton *et al.* 2003). It is difficult to predict the occurrence of thrips with any certainty, either temporally or spatially as populations tend to fluctuate enormously (Hoddle & Robinson 2004).

Thrips life cycles vary with suborder. Species belonging to the suborder Tubulifera lay their eggs externally on host plant material, their metamorphosis consists of two larval instars and two pupal stages (Figs. 3.36A-D). Species belonging to the suborder Terebrantia lay their eggs within the host plant tissue, have two larval instars, one propupal and one pupal stage. Because of the wide variation in life cycle developmental time within and between thrips species, an average range of the stages in the life cycles were calculated using time scale data from Lewis (1973). The average time for an egg to hatch is 4.4 days, followed by two larval stages totalling 7 days. The propupa, pupa I and pupa II stages average out at 4.5 days and adult longevity averages 34.3 days. The average life cycle of thrips species was calculated at 50.2 days, or 7.2 weeks.

Thrips feed by piercing and rasping the surface of the fruit or leaf with their mouthparts, at the same time releasing substances which help predigest the plant tissue. Liquids are released from the plant cells which are then taken up by the thrips. Plants infested with thrips may not be able to photosynthesize properly, can loose a lot of water and dehydrate, and may become prone to pathogens through the damaged tissue (Figs. 3.37A and B).



Figures 3.36A. Thrips eggs. **B.** First instar larva. **C.** Second instar larva **D.** Adult thrips. (Photo Credits: **A.** Regents University of California. **B.** University of Florida. **C & D.** University of Florida).

Figures 3.37A & B. Thrips damage on *Capsicum* plants (Photo Credits: University of Florida).

IV

DISCUSSION

4.1 Consolidation of findings

The aims of this study are set out in Section 1.4. It is hoped that by achieving these aims, implementation of control methods can be devised incorporating IPM practices in managing major insect pests.

The species of *Capsicum* under cultivation was identified independently by three specialists as *Capsicum baccatum* var. *pendulum*. This information was important as the phenology of the plant has to be taken into account when undertaking a study such as this.

A total of 1415 insect specimens belonging to 8 orders were collected from the dry traps. Reference collections were prepared and identified to genus and species level, where possible, by specialist entomologists. An insect reference collection has been prepared and a database created listing insects associated with *C. baccatum* (Appendix 4).

Very little was known about best practices for cultivation or about the insects and disease associated with *Capsicum baccatum* var. *pendulum*. An extensive literature review of both international and domestic resources provided very little base-line information about the insect communities of capsicums. The insects caught during this study period differed somewhat from those found in New Mexico (cf. Table 1.3). New Mexico has a number of beetles, specifically species of Chrysomelidae, and hemipteran pests associated with cultivated *Capsicum*. The insect pests found in Tzaneen (cf. Table 1.5) are similar to

those found in the Makana District with the exception of the tephritid *Ceratitis cosyra*, which does not occur so far south, and *Ceratitis rosa*, of which only 7 individuals were caught during the whole study period.

4.2 Overview of *Capsicum* pests in the Makana area

The *Capsicum* growers in the Makana district ratooned some of the previous years' lands to see whether the crop would be economically viable for a second season. By the addition of this variable, this study also included a comparison between the ratooned and new seedling lands to see whether there were any differences in the insect compositon and phenology regarding type of land. Although a 'control' site would have provided additional data, it was not essential for this study.

Evaluations were made of the composition and densities of the primary pest species and how they varied over time. By analyzing the data collected throughout the study period, the most frequently occurring insects associated with *Capsicum baccatum* were assessed.

4.2.1 African Bollworm

The African Bollworm, *Helicoverpa armigera*, is generally considered as the most economically important phytophagous insect on cultivated crops in South Africa. Their wide range of cultivated and wild host plants, high fecundity, short generation time, facultative diapause, ability to migrate over vast distances and propensity to develop resistance to insecticides ensures the continued success of this insect pest. African Bollworm populations are unpredictable in that the incidence and severity of damage caused varies on a temporal scale and between crops and regions. High value crops often have a low economic damage threshold, thus causing a reliance on the frequent and often heavy use of synthetic pesticides as a means of control. Populations of *H. armigera* differ regionally in that they target a diverse range of host plants, which can give rise to misinterpretations of pest status on particular crops. One of the factors limiting integrated control programmes is that growers are dealing with a complex of pests and methods of control that may be incompatible (Cherry *et al*. 2003). Natural enemies alone cannot

combat African Bollworm populations and chemical control is often relied upon. In many parts of the world *H. armigera* populations have a propensity to develop resistance to insecticides (Fitt 1989, Cherry *et al*. 2003). Up to 15 treatments per season of broad-spectrum pesticides were sprayed on cotton in South Africa for preventitive control measures against *H. armigera* (van Hamburg & Guest 1997, cited by Cherry *et al*. 2003), the result of which was resistance to a number of insecticides, leading to more insecticide applications and escalating cost to the farmer (Cherry *et al*. 2003).

A spraying programme against *H. armigera* on cotton was developed in 1975 based on scouting egg density counts, reducing the average number of insecticide treatments for preventitive control measures from 15 to 8 applications per growing season. It was later established that egg counts were a poor indicator of the damage caused by larval populations and thresholds based on egg counts lead to excessive insecticide applications (van Hamburg 1981, cited in Cherry *et al*. 2003). A new scouting method was developed based on larval counts, which further reduced average insecticide applications to 2 or 3 per season (Kfir & van Hamburg 1983). This system resulted in a 60% reduction of pest control costs for cotton growers and still holds today (Cherry *et al*. 2003).

Given the highly polyphagous nature of African Bollworm, the total number collected throughout the study period, using monitoring traps and scouting procedures, was not as high as expected. However, population sizes can differ quite considerably from season to season. Because it has been shown that African Bollworm is able to complete its life cycle on *C. baccatum*, it would therefore be advantageous to growers to continue surveillance (i.e. monitoring and scouting) for this pest in the future.

4.2.2 False Codling Moth

False Codling Moth (FCM) (*Thaumatotibia leucotreta*) has been recorded as a major pest of economic importance in South Africa for more than a century. A number of indigenous and exotic host plants act as reservoirs and refuges from which False Codling Moth populations are able to invade cultivated crops. During the study period, the three sites

with the highest number of False Codling Moth adults were Varnam Seedling 1, Varnam Seedling 2 and Varnam Ratooned. On this farm there are a number of mature oak trees (potential hosts) in the vicinity of the sites which may have been the reservoir from which the False Codling Moth adults were lured by the pheromone-based traps. Although a false-positive was recorded for False Codling Moth on *C. baccatum*, they are able to complete their life cycle in this crop. There may be preferred host plants in the surrounding areas, but should those hosts be removed (i.e. destroyed by fire or cut down), False Codling Moth could move into the *Capsicum* lands. Another reason for their relative absence in a damaging capacity in the crop may be because they have not 'found' it yet in space and time. Again, growers should continue to run surveillance programmes in *C. baccatum* lands to monitor this potential pest.

4.2.3 Mediterranean Fruit Fly

Mediterranean Fruit Fly *Ceratitis capitata* caused the most pod damage of the insect pests associated with *C. baccatum*. Mediterranean Fruit Fly also have a very extensive range of plant hosts, both cultivated and wild (White & Elson-Harris 1992). Damage by Mediterranean Fruit Fly to commercially grown fruit can reach up to 100%. Its successful distribution is due to a number of traits. In South Africa Mediterranean Fruit Fly is a year-round pest, highly phytophagous, multivoltine (producing up to 15 generations per year), does not undergo diapause and has a high fecundity. Extensive research continues to be conducted regarding the management of Mediterranean Fruit Fly populations world-wide, incorporating a number of control methods that has led to many positive results.

4.2.4 Thrips

The extent of cumulative thysanopteran damage to *C. baccatum* foliage, incorporating all damage scores, was 47% throughout the study period. Just over half of the plants scouted throughout the study period were not affected by thrips (Table 3.19). Nevertheless, although thrips clearly inflict damage to the crop (cosmetic damage, abscission of buds, blossoms and leaves, photosynthesis reduction due to leaf damage and reduction in pollen yield), the precise nature and extent of such damage on yield remains uncertain. Some of

the species collected and identified were not phytophagous but predatory thrips. Of the four species which are generally of primary economic importance, only two, *Thrips tabaci* (Onion thrips) and *Frankliniella occidentalis* (Western Flower thrips), were collected during the 2005-2006 growing season. The other species of economic importance that were anticipated, *Thrips palmi* (Melon thrips) and especially *Scirtothrips dorsalis* (Chillie thrips), were not collected, if they did occur. *Scirtothrips dorsalis* originally from Asia is a pest on many crops including peppers. *Thrips palmi* became a major pest on curcubits and solanaceous crops in Japan in 1978 and rapidly dispersed internationally causing severe economic damage (Mound 1997).

Thrips adapt to a wide range of environments and are predisposed to an invasive lifestyle which helps increase their distribution. The successful establishment of thrips is due to a number of biological and behavioural traits: they are polyphagous, multivoltine, have a high rate of fecundity with short generation times, often lack obligate diapause and many species are parthenogeneic. Thrips are also vectors of numerous pathogens and viruses including the tomato spotted wilt *Tospovirus*. Thrips populations radically fluctuate and are difficult to predict. Control of thrips populations is problematical. Natural enemies are usually generalist predators that prey on a number of arthropods. Parasitoids are usually specific at subfamily level and cause only a low level of mortality. Fungal entomopathogens rarely control populations and there are no known thrips viral diseases. The application of chemical insecticides with minimal toxic residue and no adverse impact on natural enemies should be adopted.

4.3 Composition and phenology of insect pests

The results clearly show the seasonal changes in population densities for each of the principal insect pests of *Capsicum*. Each species is multivoltine and their fluctuations vary seasonally both within and among the pest populations (cf. Figs. 3.2, 3.3, 3.5, 3.7, 3.8, 3.10, 3.12, 3.13, 3.15, 3.17, 3.18, 3.24 and 3.26; Tables 3.4, 3.8, 3.12 and 3.16).

4.4 Economic implications of *Capsicum* pests in the Makana area

For an insect to reach 'pest status', from a producer's point of view, the classification would largely be based upon the economics involved in controlling the insect and producing of the crop (Pedigo & Rice 2006). Many consumers are not prepared to accept damage or blemishes on market produce, whether it is purely superficial or not. Insecticide residues are also not acceptable to the local consumer and many countries importing produce have stringent criteria regarding insecticide residues which are strictly enforced. Insecticide applications are detrimental to pests' natural enemies because few insecticides are target-specific. There is also an added risk of pests developing resistance to insecticides through natural selection, which may be achieved by a mutation in a single gene within a population (Hemingway *et al*. 2002, Pedigo & Rice 2006). The accidental introduction or dispersal of a resistant pest species may be facilitated through natural migration or human transportation (i.e. export produce) over a large area in a relatively short period of time (Denholm *et al*. 2002).

The timing of control measures often relies on determining thresholds. An accurate assessment of pest populations and calculating potential yield losses will help to determine when control measures should be implemented. Unfortunately, a quantitative measure of damage to plants and fruit in this study could not be related to the total number of the four predominant insect pests. Although infestation of fruit on the plants was recorded for each of the sites throughout the study period, a system to quantify damaged fruit, which was pre-sorted and left in the lands by the picking crew, was not in place. Further sorting was undertaken at the processing factory and here too, there was no system in place to record rejected fruit. Fruit infestation levels need to be determined and recorded both in the lands and at the factory to calculate loss of yield and economic threshold levels. This would be especially valuable with regard to *Ceratitis capitata*. The economic implication of establishing these thresholds is enormous. Costs of insecticide applications and day-to-day farming expenditure could be significantly reduced.

It is evident from Tables 4.1-4.3 that there were no significant differences per hectare in the extent of damage between type of land (i.e. ratooned and seedling). Thus, the

economic solution for the grower is simply related to differences in input costs (i.e. fertilizer, herbicides, insecticides, labour, running costs and transport), associated with the seedling and ratooned lands.

A cost analysis was undertaken to establish the economic loss given certain percentages of damage for the 2005-2006 season. The price per ton of fruit was R2800.00. The mean number of pods per plant was calculated as 86 (70 plants sampled and the mean total pods calculated). These calculations were based on the premise of 24700 plants planted per hectare (spacing of 45 cm between plants and 1.8 m between rows). The average number of pods per crate was calculated as 909. Full crates of fruit weigh an average of 10 kg (this is excluding tare of the crate, which is 2 kg). Insect-induced pod loss is unevenly distributed among lands when adjusted on a per hectare basis as is apparent from Tables 4.1-4.3. The proportion of rejected fruit at the factory was 15%, which included pods rejected mainly on cosmetic grounds such as colour and size, and to a lesser degree damage or infestation by insects (D. Duncan, pers. comm.). Given the average percentage rejection rate at the factory of 15%, damage during the 2005-2006 season would probably have been between 20 and 30%.

Table 4.1 Total weight (metric tons) should there be no damage.

Lands	Size (hectare)	0% Damage	95% Confidence interval	
		Total Weight	Lower 95%	Upper 95%
Total lands	13.23	310.34	293.65	327.04
BR	3.00	70.37	66.59	74.16
IR	0.60	14.07	13.32	14.83
VR	3.00	70.37	66.59	74.16
BS	2.00	46.92	44.39	49.44
IS	0.38	8.91	8.43	9.39
VS 1	2.00	46.92	44.39	49.44
VS 2	1.50	35.19	33.29	37.08
LMS	0.75	17.59	16.65	18.54
Ratooned	6.60	154.82	146.49	163.15
Seedlings	6.63	155.52	147.16	163.89

Table 4.2 Total possible income (South African Rands) should there be no damage.

Lands	Size (hectare)	0% Damage	95% Confidence interval	
		Total Possible Income	Lower 95%	Upper 95%
BR	3.00	197044.37	186445.10	207646.25
IR	0.60	39408.87	37289.02	41529.25
VR	3.00	197044.37	186445.10	207646.25
Total ratooned	6.60	433497.62	410179.22	456821.75
BS	2.00	131362.91	124296.73	138430.83
IS	0.38	24958.95	23616.38	26301.86
VS 1	2.00	131362.91	124296.73	138430.83
VS 2	1.50	98522.19	93222.55	103823.13
LMS	0.75	49261.09	46611.28	51911.56
Total seedlings	6.63	435468.06	412043.67	458898.22
Total production	13.23	868965.68	822222.90	915719.97

Table 4.3 Loss of income (South African Rands) per land given damage at 5% increments.

Lands	Size (hectare)	Lost income per 5% increment in damage		
		Average	95% Confidence interval	
			Lower 95%	Upper 95%
BR	3.00	9852.22	9322.26	10382.30
IR	0.60	1970.44	1864.45	2076.46
VR	3.00	9852.22	9322.26	10382.30
Total ratooned	6.60	21674.88	20508.97	22841.06
BS	2.00	6568.15	6214.84	6921.54
IS	0.38	1247.95	1180.82	1315.09
VS 1	2.00	6568.15	6214.84	6921.54
VS 2	1.50	4926.11	4661.13	5191.16
LMS	0.75	2463.05	2330.56	2595.58
Total seedlings	6.63	21773.41	20602.19	22944.91
Total production	13.23	43448.29	41111.16	45785.97

Bearing in mind that 5% increments represent a 1-in-20 proportion, this may be useful in designing a scouting programme to establish damage on a plant-to-plant and individual land basis. Twenty random pods, from various levels of the plant, could be individually inspected for damage and a proportion of damage calculated.

Modern agricultural practices have brought about some major changes in the agricultural industry, not all of which have been constructive. Monocultures, where a single crop is grown over a large tract, have led to diminished diversity in the flora that provides suitable habitats for beneficial insects. If the crop is under irrigation, this will encourage pest population growth because a food source is provided over a longer period of time. Cultivars have been developed to improve yields, but in some instances, the production of secondary chemical defensive compounds are inadvertently reduced or bred out of the plants (Harborne 1986). Natural defences of the plants are weakened, making the plants more susceptible to pests.

4.5 Pest control strategies in general

Preventative strategies within an IPM framework (i.e. the use of pesticides, biocontrol, monitoring, trap cropping) are implemented without reference to pest population sizes, whereas remedial strategies, primarily the application of pesticides, are based on the calculation of an economic injury level (EIL). With regard specifically to the *Capsicum baccatum* crop, preventative measures are more practical than remedial strategies, given the fact that once a pod is damaged it is worthless. Therefore no EIL's need to be calculated for African Bollworm, False Codling Moth or Mediterranean Fruit Fly damage to *C. baccatum*. However an EIL could be calculated for damage caused by thrips, which targets growth stages of the plant as opposed to the other three insect pests which primarily damage and destroy the pods.

4.5.1 Surveillance programmes

It has been reiterated throughout the literature that scouting and monitoring go hand-in-hand, as both are equally important aspects of surveillance. Surveillance programmes are used to determine whether pests are present, and to provide an estimate of the size, distribution and dynamics of their populations (Pedigo & Rice 2006). Insect pest surveys entail collecting information about an insect population at a particular time within a given area. The survey may be conducted over a growing season or at a specific stage of the pest's life cycle (Higley & Peterson 1994). The biology and ecology of the pest needs to be understood and too often the complete natural history, which is an important component of applied science, is ignored (Walter 2003). Quantitative surveys are used where the abundance of pest populations are sampled in time and space and future population trends and possible damage can be calculated and appraised (Pedigo & Rice 2006). A quantitative estimation of the population density can be estimated by sampling according to statistical principles.

Silverstein (1990) established the major causes for failure in past large-scale field tests, which are also applicable to small-scale field work: a) insufficient knowledge of insect behaviour; b) inadequate definition of chemical communication systems; c) high

population density; d) insufficient resources; e) inadequate pheromone formulations; f) improper distribution of traps or release sources; g) invasion of insects from outside the test area; and h) poor timing. These aspects need to be considered when conducting field work.

The method adopted was of considerable importance in determining the surveillance programme and type of traps to use to monitor insect populations. A surveillance programme needs to be specifically developed for a cropping system. If the methodology is simply adapted from another crop, this could well lead to generalisations being made predicated on false assumptions. Many factors contributed towards creating the surveillance programme, including which traps were best suited for monitoring and how many plants per site must sampled to obtain statistically rigorous data. The scouting pilot trial established the number of plants per site to be sampled (cf. Section 2.2.3). The number of sampling techniques was also statistically analysed, reducing the techniques employed from six to two. Both calculations were invaluable as they provided parameters in which to work and proved to be both labour- and time-saving, and most importantly, were completely supported statistically.

4.5.2 Intervention strategies

4.5.2.1 Cultural control methods

Agronomic practices to reduce the occurrence of insect pests in a variety of cropping systems include manipulation of planting times and crop composition, planting of early-season hosts to attract and entrap the first generation, cultivation of stubble, destroying crop residues and removing or manipulating alternative hosts. Cultural control methods may include environmental manipulation, making habitats attractive to natural enemies, providing additional resources such as nectar and pollen producing plants or supplementary food sprays to boost natural enemy survival, fecundity, longevity and behaviour thereby increasing their effectiveness (Landis *et al*. 2000).

In trying to establish some measure of control for the four insect pests, one aspect is constant throughout, that of land sanitation. All dropped fruit should be collected and destroyed on a regular basis (i.e. by burying the discarded fruit or putting it through a hammermill) (Grové 2001). This will help to reduce further infestation of the crop. However sanitation alone is not effective as insect pests may invade the lands from surrounding areas (e.g. *C. capitata*). Cultivating between rows and hoeing between plants to eliminate weeds not only removes possible alternative hosts but also loosens and turns the soil over, enabling natural enemies to access larvae and pupae.

Identification and possible removal of alternative host plants around *Capsicum* lands should be considered. Three common alternate hosts for *C. capitata* in South Africa are bugweed (*Solanum mauritianum*), wild growing guava trees and bramble (Grové 2001). A research study, conducted by Cockburn (2007), identified a number of host plants in the natural vegetation surrounding *C. baccatum* lands on Varnam Farm. Plants from indigenous thicket, weeds and invasive alien species were collected and identified. The most probable indigenous host plant species were *Harpephyllum caffrum* (Bernh.) (Anacardiaceae), *Clausena anisata* (Willd.) (Rutaceae), *Sideroxylon inerme* (L.) (Sapotaceae) and *Olea europea* subspecies *africana* (L.) (Oleaceae). Alternative weedy host plants included various *Solanum* species, *Opuntia* species and *Passiflora carerulea* (L.) (Passifloraceae). Plants attracting *C. capitata* parasitoids and predators can be grown on the perimeter of the land or even interspersed within the crop.

Greathead & Girling (1989) suggested that by making improvements to cultural control in traditional farming, aimed at conserving and enhancing natural enemy populations, the prospect of biological control of *H. armigera* in Africa would be very favourable. It has been shown that *H. armigera* parasitoids are associated with certain food plants, and this affects the pest mortality rates in different cropping systems (van den Berg *et al*. 1990, van den Berg & Cock 1993).

Management of pests using cultural control methods is not always possible. Thrips population numbers are reduced to a degree by the removal of weeds and other host

plants from lands and surrounding vegetation. However these methods, together with planting cover crops, windbreaks and modifying tillage practices have been largely ineffective in controlling thrips populations (Groves *et al*. 2002, Hummel *et al*. 2002).

4.5.2.2 Biological control

Biological control is the use of a pest species' natural predators, pathogens or parasitoids, which are often highly species-specific, to bring about control rather than relying on synthetic insecticides (Davies 1988, Kogan 1998). For example, Pell *et al.* (1993) conducted a study dispersing the pathogen, *Zoophthora radicans* Brefeld. (Zygomycetes: Entomophthorales) using a diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae) pheromone-based trap. Rather than the uncontrolled application of synthetic insecticides, some alternative means of pest control could be considered within an IPM framework.

Due to the phylogenetic differences among the four insect pests under discussion and the fact that some of the natural enemies are species-specific, each of the four pests are considered separately in this section.

A. African Bollworm

Without the application of pesticides, natural control of *Helicoverpa* species is inadequate in preventing economic damage to many high value crops (Fitt 1989, Bedford *et al*. 1998). Predator numbers do not reach the densities required to control *H. armigera* populations (Fitt 1989). Generalist predators associated with *H. armigera* in different cropping systems in Africa have been studied by van den Berg *et al.* (1988), van den Berg & Cock (1993), Watmough (1991, cited in Cherry *et al*. 2003), Watmough & Kfir (1995) and van Hamburg & Guest (1997, cited by Cherry *et al*. 2001). Predators from Africa include species of Anthocoridae and Reduviidae (Hemiptera), Carabidae, Staphylinidae and Coccinellidae (Coleoptera), Asilidae (Diptera), and Vespidae, Eumenidae, Sphecidae and Formicidae (Hymenoptera) (van den Berg *et al*. 1988). However further studies conducted in South Africa by Watmough (1991, cited in Cherry *et al*. 2003), Watmough & Kfir (1995) and van Hamburg & Guest (1997, cited by Cherry *et al*. 2003) produced an

even more comprehensive list of predators, including a mouse, *Mastomys natalensis* (Smith), as an important pupal predator. There are no records of introductions of exotic predators to Africa. Predators are not normally host-specific, which would be a limiting factor with regard to the possible importation of exotic species (Cherry *et al*. 2003).

Studies on the natural enemies of *H. armigera* have mainly concentrated on egg and larvae parasitoids. The wasp, *Telenomus ullyetti* Nixon (Hymenoptera: Scelionidae), is an egg parasitoid specific to *H. armigera*, whereas *Trichogramma* spp. (Hymenoptera: Trichogrammatidae), also an egg parasitoid, have a wide range of lepidopteran hosts (Cherry *et al*. 2003) (Fig. 4.1). According to Fitt (1989), some *Trichogrammatoidea* spp. and *Microplitis demolitor* (Hymenoptera: Braconidae), which target the early instars, provide some level of control.

Larval parasitoids predominantly belong to the families Ichneumonidae, Braconidae (Hymenoptera) and Tachinidae (Diptera). Most of them attack a range of host species, although five braconid wasps of the genus *Cardiochiles* have been recorded only on *H. armigera* (Cherry *et al*. 2003). Effectiveness of larval parasitoids is generally minimal as, although the rate of feeding is diminished, the host is not killed until the final instar or pupal stage when considerable damage has already been caused (Fitt 1989).

Figure 4.1 *Trichogramma* species, egg parasitoids of *Helicoverpa armigera*. (Photo Credit: Denis Crawford, www.bugsforbugs.com.au).

With regard to abundance and action of natural enemies, polycultures are preferable to monocultures. This is also consistent with ecological theory, where predictions are that insect pests find host plants more readily in a monoculture cropping system.

The introduction of exotic parasitoids does not always have positive results. It is difficult to establish the impact of egg parasitoids as *H. armigera* eggs have a naturally high rate of mortality. Numerous unsuccessful attempts have been made at biological control on *H. armigera* in South Africa through the introduction and augmentation of exotic and indigenous larval parasitiods (Cherry *et al*. 2003).

Greathead & Girling (1989) state that classical biological control measures do not seem promising because of the highly favourable traits *H. armigera* populations possess to be a successful insect pest (i.e. the high degree of polyphagy, ability to adjust to the seasonality of their habitat and their mobility). Augmentation of natural enemies may be possible in the long term and should be applied in conjunction with the judicious use of selective pesticides, effective sampling and monitoring programmes to determine action thresholds, and the development and conservation of beneficial insect populations. Often natural enemy populations are unable to respond to the mobility and high fecundity of *H. armigera*. Asynchrony between *Helicoverpa* species and their natural enemies is one of the major components limiting the effectiveness of natural control (Fitt 1989).

B. False Codling Moth

Predators include *Rhinocoris albopunctatus* (Stål) (Hemiptera: Reduviidae) and *Orius* sp. (Hemiptera: Anthocoridae) (Newton 1998), *Pheidole megacephala* (F.) (Hymenoptera: Formicidae) that attack pupating larvae (Steyn 1954, cited in van den Berg 2001), and shrews (Mammalia: Soricidae) that are believed to feed on pupae (Omer-Cooper 1939, cited in van den Berg 2001).

Gunn (1921) found that egg parasitism is irregular in citrus and guava orchards and that it only increased only from January or February. This was later confirmed by Catling & Aschenborn's (1974) report that *Trichogrammatoidea cryptophlebiae* Nagaraja (= *lutea* Girault) (Hymenoptera: Trichogrammatidae) an egg parasitoid, increased in numbers from January onwards. *Chelonus curvimaculatus* Cameron (Hymenoptera: Braconidae) was reported as an egg-larval parasitoid (Searle 1964, cited in van den Berg 2001, Broodryk 1969). Numerous other larval parasitoids have been recorded in southern Africa, specifically *Apophua leucotreta* (Wilkinson) (Hymenoptera: Ichneumonidae), *Agathis bishopi* (Nixon), *Agathis leucotreta* (Nixon), *Bassus* sp. and *Phanerotoma curvicarinata* Cameron (all Hymenoptera: Braconidae), *Oxycoryphe edax* Waterston (Hymenoptera: Chalcidoidea), and an unidentified tachinid fly (Diptera: Tachinidae) (Newton 1998, van den Berg 2001). Annecke & Moran (1982) state that even though *Trichogrammatoidea cryptophlebiae* is an abundant natural enemy and egg parasitoid of *T. leucotreta*, the rate of parasitism is achieved too late in the season to significantly reduce populations.

Biological control has been attempted by releasing vast numbers of *T. cryptophlebiae* in citrus orchards at Citrusdal, Western Cape, South Africa. A parasitoid mass release programme, when used in conjunction with strict orchard hygiene, suppressed the high level of infestation of *T. leucotreta* (Schwartz *et al*. 1982, cited in van den Berg 2001), but numerous parasitoid releases have been undertaken with variable and sometimes unsatisfactory results. Classical biological control of *T. leucotreta* does not seem viable at present, and given information on the distribution of its natural enemies, the prospects seem poor (CIBC 1984).

C. Mediterranean Fruit Fly

Parasitic Hymenoptera, especially species of the Opiinae (Braconidae), attack larvae and puparia of fruit-associated tephritids (Christenson & Foote 1960, Wharton & Gilstrap 1983). Other parasitoids are Chalcidoidea (White & Elson-Harris 1992), *Opius concolor* (Braconidae) (Annecke & Moran 1982), *Opius humilis* (Braconidae) (Du Toit 1998),

Psyttalia concolor and *Psyttalia humilis* (Braconidae) (Grové 2001) and *Trichopria capensis* (Diapriidae) (Annecke & Moran 1982). Wharton *et al*. (2000) reported the most notable of the parasitic Hymenoptera belong to the families Braconidae, Chalcididae, Diapriidae, Eulophidae, Eupelmidae, Eurytomidae, Figitidae, Ichneumonidae and Pteromalidae (Clausen *et al*. 1965, Wharton *et al*. 1981, Hoffmeister 1992).

Birds and rodents have been shown to account for a far higher level of larval mortality than invertebrate predators and parasitoids (Drew 1987). Pupae are also targeted by predators and parasitoids. Ants are efficient predators (Wong *et al*. 1984) and are able to inflict a reasonable measure of mortality on tephritid pupae. Other ants include *Pheidole megacephala* Fabricius and the fire ant, *Solenopsis geminata* Fabricius, which are also *C. capitata* predators (Hodgson *et al*. 1998). Bateman (1972) identified other invertebrate predators: Carabidae and Staphylinidae (Coleoptera), Chrysopidae (Neuroptera) and Pentatomidae (Hemiptera). Hodgson *et al*. (1998) reported that by loosening the soil surface, ant predation and movement is increased as pupae become more exposed thus increasing predation and mortality rates. Soil disturbances caused by farming practices (i.e. cultivating and manual hoeing), present additional opportunities for predators and parasites (i.e. birds, ants, beetles and wasps to name a few).

Fopius arisanus Sonan, (Hymenoptera: Braconidae) was established in Hawaii as a biological control agent for fruit fly and is regarded as one of the most successful biological control achievements (Lopez *et al*. 2003). Another braconid parasitoid, *Fopius ceratitivorus* Wharton, was discovered during preliminary surveys for a biological control programme on coffee berry borer. This recent discovery demonstrates the necessity for more extensive research on the natural enemies of *C. capitata* in Africa (Wharton *et al*. 2000). Unlike other biological control parasitoids, *F. ceratitivorus* was collected from *C. capitata* in east Africa, its purported region of origin. *Fopius ceratitivorus* oviposits into *C. capitata* eggs and recently hatched larvae, and complete their development in the host's puparia. Their ability to parasitise eggs and early instar larvae is a valuable trait in biological control agents. However, some parasitoids are generalists and may attack a

number of insect species. This may be a ‘double-edged’ sword as limiting attack to targeted pests is not possible (Sivinski 1996).

D. Thrips

One of the factors adding to the establishment of any successful invasive species in newly colonised regions is that their natural enemies (i.e. predators, parasitoids, parasites and pathogens) may not move with the population or may be absent from the new ecosystem (Keane & Crawley 2002, Shea & Chesson 2002, Torchin *et al.* 2003).

The natural enemies of thrips are mostly generalist predators (i.e. predatory thrips (*Franklinothrips* spp.) and phytoseiid mites (*Neoseiulus* spp.), that prey on a number of arthropods (Hoddle *et al.* 2004, Hoddle & Robinson 2004). Other predators include green lacewings, *Chrysopa* and *Chrysoperla* spp. (Chrysopidae), minute pirate bugs, *Orius* spp. (Hemiptera: Anthocoridae) and *Macrotracheliella nigra* Parshley (Hemiptera: Anthocoridae), predatory mites, *Euseius* spp. (Phytoseiidae: *Amblyseius*), *Anystis agilis* (Banks) (Anystidae) and *Euseius tularensis* Congdon (Phytoseiidae). Fungal entomopathogens, *Neozygites* spp. (Neozygitaceae) and *Verticillium* spp. (Hypocraeceae) rarely control thrips populations even though some are uniquely associated with thrips (i.e. *Entomophthora thripidum* (Entomophthorales: Zygomycetes) and *Neozygites parvispora* (Entomophthorales: Zygomycetes) (Butt & Brownbridge 1997). Various hymenopteran egg parasitoids, *Megaphragma* spp., *Megaphragma mymaripenne* Timberlake (Trichogrammatidae), larval parasitoids, *Ceranisus* spp. (Eulophidae) and a larval endoparasitic wasp *Thripobius semiluteus* Bouček (Eulophidae) have a tendency to be specific at subfamily level but rarely to genus and generally only low levels of mortality are caused (Morse & Hoddle 2006, Dreistadt *et al*. 2007). Parasitic nematodes specialising on thrips, *Thripinema* spp. (Tylenchida: Allantonematidae) will delay oogenesis in females although growth rates do not alter and it is uncertain as to whether control of field populations can be achieved by these worms (Loomans *et al.* 1997, Lim *et al.* 2001). No viral diseases of thrips are known (Morse & Hoddle 2006).

Although beneficial insects are used as biological control agents for thrips species, control using this technique is limited (Parrella & Lewis 1997, Neuenschwander & Markham 2001, Hoddle *et al*. 2002, Hoddle & Robinson 2004, Morse & Hoddle 2006). It may be more advantageous to preserve and establish populations of natural enemies as part of an integrated pest management programme. The rate of insecticide applications need to be reassessed and the possibility of switching to products with little or no toxic residues or adverse impact on natural enemy populations considered.

4.5.2.3 Bioinsecticides and Pathogens

The use of biopesticides is becoming more frequent as further research is undertaken. Christian *et al*. (2005) carried out the first comprehensive field trial using *Helicoverpa armigera* stunt virus (HaSV) (Tetraviridae: *Omegatetravirus*) as a control agent in a sorghum cropping system. Results showed a reduction of 50% in larval populations in sorghum, indicating that HaSV can be utilized as an effective control measure. *Helicoverpa armigera* nucleopolyhedrovirus (HearNPV) (Baculoviridae) has been shown to have a major impact on both damage and fruit cull on citrus (Moore *et al*. 2004). Research using HearNPV isolates in Africa is limited, although Roome (1975) conducted comprehensive trials on sorghum and cotton in Botswana. Control and efficacy on cotton was marginal, but long-lasting control and high efficacy was attained on sorghum.

Van den Berg (2001) reported that a fungus, *Beauveria bassiana*, has often been recorded from *T. leucotreta* pupae found in leaf litter. Schwartz (1981, cited in van den Berg 2001) observed that an unidentified granulovirus infected and destroyed *T. leucotreta* larvae in laboratory cultures. These two findings have facilitated the development of alternative means of control. Moore (2003) developed and evaluated a biological control agent, *Cryptophlebia leucotreta* granulovirus (CrleGV) for management of *T. leucotreta* populations on citrus. *Thaumatotibia leucotreta* females oviposit throughout the period when a host plant bears fruit (Newton 1998). Eggs are relatively small, translucent and flat and are laid singly which makes scouting difficult. On hatching the larva bores into the fruit within a few hours, depending on toughness of the fruit. Therefore the time

window within which to target the neonate larvae, and subsequent larval instars, is extremely limited as it is an internal fruit feeder. A granulovirus has been developed by Cirtus Research International (Pty) Ltd from a naturally-occurring indigenous pathogen, *Cryptophlebia leucotreta* granulovirus (CrleGV-SA), and is commercially produced by River Bioscience (Pty) Ltd and registered for use on citrus in South Africa as Cryptogran™. The product is sprayed onto the crop and *T. leucotreta* neonate larvae ingest the virus particles while boring into the fruit. The particles are absorbed through the microvilli of the midgut and replicate. The virus infects the larva's entire body, causes cessation of feeding and the larva exits the fruit and in due course dies. The integument of the infected larva eventually ruptures, releasing millions of virus particles into the environment where other larvae may be infected.

Although Cryptogran™ is currently registered for use on citrus, research determining its application on other economically important crops is presently being conducted. Two applications of Cryptogran™ per season in citrus orchards are recommended; the first to coincide with the initial major peak in *T. leucotreta* which occurs around December in South Africa; and the second application 3-4 weeks prior to harvest. Two years' worth of data has been collected from field trials on avocados which will soon be included in the registration for the use of Cryptogran™. Laboratory trials have been conducted on grapes and plums and formal field trials for grapes, and possibly also persimmons and pomegranate, are planned. Although registration does not presently include avocado, grape, litchi, persimmon and pomegranates, some commercial growers have used Cryptogran™ on these crops, albeit without River Bioscience (Pty) Ltd's recommendation (Moore pers. comm. 2007).

Entomopathogenic fungi have been evaluated as a potential IPM tool against injurious insect pests. Ekesi *et al.* (2002) conducted laboratory trials where a high mortality rate of *C. capitata, C. rosa* and *C. cosyra* puparia was achieved using entomopathogenic fungi, *Metarhizium anisopliae* and *Beauveria bassiana,* which led to a significant reduction in adult emergence. However fungal entomopathogens rarely control thrips populations and there are no known thrips viral diseases.

A commercial formulation of Neem, a plant-derived bioinsecticide, was tested on *C. capitata* to determine its effect on fecundity and longevity. Laboratory tests showed that the Neem compound significantly reduced fecundity by interfering with oogenesis and resulted in sterility of *C. capitata* females (Di Ilio *et al.* 1999). Although some organic farmers use dried chilli powder to discourage pests, the method for doing this is not published.

Baculoviruses are a widely studied group of insect pathogenic viruses, which are often species-specific. They have been used, in particular, on lepidopterous pests as control agents and have no known adverse ecological or health effects (Davies 1988). Casida & Quistad (1998) reported that effectiveness of baculoviruses is limited because of their photosensitivity and slow action. The use of a granulovirus as a component of Integrated Pest Management has many advantages: it is species-specific; chemically there are no harmful effects to natural enemies, humans or the environment; it is compatible with chemical control programmes; no pre-harvest intervals are required, and there are no residual chemical effects. Research in these areas has been and is still being conducted and the use of baculoviruses form an integral part of pest control.

4.5.2.4 Pesticides

As producers become more aware of the benefits of IPM programmes, a shift is being made towards a more holistic approach to pest management resulting in a decrease in frequency and number of insecticide spray applications. The implementation of restrictions by government bodies in some countries has lead to the reduction, and in some instances banning, of particular insecticides used to control pest populations (i.e. for African Bollworm which has developed resistance to a range of pesticides).

Monitoring pests is an integral part of an effective control strategy, and crucial in determining population build up and pest presence. Economic thresholds are yet to be determined for some pest (i.e. Tephritidae) populations in different commercial cropping

systems. A sudden increase of pest populations in the crop gives an indication of when chemical control may be required. For chemical control to be economically and efficiently applied, growers should maintain monitoring records and information for all previous seasons to enable them to make an informed decision of when to apply control measures and, if necessary, full-cover insecticide sprays.

There are no chemical insecticides registered for the control of *T. leucotreta* on the tropical and subtropical crops listed earlier (cf. Section 3.6.1). Chitin synthesis inhibitors, used for the control of the litchi moth, *Cryptophlebia peltastica*, will control *T. leucotreta* populations on litchi and damage to macadamia is reduced when endosulfan, cypermethrin or cyhalothrin are used for the control of Pentatomidae. A mark-release-recapture experiment was conducted using coloured water (van den Berg 2001) and this showed that adults drink water. This information is useful when looking at alternative ways of controlling populations possibly by using an insecticide-based baiting and pheromone-based trapping programme.

Three compounds (Malathion, Spinosad and Phloxine B) used in bait sprays to suppress fruit fly populations were tested by Vargas *et al*. (2001) for mode of kill and their effect on non-target natural enemies. Malathion kills by contact, vapour action and stomach poisoning (Matsumura 1975). Spinosad has a limited contact mortality rate and mode of kill is primarily by ingestion (DowElanco 1994). Phloxine B kills by ingestion only (Heitz 1995). From an environmental standpoint, it is advantageous to use ‘softer insecticides’with IPM programmes and avoid the application of broad spectrum contact poisons (Vargas *et al*. 2001). Research has been conducted by scientists in Hawaii and Texas using Phloxine B (also known as FDA-approved red dye number 28) in controlling *C. capitata* populations. Some insects, such as *C. capitata*, often share regurgitated food, which accelerates the spread of the dye-and-bait mixture through the population (Thomas *et al*. 2001). McQuate *et al*. (2005) used a combination of mass trapping together with a Spinosad-based bait spray, both implemented before fruits became susceptible to *C. capitata* oviposition, and found these control components to be compatible with biological control. A new Spinosad formulation, GF-120, outperforms Phloxine B on a

variety of evaluation criteria including attractiveness, rainfastness, longer efficacy, it is safe to handle and has a positive ecological and organic profile (Barnes, pers. comm.), and deserves serious consideration by *Capsicum* growers.

Fruit fly control in South Africa is undertaken primarily by using a mixture of bait (protein hydrolysate) plus a poison (i.e. Dipterex SP or Malathion). The mixture is usually applied using a tractor-mounted applicator or knapsack sprayer. However baits loose their efficacy after approximately 1 day and are rendered ineffective by rainfall. EurepGAP (The Global Partnership for Safe and Sustainable Agriculture) legislation is in favour of minimising pesticide use out of concern for human safety and environmental issues. Pressure is being exerted on growers to phase out organophosphate baits which are the foundation of *C. capitata* baiting programmes, and the use of Malathion.

Perimeter baiting stations can be set up to try and keep adults out or lure them off the crop. Traps that are well designed, incorporating the appropriate visual cues (i.e. colour and shape) specific to the pest species, can be set up at baiting stations using female-targeted synthetic attractants with a pesticide (Epsky & Heath 1998). Application of a protein bait and insecticide mixture can also be applied along perimeters and to plants or trees associated with resting and feeding areas of adults rather than to the crop itself.

The development of the M3® (Quest Developments CC) bait station has provided the South African citrus industry with an environmentally friendly, non-toxic IPM tool. Approximately 400 M3® bait stations per hectare are set up prior to fruit colour break. Sensus Traps are also set up for monitoring the influx of fruit fly populations. The majority of the M3® Traps are positioned approximately 10m from the perimeter of the land; a reduced number of traps are placed in the second row from the edges (representing the ‘borders’), and the remaining traps are placed in the centre. The number of fruit fly caught in the perimeter monitoring traps were highest followed by the border traps and traps placed in the centre. Using the M3® bait station method, there are no pesticide applications on fruit, there are no known effects on natural enemy populations, the traps and bait are rain-fast and there is no contamination of groundwater systems (Ware *et al*. 2003).

Experiments have been conducted on fruit wounds attracting *C. capitata* in citrus orchards where isolated fruit are artificially wounded which attracted fruit flies (Papaj *et al*. 1989, cited in White & Elson-Harris 1992, Hendrichs *et al*. 2001). As a control method, damaged fruit was treated with a contact insecticide or sticky substance, such as Plantex® or Tanglefoot®, providing some means of control and diverting flies from fruit which is undamaged (Papaj *et al*. 1989, cited in White & Elson-Harris 1992). This, however, would not be a very practical method of control in a *Capsicum* cropping system. Damage to certain fruit by thrips constitutes cosmetic damage only, but this has a negative economical impact on domestic and international export markets. The damage may look unsightly although the integrity of the fruit is not compromised. Because thrips attack terminals of the plant and young fruit at an early stage of development, damage may only be noticed when leaves or fruit are larger, long after the population has left the orchard or land (Dreistadt *et al*. 2007). Most thrips species are difficult to control effectively with insecticides due to their size, cryptic feeding, behavioural and biological traits. To prevent damage, growers usually use insecticide spray programmes as a preventative measure against thrips damage. These spray programmes are usually implemented early on in the season to prevent cosmetic damage.

Other chemical control methods include insect growth regulators, neuroactive insecticides and respiratory inhibitors. Insect growth regulators are modeled on insect juvenile hormones and, under restricted conditions, are extremely effective. Although the safety of the application of these regulators with regard to mammals is evident, they are still limited in agricultural applications by their slow action and are only effective during a narrow window period in the insect's life cycle (Casida & Quistad 1998). Neuroactive insecticides have been used as insecticides for the past 50 years, and are effective, inexpensive and contain ideal properties to overcome otherwise resistant strains, however they have a detrimental impact on the environment. Respiratory inhibitors have played a small role as insecticides, but they have a high toxicity to fish and on other non-target species (Casida & Quistad 1998).

4.5.2.5 Bacillus thuringiensis (Bt) *sprays*

As pressure to reduce chemical application has increased, more emphasis has been placed on plant breeding, the use of molecular manipulation and the development of insect resistant plant varieties. Genetic engineering has had a vast impact on pest control procedures and includes a number of applications. It has made monitoring of resistance genes in natural populations possible. With genetic engineering it is now possible to produce insecticidal peptides and proteins and deliver these to insects via bacterial, baculoviral and plant systems (Davies 1988). Plant geneticists have developed cultivars which are resistant to pests and/or diseases (Kogan 1998). Genetically engineered crops contain a permanent systemic insecticide, *Bacillus thuringiensis* (Bt), and have contributed considerably to the reduction in the amount of synthetic chemical insecticide application (Casida & Quistad 1998).

Bacillus thuringiensis Berliner (Bt) is used against lepidopteran pests in Africa and several subspecies or serovars are effective against *H. armigera* (Glare & O'Callaghan 2000, cited by Cherry *et al*. 2003). Bt has become one of the most important means of controlling lepidopteran larvae in vegetable crops in West Africa (Cherry *et al*. 2003).

Advances have been made in plant breeding and molecular technology programmes to manage *Tospovirus* diseases vectored by thrips (Kuo 1996, Culbreath *et al.* 2003, Whitfield *et al.* 2005). Extensive research has been undertaken to develop vegetable plant varieties tolerant or resistant to thrips, but progress has been slow (Mollema & Cole 1996, Bowman & McCarthy 1997, Shelton *et al*. 1998, Alabi *et al*. 2003, Frei *et al*. 2004,).

4.5.2.6 Trapping strategies

There are many different trapping strategies (i.e. baited or pheromone-based, malaise, pitfall, light), and the biology of the insect should be taken into account when choosing a trapping method. For example, there are contradictory findings as to whether adult *T. leucotreta* are attracted to light traps. Gunn (1921), Catling & Aschenborn (1978) and Begemann & Schoeman (1999) state that adult moths are not attracted to light traps.

However Reed (1974) used black light traps to successfully monitor *T. leucotreta* in cotton over a period of four years.

Pheromone and baited traps play an important role in IPM as they are used for monitoring and surveillance and provide a means of early pest detection and infestation in new areas. Pheromone-based traps may also be treated with insecticides, hormone analogs or pathogens, which are subsequently transmitted through the pest population. Sex pheromones used in baited traps and can be either male- or female-specific depending on the pheromone used in the lure and the biology of the species as some do not produce pheromones. The objective of this method of trapping is to reduce the number of reproductive sexuals as to be insufficient to maintain a population and cause mating disruption. This would depend on the biology of the pest and whether they undergo multiple matings. Removal of males from pest populations, unless the ratio is proportionately higher, is not likely to have a significant impact on the size of future generations as compared to the removal of females from the population (Foster & Harris 1997). Other pheromone trapping functions are mass trapping, disruption of mate-finding or aggregation to suppress pest populations (Silverstein 1981).

The pheromone-based traps proved to be very effective in luring pest insects. However, one of the risks of using pheromone traps is the possibility of a false-positive catch. A false-positive catch is obtained when insects that are not damaging the crop are attracted from outside the crop area by the pheromone lure in the trap, giving a positive datum that is not relevant to the crop. In this study, a false-positive catch was noted for the False Codling Moth (*Thaumatotibia leucotreta*). Only two of the five trap types recorded catches of False Codling Moth; the Mediterranean Fruit Fly Trap and the False Codling Moth Trap. The occurrence of False Codling Moth was almost 100% in the False Codling Moth Traps for all lands over the study period. The presence of False Codling Moth on Mediterranean Fruit Fly Traps may have been purely incidental catches. The mean number of adult False Codling Moth began increasing from around week 5 (19-25 December 2005), and it was surprising that False Codling Moth occurred at this time as there were no suitably sized pods for oviposition present in any of the lands. Weekly

scouting records showed that very few False Codling Moth larvae, 47 in total, were collected from damaged pods throughout the study period. The False Codling Moth false-positive catch is a good example of why monitoring and scouting should run concurrently.

4.5.2.7 Trap cropping

Landscape structure and ecology (i.e. the spatial pattern of vegetative patches, their distribution, size and shape) affect how pests interact with host plants and are influenced by size, fragmentation and connectivity of host patches. These factors affect the deployment of trap crops: a) stands can be planted around the perimeter of the valuable crop; b) sequential trap crops are planted either earlier or later to attract pests off the main crop; c) multiple trap cropping involves planting several plant species simultaneously in order to control several insect pests at once, or providing a changing variety of plant species that are at different developmental and growth stages that enhance their attractiveness to highly polyphagous pest species over the main crop; and d) the push-pull strategy which uses a combination of repellent intercrops and attractant dead-end crops (Cook *et al*. 2007, Shelton & Badenes-Perez 2006).

Different types of trap cropping systems exist. Dead-end trap crops, on which insects and their progeny cannot survive, serve as a sink for pests. Genetically engineered *Bacillus thuringiensis* (Bt) trap crops can be planted early on in the season attracting insect pests and subsequently becoming dead-end trap crops. Genetically engineered plants are also effective in controlling insect-vectored pathogens, where the virus is trapped. Using Bt crops, it is possible to use the same plant species as the barrier crop and the protected crop. Control of the pepper maggot, *Zonosemata electa* (Diptera: Tephritidae), in bell peppers was achieved using hot cherry peppers as a perimeter trap crop (Boucher *et al*. 2003, cited in Shelton & Badenes-Perez 2006).

However, depending on the pest species, the use of trap crops may not be an option. For instance trap cropping has rarely been successfully applied against *H. armigera.* The trap crops may be more attractive than the higher-value crop for a brief period of time before sequential plantings of the trap crop become necessary. There is also the risk of the pest

population building up on a trap crop and acting as a concentrated source before the trap crop can be removed. Ideally, management of *H. armigera* should be applied on an area-wide or regional level. In theory this suggestion sounds practical and in a monoculture system it may succeed, but in most parts of Africa and Asia, where farms are small and farmers grow a number of cash crops, this is probably not feasible (Fitt 1989). When numerous pests from several orders, families and species occur in a cropping system, decisions will need to be taken on which, or how many trap crop(s) should be grown as not all will hold the same level of attraction to all insect pests. The most damaging of the pests would have to be identified and the appropriate trap crops for those insects planted. This would limit the efficacy of this approach somewhat, but used in conjunction with other IPM strategies, trap cropping is still a valuable tool.

4.5.2.8 Push-Pull Strategy

The push-pull strategy is an effective and powerful IPM tool which has not yet been used to its full potential. Push-pull strategies aim to make protected resources hard to locate, unattractive or unsuitable to a pest by using numerous strategies (Cook *et al*. 2007). A combination of IPM methods is employed to manipulate or modify behaviour, causing disruption of pest populations. Stimuli may affect a number of behavioral traits such as normal avoidance tactics to natural enemies, the failure either to locate the host crop or its acceptance as a site for feeding and reproduction. Stimuli may be effective over a long or short range. The push component uses visual and chemical cues; the chemical cues can be synthetic or plant- or insect-derived semiochemicals used to affect host recognition and selection over long ranges. These include synthetic repellents, non-host volatiles, host volatiles, visual cues, anti-aggregation and alarm pheromones. Pest orientation may be disrupted using host-derived volatiles. These are usually present at specific ratios, but when ratios of some of the key volatiles are presented at inappropriate ratios, can lead to the disorientation of insect pests. Short range push strategies affecting host acceptance comprise deterring pheromones, visual cues, anti-feedants and oviposition deterrents. Pull components include visual stimuli, host volatiles, sex and aggregation pheromones, gustatory and oviposition stimulants (Cook *et al*. 2007).

Push-pull strategies also include intercropping and trap cropping. Push stimuli are achieved by intercropping with non-host plants which have repellent or deterrent attributes to the target pest. It also reduces pest densities in crops and provides diversified systems which may lead to an increase in natural enemy abundance and therefore higher herbivore mortality. Trap crops are used to prevent insects from targeting an economically valuable crop by interception or the attraction of insects towards an alternative, less valuable crop where it can be destroyed more easily and economically (Kogan 1998, Shelton & Badenes-Perez 2006, Cook *et al.* 2007). Means of attraction to trap crops can be further enhanced by using semiochemicals. One of the most successful examples of trap cropping took place in California in the 1960s, using alfalfa as a trap crop for *Lygus* bugs in cotton, which is still practiced commercially today (Shelton & Badenes-Perez 2006). Stands are planted to trap crops as a sink, in order to manipulate pests or the pathogens they vector by attraction, diversion, interception or retension thereby reducing possible damage to the main crop (Shelton & Badenes-Perez 2006).

4.5.2.9 Sterile Insect Technique (SIT)

SIT which is highly specific and has no adverse effects on the environment, involves the mass-rearing and release of sterilized males (Davies 1988). Another form of genetic control is the release of males of a subgroup which are genetically incompatible with the local strain of females.

SIT is a successful means of control for a number of pest insects but there are, however, numerous limiting factors when using this technique. SIT is species-specific so, for instance there are 22 species of Tsetse fly in Africa, a technique would have to be implemented for each. The determination of sexuals in some species is sometimes difficult, although in Mediterranean Fruit Fly this is easy to perform. Populations of fertile pest insects are reared in secure facilities, to prevent their escape or release, before irradiation. In February 2003 the irradiation machinery at a facility in Mexico failed and 4

million fertile screwworms were released before the malfunction was detected. There are also human health risks to factory workers in these facilities.

SIT involves the irradiation of large numbers of males rendering them sterile. These sterile males are released *en masse* to mate with females from natural populations in an attempt to markedly reduce the rate of reproduction. Radiation treatment can affect the health of the sterilized males, placing them at a disadvantage when competing for females. For a SIT programme to be successful, an overwhelming number of sterile males need to be released to out-compete the males from the natural populations. A prerequisite however is the application of chemical control prior to mass release in order to reduce the number of naturally occurring males thereby giving the sterile males a better chance of mating with fertile females (Ware *et al*. 2003). The costs of breeding and maintaining large numbers of insects for sterile insect release programmes can be prohibitively expensive and often unattainable for poorer countries. Some governments and federal agencies do however fund SIT programmes on a regional basis. Possible immigration of insect pests through adventive introductions needs to be monitored as there is always the possibility of migration from populations outside the control area. Repeated releases of sterile males are required to exterminate the population.

Eradication programmes (e.g. those implemented for *Ceratitis capitata* and *Cochliomyia hominivorax*), applied on a region-wide scale may include a number of environments, which may exclude the application of insecticide applications. These environments would include urban and suburban locations, national parks, organic growing areas and catchment areas. Under these circumstances it would be crucial to maximise the biological control components (Lopez *et al*. 2003). Cost effectiveness of control methods is potentially limiting to the commercial use of these systems.

4.6 Proposed *Capsicum* pest control strategies for the Makana area

The control of phytophagous insect populations, particularly with regard to high value crops, is not likely to be achieved through classical biological control methods alone.

Cultural control, by manipulating the crop environment to conserve and enhance natural enemies, should also form part of the IPM programme. The use of alternative microbiological insecticides, such as Bt and HearNPV, and botanically-based treatments can be used early in the season to suppress the initial build up of pest populations without destroying the natural enemy populations. A study conducted on cotton in Australia using indigenous predators as the basic component of an IPM programme in conjunction with supplementary food sprays for beneficial insects, intercropping of lucerne, Bt and NPV biopesticides and limited synthetic insecticides, produced yields and economic returns equivalent to, or better than, using a conventional cropping programme (Mensah 2002).

4.6.1 African Bollworm Control Programme

African Bollworm populations were surprisingly low during the 2005-2006 growing season, given their notorius reputation as the most damaging insect pest on cultivated crops in South Africa. However, the low occurrence during this study period does not guarantee this will always be the case. It is therefore suggested that a surveillance programme, including both monitoring traps and scouting, be implemented and maintained for all subsequent seasons.

4.6.2 False Codling Moth Control Programme

During the 2005-2006 study False Codling Moth populations were not deleterious to the *C. baccatum* crop. A false positive was recorded as adults were attracted to the pheromone-based monitoring traps placed in the lands and only very few larvae were present in the crop. False Codling Moth is a potential pest on *C. baccatum* as it has been shown that they are able to complete a life cycle on this crop. A surveillance programme using both scouting and monitoring traps should be applied and maintained for all subsequent seasons.

4.6.3 Mediterranean Fruit Fly Control Programme

During the 2005-2006 growing season, the most damage to the crop was caused by Mediterranean Fruit Fly. A preventative strategy should be put in place for the control of Mediterranean Fruit Fly populations in *C. baccatum*. Populations from surrounding vegetation invade the lands from a number of alternative host plants. Mediterranean Fruit Fly use the surrounding vegetation for shelter during inclement weather as well as reproductive and resting areas. Bait stations and protein-based traps should be deployed *en mass* in the surrounding vegetation and along the perimeter of the land. The number of traps can be decreased further into the land. The bait stations and traps should be set up before the fruit develops to suppress potentially invasive populations. An early baiting programme can control the pest population at a low level during the early stage of the season (Du Toit 1998). Mediterranean Fruit Fly females are polyandrous (i.e. mate with more than one male), and it would seem more logical to target the reproductive females, thereby ensuring the decline of future generations. Females leave their host plants regularly in search of protein and nutrients to increase their fecundity. This would mean that they would have to pass numerous bait stations on their way out of the land as well as on their way back in, thereby increasing their chances of mortality. When using chemical sprays for control, 'softer' insecticide products could be considered which are not as harmful to natural enemies or the environment. In particular, a barrier of GF-120 in the natural vegetation around *Capsicum* lands could be deployed a few weeks before ripening of the pods and the expected influx of fruit flies.

Monitoring traps placed in the surrounding vegetation will give an indication of the direction where the majority of Mediterranean Fruit Fly are invading. Once this is established, a scout can be dispatched to identify possible alternative plant hosts in that area. Most of the pheromone-based traps used for monitoring are male-specific; females are attracted to the protein-based baits. A new trapping system developed by Chempac CC uses a food lure that attracts both sexes. It is very effective when used as a monitoring tool but is too expensive to for mass trapping purpopses (Barnes, pers. comm.).

4.6.4 Thrips Control Programme

Establishing a control programme for thrips on *C. baccatum* is somewhat difficult given their unusual biological and highly invasive traits. No cosmetic damage is caused to *C. baccatum* fruit, but the transmission of viruses and injury to buds, flowers and leaves is damaging to plant health and ultimately to yield. Identification of the numerous thrips species causing the damage must be established. An EIL should be calculated to establish the cost of implementing control measures. The application of chemical insecticides with minimal toxic residue and no adverse impact on natural enemies should be adopted. Spray applications of these 'softer' insecticides should be considered early in the season before buds are present. If early populations are targeted this should reduce the number and size of subsequent populations. Surveillance strategies, which include using a monitoring trap (Yellow Card Trap) as well as scouting for damage to the plant, should be employed throughout the growing season.

4.7 Conclusion

An underlying common factor for the sustainable management of all four insect pests studied was the necessity to implement land sanitation. This can be achieved by removal of weeds, which act as alternate hosts in the lands, by cultivating between rows and hoeing between plants. Using these methods of weed removal loosens the soil which in turn facilitates access to soil dwelling pests by natural enemies. Crop debris, such as fallen fruit, should be regularly removed from the lands, eliminating potential reservoiurs from which potential pest populations could emanate. Crop debris should be destroyed and this can be achieved by either putting it through a hammermill or burying it in a deep hole and compressing the soil.

A strategy to measure the loss of yield should be implemented to more accurately calculate losses incurred. A system should be implemented in each land where damaged and fallen fruit are collected from the land as well as from the pre-sorting area adjacent to the land. These crates should be weighed and records kept of discarded fruit from individual lands. The damaged fruit should then be destroyed. By implementing this

system, growers will be able to more accurately calculate the economic implications and yield per land. A system should be set up to run concurrently in the processing factory where pods are again sorted, the damaged pods removed and weighed and records kept. The proposed factory system should be feasible as records are already kept with regards to the grower's name, fruit received and weight of rejected fruit. The growers would however need to mark the crates according to which lands they harvested and factory personnel would need to record this. Staff at the processing factory would need to separate pods with cosmetic damage from pods with insect damage so that only insect damage is recorded.

One of the core aspects of any pest control programme has to be a reliable surveillance strategy, managed and maintained by trained scouts. Designing a scouting programme incorporating the inspection of 20 random pods per plant will enable growers to calculate the proportion of damage. By using different trapping methods, an assessment of insects present in a cropping system can be determined. Once the pest insects have been identified, means of control can be determined and implemented. As a result of this research, technology transfer can be achieved through the development of a training course for growers and farm workers, enabling them to manage and maintain surveillance programmes in *C. baccatum* lands. This will also hopefully help growers to make informed decisions with regards to pest control strategies within an IPM context.

Integrated crop management does not prohibit the use of insecticides, but rather promotes the intelligent use and application of these chemicals. A more holistic approach has been established with the introduction of IPM, which moves away from the eradication of a pest and towards pest management at a level economically acceptable to the agriculturalist. IPM has many advantages: lower costs to the producer and a long-term sustainable programme with minimal effects to the environment and end users. Foreign markets are exerting pressure to reduce the application and use of pesticides to meet the pesticide residue tolerance limits on imported crops. This should further reduce the usage of pesticides in future.

This research was conducted to determine the composition and phenology of insect pests associated with *Capsicum baccatum* cultivated in the Makana District. As cultivation of this crop has only recently commenced in the area, it was important to establish which insects are the most damaging or have the potential and capacity of becoming major pests in the future. With regard to this cropping system, literature is scarce, at both an international and domestic level. A general representation of the phenology of both the crop and the insects has now been provided. Based on this information, profitable avenues for further research to establish sustainable IPM programmes designed specifically for this highly profitable crop have been highlighted.

REFERENCES

ABATE, T., VAN HUIS, A., & AMPOFO, J.K.O. (2000) Pest management strategies in traditional agriculture: an African perspective. *Annual Review of Entomology* 45: 631-659.

ACOCKS, J.P.H. (1953) *Veld Types of South Africa*. Botanical Survey of South Africa. Memoir No. 28, Government Printer, Pretoria.

ALABI, O.Y., ODEBIYI, J.A. & JACKAI, L.E.N. (2003) Field evaluation of cowpea cultivars (*Vigna unguiculata* [L.] Walp.) for resistance to flower bud thrips (*Megalurothrips sjostedti* Trybom) (Thysanoptera: Thripidae). *International Journal of Pest Management* 49: 287-291.

ANDREWS, J. (1995) *Peppers The Domesticated Capsicums.* University of Texas Press, Austin.

ANGELINI, A. & LABONNE, V. (1970) Mise au point sur l'étude de *Cryptophlebia* (*Argyroploce*) *leucotreta* (Meyr.) en Côte d'lvoire. *Coton et Fibres Tropicales* 25: 497-500.

ANNECKE, D.P. & MORAN, V.C. (1982) *Insects and Mites of Cultivated Plants in South Africa*. Butterworths, Pretoria.

APHIS, (2007a) Anthropod pests. *Helicoverpa armigera*. Retrieved: 9 November 2007 http://www.aphis.usda.gov

APHIS (2007b) Anthropod pests. *Ceratitis* spp. Retrieved: 9 November 2007 http://www.aphis.usda.gov

AVERILL, A.L. & PROKOPY, R.J. (1989) Biology and physiology; host-marking pheromones. In: Robinson, A.S. & Hooper, G. (Eds.) *Fruit Flies; Their Biology, Natural Enemies and Control. World Crop Pests* 3(A). Elsevier, Amsterdam, pp. 207-219.

BARNES, B.N. (1983) Fruit flies – seasonal occurrence, control and monitoring on pome and stone fruits. *The Deciduous Fruit Grower*. April, pp. 139-146.

BATEMAN, M.A. (1972) The ecology of fruit flies. *Annual Review of Entomology* 17: 493-518.

BECHINSKI, E.J. (1994) Designing and delivering in-the-field scouting programs. In: Pedigo L.P. & Buntin G.D. (Eds.) *Handbook of Sampling Methods for Anthropods in Agriculture*. CRC Press, Baca Raton, Florida.

BEDFORD, E.C.G, VAN DEN BERG, M.A. & DE VILLIERS, E.A. (1998) *Citrus Pests in the Republic of South Africa*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit.

BEGEMANN, G.J. & SCHOEMAN, A.S. (1999) The phenology of *Helicoverpa armigera* (Huebner) (Lepidoptera: Noctuidae), *Tortrix capensana* (Walker) and *Cryptophlebia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) in citrus at Zebediela, South Africa. *African Entomology* 7: 131-148.

BELL, J.C. & McGEOCH, M.A. (1996) An evaluation of the pest status and research conducted on phytophagous Lepidoptera on cultivated plants in South Africa. *African Entomology* 4: 161-170.

BOLLER, E.F. & PROKOPY, R.J. (1976) Bionomics and management of *Rhagoletis*. *Annual Review of Entomology* 21: 223-246.

BOSHOU, L. (2005) A broad review and perspective on breeding for resistance to bacterial wilt. *American Phytopathological Society*, 225-238.

BOSLAND, P.W. (1996) Capsicums: innovative uses of an ancient crop. In: Janick J. (Ed.) *Progress in New Crops,* ASHS Press, Arlington, Virginia, pp. 479-487.

BOUCHER, T.J., ASHLEY, R., DURGY, R., SCIABARRASI, M. & CALDERWOOD, W. (2003) Managing the pepper maggot (Diptera: Tephritidae) using perimeter trap cropping. *Journal of Economic Entomology* 96: 420-432.

BOWMAN, D.T. & McCARTHY, J.C. (1997) Thrips (Thysanoptera: Thripidae) tolerance in cotton: sources and heritability. *Journal of Entomological Science* 32: 460-471.

BROODRYK, S.W. (1969) The biology of *Chelonus* (*Microchelonus*) *curvimaculatus* Cameron (Hymenoptera: Braconidae). *Journal of the Entomological Society of Southern Africa* 32: 169-189.

BUTT, T.M. & BROWNBRIDGE, M. (1997) Fungal pathogens of thrips. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom, pp. 399-433.

CABI (Commonwealth Agricultural Bureau International, Wallingford, UK) (2004) Crop protection compendium: global module. Retrieved: 14 November 2007 http://www.cabicompendium.org/cpc

CALIFORNIA ANTILLES TRADING CONSORTIUM (2005) *Capsicum* peppers. Retrieved: April 13, 2005 from http://www.calantilles.com/capsicum_peppers.htm

CAMPBELL, L.R., ROBB, K.L. & ULLMAN, D.E. (2004) *The Complete Tospovirus Host List.* Retrieved: 14 November 2007 http://www.oznet.ksu.edu/tospovirus/hostlist.html

CARARA AGRO PROCESSING SERVICES (2006) Guide to pepper production in the Eastern Cape. (Unpublished).

CASELTON, G. 2005. Chile-Head. Retrieved: July 7, 2005 from http://www.g6csy.net/chile/database.htm

CASIDA, J.E. & QUISTAD, G.B. (1998) Golden age of insecticide research: past, present, or future? *Annual Review of Entomology* 43: 1-16.

CATLING, H.D. & ASCHENBORN, H. (1974) Population studies of the false codling moth, *Cryptophlebia leucotreta* Meyrick, on citrus in the Transvaal. *Phytophylactica* 6: 31-38.

CATLING, H.D. & ASCHENBORN, H. (1978) False codling moth *Cryptophlebia leucotreta* (Meyrick). In: Bedford. E.C.G. (Ed.) *Citrus Pests in the Republic of South Africa. Science Bulletin, Department of Agricultural Technical Services* 391: 165-170.

CHERRY, A., COCK, M., VAN DEN BERG, H. & KFIR, R. (2003) Biological control of *Helicoverpa armigera* in Africa. In: Neuenschwander, P., Borgemeister, C. & Langewald, J. (Eds.) *Biological Control in IPM Systems in Africa*. CAB International, Wallingford, pp. 329- 346.

CHILDERS, C.C. (1997) Feeding and oviposition injuries to plants. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom, pp. 505-537.

CHILDERS, C.C. & ACHOR, D.S. (1995) Thrips feeding and oviposition injuries to economic plants, subsequent damage and host responses to infestation. In: Parker, B.L., Skinner, M. & Lewis, T. (Eds.) *Thrips Biology and Management*. Plenum, New York, pp. 31-51.

CHRISTENSON, L.D. & FOOTE, R.H. (1960) Biology of fruit flies. *Annual Review of Entomology* 5: 171-192.

CHRISTIAN, P.D., MURRAY, D., POWELL, R., HOPKINSON, J., GIBB, N.N. & HANZLIK, T.N. (2005) Effective control of a field population of *Helicoverpa armigera* by using the small RNA virus *Helicoverpa armigera* Stunt Virus (Tetraviridae: *Omegatetravirus*). *Journal of Economic Entomology* 98: 1839-1847.

CIBC (Commonwealth Institute of Biological Control) (1984) Possibilities for the biological control of the false codling moth, *Cryptophlebia leucotreta* (Lep., Tortricidae). *Biocontrol News and Information* 5: 217-220.

CLAUSEN, C.P., CLANCY, D.W. & CHOCK, Q.C. (1965) Biological control of the Oriental fruit fly (*Dacus dorsalis* Hendel) and other fruit flies in Hawaii. *Technical Bulletin, United States Department of Agriculture* 1322: 1-102.

COCKBURN, J.J. (2007) Field monitoring of Mediterranean Fruit Fly (*Ceratitis capitata*) (Wiedemann) (Diptera: Tephritidae) populations on Cherry Peppers (*Capsicum baccatum*) (Linnaeus) (Solanaceae) in the Belmont Valley, Eastern Cape. Unpublished Honours Project, Department of Zoology & Entomology, Rhodes University, Grahamstown, South Africa.

COOK, S.M., KHAN, Z.R. & PICKETT, J.A. (2007) The use of push-pull strategies in integrated pest management. *Annual Review of Entomology* 52: 375-400.

COPELAND, R.S., WHARTON, R.A., LUKE, Q. & DE MEYER, M. (2002) Indigenous hosts of *Ceratitis capitata* (Diptera: Tephritidae) in Kenya. *Annals of the Entomological Society of America* 95: 672-694.

COWLING, R.M. (1983) Phytochorology and vegetation history in the south-eastern Cape, South Africa. *Journal of Biogeography* 10: 393-419.

CULBREATH, A.K., TODD, J.W. & BROWN, S.L. (2003) Epidemiology and management of tomato spotted wilt in peanut. *Annual Review of Phytopathology* 41: 53-75.

DAIBER, K.C. (1976) A survey of the false codling moth [*Cryptophlebia leucotreta* Meyr.] in peach orchards. *Phytophylactica* 8: 97-102.

DAIBER, K.C. (1979) A study of the biology of the false codling moth [*Cryptophlebia leucotreta* Meyr.]: the egg. *Phytophylactica* 11: 129-132.

DAIBER, K.C. (1980) A study of the biology of the false codling moth *Cryptophlebia leucotreta* (Meyr.): the adult and generations throughout the year. *Phytophylactica* 12: 187-193.

D'ARCY, W.G. (Ed.) (1986) *Solanaceae Biology and Systematics*. Columbia University Press, New York.

DAVIES, R.G. (1988) Insecticidal control. In: Davies R.G. & Imms A.D. (Eds.) *Outlines of Entomology,* Chapman and Hall, New York, pp. 326-342.

DENHOLM, I., DEVINE, G.J. & WILLIAMSON, M.S. (2002) Insecticide resistance on the move. *Science* 297: 2222-2223.

DE VILLIERS, E.A., FOURIE, P.F. & PETTY, G.J. (1987a) Miscellaneous pests. In: Myburgh, A.C. (Ed.) *Crop Pests in Southern Africa. Citrus and Other Subtropicals*. Government Printer, Pretoria, pp. 109-111.

DE VILLIERS, E.A., DU TOIT, W.J. & PETTY, G.T. (1987b) Thrips. In: Myburgh, A.C. (Ed.) *Crop Pests in Southern Africa. Citrus and Other Subtropicals*. Government Printer, Pretoria, pp. 71-75.

DeWITT, D. (2005) Pepper Profile: *Capsicum baccatum* species. Retrieved: June 13, 2005 from http://www.fiery-foods.com

DeWITT, D. & BOSLAND, P.W. (1996) *Peppers of the World An Identification Guide*, Ten Speed Press, Berkeley, California.

DI ILIO, V., CRISTOFARO, M., MARCHINI, D., NOBILI, P. & DALLAI, R. (1999) Effects of a neem compound on the fecundity and longevity of *Ceratitis capitata* (Diptera: Tephritidae). *Journal of Economic Entomology* 92: 76-82.

DOWELANCO (1994) Spinosad technical guide. DowElanco, Indianapolis.

DRAKE, V.A. & FARROW, R.A. (1985) A radar and aerial trapping study of an early spring migration of moths (Lepidoptera) in inland New South Wales. *Australian Journal of Ecology* 11: 223-235.

DRAKE, V.A., HELM, K.F., READSHAW, J.L. & REID, D.G. (1981) Insect migration across Bass Strait during spring: a radar study. *Bulletin of Entomological Research* 71: 449-466.

DREISTADT, S.H., PHILLIPS, P.A. & O'DONNEL, C.A. (2007) Thrips. Pest Notes. Publication 7429, University of California, Davis. Retrieved: 14 November 2007. www.ipm.ucdavis.edu.

DREW, R.A.I. (1987) Reduction in fruit fly (Tephritidae: Dacinae) populations in their endemic rainforest habitat by furgivorous vertebrates. *Australian Journal of Zoology* 35: 283-288.

DREW, R.A.I. (1989) The tropical fruit flies (Diptera: Tephritidae: Dacinae) of the Australasian and Oceanian regions. *Memoirs of the Queensland Museum* 26: 1-521.

DREW, R.A.I. & LLOYD, A.C. (1989) Biology and physiology; nutrition; bacteria associated with fruit flies and their host plants. In: Robinson, A.S. & Hooper, G. (Eds.) *Fruit Flies; Their Biology, Natural Enemies and Control. World Crop Pests* 3(A). Elsevier, Amsterdam, pp. 131-140.

DU TOIT, W.J. (1998) Fruit flies. In: Bedford, E.C.G., van den Berg, M.A. & de Villiers, E.A. (Eds.) *Citrus Pests in the Republic of South Africa*. Dynamic Ad: Nelspruit, pp. 229-233.

EKESI, S., MANIANIA, N.K. & LUX, S.A. (2002) Mortality in three African tephritid fruit fly puparia and adults caused by the entomopathogenic fungi, *Metarhizium anisopliae* and *Beauveria bassiana*. *Biocontrol Science and Technology* 12: 7-17.

EPSKY, N.D. & HEATH, R.R. (1998) Exploiting the interactions of chemical and visual cues in behavioural control measures for pest Tephritid fruit flies. *Florida Entomologist* 81: 273-282.

ESHBAUGH, W.H. (1983) The genus *Capsicum* in Africa. *Bothalia* 14: 845-848.

ESHBAUGH, W.H. (1993) History and exploitation of a serendipitous new crop discovery. In: Janick J. & Simon J.E. (Eds.) *New Crops*, Wiley, New York, pp. 132-139.

ÉTIENNE, J. (1972) Les principales Trypétides nuisibles d l'ile de la Réunion. *Annales de la Societé Entomologique de France* 8: 485-491.

FARROW, R.A. & DALY, J.C. (1987) Long-range movements as an adaptive strategy in the genus *Heliothis* (Lepidoptera: Noctuidae): a review of its occurrence and detection in four pest species. *Australian Journal of Zoology* 35: 205-209.

FIMIANI, P. (1989) Pest status; Mediterranean region. In: Robinson, A.S. & Hooper, G. (Eds.) *Fruit Flies; their Biology, Natural Enemies and Control. World Crop Pests* 3(A). Elsevier, Amsterdam, pp. 37-50.

FISCHER-COLBREI, P. & BUSCH-PETERSEN, E (1989) Pest status; temperate Europe and west Asia. In: Robinson, A.S. & Hooper, G. (Eds.) *Fruit Flies; Their Biology, Natural Enemies and Control. World Crop Pests* 3(A). Elsevier, Amsterdam, pp. 91-99.

FITT, G.P. (1989) The ecology of *Heliothis* species in relation to agroecosystems. *Annual Review of Entomology* 34: 17-52.

FLETCHER, B.S. (1987) The biology of dacine fruit flies. *Annual Review of Entomology* 32: 115-144.

FLORIDATA (2005) *Capsicum* spp. Retrieved: April 13, 2005 from http://www.floridata

FOSTER, S.P. & HARRIS, M.O. (1997) Behavioral manipulation methods for insect pest-management. *Annual Review of Entomology* 42: 123-146.

FREI, A., BUENO, J.M., DIAZ-MONTANO, J., GU, H., CARDONA, C. & DORN, S. (2004) Tolerance as a mechanism of resistance to *Thrips palmi* in common beans. *Entomologia Experimentalis et Applicata*. 112: 73-80.

FULLER, C. (1901) The Natal codling moth, *Carpocapsa* sp. *Report, Department of Agriculture, Natal. First report of Government Entomologist* 1899-1900. pp. 48-51.

FYE, R.E., & McADA, W.C. (1972) Laboratory studies on the development, longevity and fecundity of six lepidopterous pests of cotton in Arizona. *US Department of Agriculture, Agriculture Research Service, Technical Bulletin* Vol 1454, p. 72.

GILMOUR, J.S.L. (1969) *International code of nomenclature of cultivated plants*. International Bureau for Plant Taxonomy and Nomenclature, Utrecht, Netherlands.

GLARE, T.R. & O'CALLAGHAN, M. (2000) Bacillus thuringiensis*: Biology, Ecology and Safety*. John Wiley & Sons, Chichester.

GREATHEAD, D.G. & GIRLING, D.J. (1989) Distribution and economic importance of *Heliothis* and of their natural enemies and host plants in southern and eastern Africa. In: King, E.G. & Jackson, R.D. (Eds.) *Proceedings of the Workshop on Biological Control of* Heliothis: *Increasing the Effectiveness of Natural Enemies*. November 11-15, 1985, New Delhi, India. Far Eastern Regional Research Office, United States Department of Agriculture, New Delhi, India, pp. 329-345.

GROVÉ, T. (2001) Order Diptera: Family Tephritidae. In: van den Berg, M.A., de Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 293-302.

GROVES, R.L., WALGENBACH, J.F., MOYER, J.W. & KENNEDY, G.G. (2002) The role of weeds and tobacco thrips, *Frankliniella fusca*, in the epidemiology of tomato spotted wild virus. *Plant Diseases* 86: 573-582.

GUNN, D. (1921) The false codling moth (*Argyroploce leucotreta* Meyr.). Department of Agriculture and Forestry, South Africa, Science Bulletin 21: 1-28.

HACKETT, D. GATEHOUSE, A.G. (1982) Diapause in *Heliothis armigera* (Hübner) and *H. fletcheri* (Hardwick) (Lepidoptera: Noctuidae) in the Sudan Gezira. *Bulletin of Entomological Research* 72: 409-422.

HANCOCK, D.L. (1987) Notes on some African Ceratitinae (Diptera: Tephritidae), with special reference to Zimbabwean fauna. *Transactions of the Zimbabwe Scientific Association* 63: 47-57.

HANCOCK, D.L. (1989) Pest status; southern Africa. In: Robinson, A.S. & Hooper, G. (Eds.) *Fruit Flies; their Biology, Natural Enemies and Control. World Crop Pests* 3(A). Elsevier, Amsterdam, pp.51-58.

HARBORNE, J.B. (1986) Systematic significance of variations in defense chemistry in the Solanaceae. In: D'Arcy, W.G. *Solanaceae Biology and Systematics*. Columbia University Press, New York, pp. 328-344.

HARTWIG, E.K. (1985) Order Thysanoptera (Thrips). In: Scholtz C.H. & Holm E. *Insects of Southern Africa*. University of Pretoria, Pretoria, pp. 176-179.

HEITZ, J.R. (1995) Pesticidal applications of photo-activated molecules. In: Heitz, J.R. & Downum, K.R. (Eds.) *Light-activated Pest Control*. ACS Symposium Series 616. American Chemical Society, Washington, pp. 1-16.

HEMINGWAY, J., FIELD, L. & VONTAS, J. (2002) An overview of insecticide resistance. *Science* 298: 96-97.

HENDRICHS, J. & HENDRICHS, M.A. (1990) Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae) in nature: location and diel pattern of feeding and other activities on fruiting and non-fruiting hosts and nonhosts. *Annals of the Entomological Society of America* 83: 632-641.

HENDRICHS, J., KATSOYANNOS, B.I., PAPAJ, D.R. & PROKOPY, R.J. (1991) Sex differences in movement between natural feeding and mating sites and tradeoffs between food consumption, mating success and predator evasion in Mediterranean fruit flies (Diptera: Tephritidae). *Oecologia* 86: 223-231.

HENDRICHS, J., ROBINSON, A.S., CAYOL, J.P. & ENKERLIN, W. (2002) Medfly areawide sterile insect technique programmes for the prevention, suppression or eradication: the importance of mating behavior studies. *Florida Entomoligist* 85: 1-13.

HEYWOOD, V.H., BRUMMITT, R.K., CULHAM, A. & SEBERG, O. (2007) *Flowering Plant Families of the World.* Firefly Books, Ontario.

HIGLEY, L.G. & PETERSON, K.D. (1994) Initiating sampling programs. In: Pedigo L.P. & Buntin G.D. (Eds.) *Handbook of Sampling Methods for Arthropods in Agriculture*, CRC Press, Baca Raton, Florida, pp. 119-136.

HILL, D. (1975) *Agricultural Insect Pests of the Tropics and their Control.* Cambridge Press, London.

HOCKEY, P.A.R., DEAN, W.R.J. & RYAN, P.G. (2006) (Eds.) *Roberts - Birds of Southern Africa*. The Trustees of the John Voelcker Bird Book Fund, Cape Town.

HODDLE, M.S., NAKAHARA, S. & PHILLIPS, P.A. (2002) Foreign exploration for *Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae) and associated natural enemies on avocado (*Persea Americana* Miller). *Biological Control* 24: 251-165.

HODDLE, M.S., OEVERING, P., PHILLIPS, P.A. & FABER, B.A. (2004) Evaluation of augmentatitive releases of *Franklinothrips orizabensis* for control of *Scirtothrips perseae* in California avocado orchards. *Biological Control* 30: 456-465.

HODDLE, M.S. & ROBINSON, L. (2004) Evaluation of factors influencing augmentative releases of *Chrysoperla carnea* for control of *Scirtothrips perseae* in California avocado orchards. *Biological Control* 31: 268-275.

HODGSON, P.J., SIVINSKI, J., QUINTERO, G. & ALUJA, M. (1998) Depth and pupation and survival of fruit fly (*Anastrepha* spp.: Tephritidae) pupae in a range of agricultural habitats. *Environmental Entomology* 27: 1310-1314.

HOFFMEISTER, T. (1992) Factors determining the structure and diversity of parasitoid complexes in tephritid fruit flies. *Oecologia* 89: 288-297.

HOWARD, C.W. (1909) Orange codling moth (*Encarmonia batrachopa*). *Report of the Department of Agriculture, Transvaal*. 1907-1908. p. 189.

HUMMEL, R.L., WALGENBACH, J.F., HOYT, G.D. & KENNEDY, G.G. (2002) Effects of production system on vegetable arthropods and their natural enemies. *Agriculture, Ecosystems & Environment* 93: 165-176.

HUNZIKER, A.T. (2001) *The genera of Solanaceae*. ARG Gantner Verlag KG, Ruggell, Germany.

IZZO, T.J., PINENT, S.M.J., MOUND, L.A. (2002) *Aulacothrips dictyotus* (Heterothripidae), the first ectoparasitic thrips (Thysanoptera). *Florida Entomologist* 85: 281-283.

JARRET, R.L. & PHAT DANG (2004) Revisiting the waxy locus and the *Capsicum annuum* L. complex. *Georgia Journal of Science* 62: 117-133.

KANT, K., KANAUJIA, K.R. & KANAUJIA, S. (1999) Rhythmicity and orientation of *Helicoverpa armigera* (Hübner) to pheromone and influence of trap design and distance on moth trapping. *Journal of Insect Science* 12: 6-8.

KEANE, R.M. & CRAWLEY, M.J. (2002) Exotic plant invasions and the enemy release hypothesis. *Trends in Ecology and Evolution* 17: 164-170.

KENNEDY, J.S. (1986) Migration, behavioural and ecological. In: Rankin, M.A. (Ed.) *Mirgration: Mechanisms and Adaptive Significance. Contributions to Marine Science* 27(Supplement): 5-26.

KFIR, R. & VAN HAMBURG, H. (1983) Further tests of threshold levels for control of cotton bollworms (mainly *Heliothis armigera*). *Journal of the Entomological Society of Southern Africa* 46: 49-58.

KIRK, W.D.J. & TERRY, L.I. (2003) The spread of western flower thrips *Frankliniella occidentalis* (Pergande). *Agriculture and Forest Entomology* 5: 301-310.

KNIPLING, E.F. & STADELBACHER, E.A. (1983) The rationale of area-wide management of *Heliothis* (Lepidoptera: Noctuidae) populations. *Bulletin of the Entomological Society of America* 29: 29-37.

KOGAN, M. (1998) Integrated Pest Management: Historical perspectives and contemporary developments. *Annual Review of Entomology* 43: 243-270.

KOK, I.B. & GEORGALA, M.B. (1978) Family Tephritidae: Fruit Flies. In: Bedford, E.C.G. (Ed.) *Citrus Pests in the Republic of South Africa*. Department of Agricultural Technical Services, Science Bulletin 391: 197-201.

KRAINACKER, D.A., CAREY, J.R. & VARGAS, R.I. (1987) Effect of larval host on life history traits of the Mediterranean fruit fly, *Ceratitis capitata*. *Oecologia* 73: 583-590.

KROON, D.M. (1999) *Lepidoptera of Southern Africa Host-Plants and Other Associates*. A catalogue. Lepidopterists' Society of Africa, Jukskei Park & D.M. Kroon, Sasolburg.

KUO, C. (Ed.) (1996) *International Symposium on Tospoviruses and Thrips of Tloral and Vegetable Crops*. *Acta Horticulturae* No. 431.

LANDIS, D.A., WRATTEN, S.D. & GURR, G.M. (2000) Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* 45: 175-201.

LEWIS, T. (1973) Thrips: *Their Ecology and Economic Importance.* Academic Press, London.

LEWIS, T. (Ed.) (1997) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom.

LIM, U.T., VAN DRIESCHE, R.G., HEINZ, K.M. (2001) biological attributes of the nematode, *Thripinema nicklewoodi*, a potential biological control agent of western flower thrips. *Biological Control* 22: 300-306.

LINGREN, P.D., SPARKS, A.N., RAULSTON, J.R. (1982) The potential contribution of moth behaviour research to *Heliothis* management. In: Reed, W. & Kumble, V. (Eds.) *Proc. Int. Workshop* Heliothis *Management, Patancheru, India, 1981*. Patancheru, India: ICRISAT, pp. 39-47.

LINGREN, P.D., WARNER, W.B., RAULSTON, J.R., KEHAT, J.R. & HENNEBERRY, T.J. (1988) Observations on the emergence of adults from natural populations of corn earworm, *Heliothis zea* (Boddie) (Lepidoptera: Noctuidae). *Environmental Entomology* 17: 254-258.

LLOYD, A.C. (1991) The distribution of alimentary tract bacteria in the host tree by *Dacus tryoni*. In: Vijaysegaran, S. & Ibrahim, A.G. (Eds.) *First International Symposium on Fruit Flies in the Tropics, Kuala Lumpur, 1988*. Malaysian Agricultural Research and Development Institute, Kuala Lumpur, pp. 289-295.

LOOMANS, A.J.M., MURAI, T. & GREENE, I.D. (1997) Interactions with hymenopterous parasitoids and parasitic nematodes. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom, pp. 355-397.

LOPEZ, M., SIVINSKI, J., RENDON, P., HOLLER, T., BLOEM, K., COPELAND, R., TROSTLE, M. & ALUJA, M. (2003) Colonization of *Fopius ceratitivorus*, a newly discovered African egg-pupal parasitoid (Hymenoptera: Braconidae) of *Ceratitis capitata* (Diptera: Tephrididae). *Florida Entomologist* 86: 53-60.

MATSUMURA, F. (1975) *Toxicology of Insecticides*. Plenum, New York.

McLEOD, M.J., GUTTMAN, S.I. & ESHBAUGH, W.H. (1982) Early evolution of chili peppers (*Capsicum*). *Economic Botany* 36: 361-368.

McQUATE, G.T., SYLVA, C.D. & JANG, E.B. (2005) Mediterranean fruit fly (Dipt., Tephritidae) suppression in persimmon through bait sprays in adjacent coffee plantings. *Journal of Applied Entomology* 129(2) 110-117.

MENSAH, R.K. (2002) Development of an integrated pest management programme for cotton. Part 2: Integration of a lucerne/cotton interplant system, food supplement sprays with biological and synthetic insecticides. *International Journal of Pest Management* 48: 95-105.

MOLLEMA, C. & COLE, R.A. (1996) Low aromatic amino acid concentrations in leaf proteins determine resistance to *Frankliniella occidentalis* in four vegetable crops. *Entomologia Experimentalis et Applicata* 78: 325-333.

MOORE, S.D. (2003) The development and evaluation of *Cryptophlebia leucotreta* granulovirus (CrleGV) as a biological control agent for the management of false codling moth, *Cryptophlebia leucotreta*, on citrus. PhD Thesis, Rhodes University, Grahamstown.

MOORE, S.D., PITTAWAY, T., BOUWER, G. & FOURIE, J.G. (2004) Evaluation of *Helicoverpa armigera* Nucleopolyhedrovisus (HearNPV) for control of *Helicoverpa armigera* (Lepidoptera: Noctuidae) on citrus in South Africa. *Biocontrol Science and Technology* 14: 239-250.

MORAN, V.C. (1983) The phytophagous insects and mites of cultivated plants in South Africa: patterns and pest status. *Journal of Applied Ecology* 20: 439-450.

MORSE, J.G. & HODDLE, M.S. (2006) Invasion biology of thrips. *Annual Review of Entomology* 51: 67-89.

MOUND, L.A. (1997) Biological diversity. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom, pp. 197-215.

MOUND, L.A. (2002) So many thrips – so few tospoviruses. In: *Thrips and Tospoviruses*, Proceedings of the 7th International Symposium on Thysanoptera, Canberra, Australia, pp. 15-18.

MOUND, L.A. & MARULLO, R. (1996) The thrips of Central and South America: an introduction (Insecta: Thysanoptera). *Memoirs on Entomology, International* 6: 1-488.

MOUND, L.A. & TEULON, D.A.J. (1995) Thysanoptera as phytophagous opportunists. In: Parker, B.L., Skinner, M. & Lewis, T. *Thrips Biology and Management*. Plenum, New York, pp. 3-19.

MUCINA, L. & RUTHERFORD, M.C. (Eds.) (2006) *The Vegetation of South Africa, Lesotho and Swaziland.* Strelitzia 19, South African National Biodiversity Institute, Pretoria.

NEUENSCHWANDER, P. & MARKHAM, R. (2001) Biological control in Africa and its possible effects on biodiversity. In: Wajnberg, E., Scott, J.K. & Quimby, P.C.

(Eds.) *Evaluating Indirect Ecological Effects of Biological Control*. CABI, Wallingford, United Kingdom, pp. 127-146.

NEWTON, P.J. (1988) Inversely density-dependent egg parasitism in patchy distributions of the citrus pest *Cryptophlebia leucotreta* (Lepidoptera: Tortricidae) and its agricultural efficiency. *Journal of Applied Ecology* 25: 145-162.

NEWTON, P.J. (1998) False codling moth, *Cryptophlebia leucotreta* (Meyrick). In: Bedford, E.C.G., van den Berg, M.A. & de Villiers, E.A. (Eds.) *Citrus Pests in the Republic of South Africa*. Dynamic Ad: Nelspruit, pp. 192-200.

NISHIDA, T., HARRIS, E.J., VARGAS, R.I. & WONG, T.T.Y. (1985) Distributional loci and host fruit utilization patterns of the Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae), in Hawaii. *Environmental Entomology* 14: 602-606.

NMSU (New Mexico State University), Chile Pepper Institute, Chile Task Force. (2005) Retrieved: June 14, 2005 from http://www.chiletaskforce.com

OISAT (2005) Online Information Service for Non-Chemical Pest Management in the Tropics. Retrieved: July 21, 2005 from http://www.oisat.org/crops/vegetables/pepper.html

OMER-COOPER, J. (1939) Remarks on false codling moth. Rhodes University, Grahamstown. Mimeograph, p. 17.

PALMER, A.R. (2004) Makana LEAP: Comprehensive Environmental Audit: Vegetation of Makana. October 12, 2004.

PAPAJ, D.R., KATSOYANNOS, B.I. & HENDRICHS, J. (1989) Use of fruit wounds in oviposition by Mediterreanean fruit flies. *Entomologia Experimentalis et Applicata* 53: 203-209.

PARRELLA, M.P. & LEWIS, T. (1997) Integrated pest management (IPM) in field crops. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom, pp. 594-614.

PARRELLA, G., GOGNALONS, P., GEBRE-SELASSIE, K., VOVLAS, C. & MARCHOUX, G. (2003) An update on the host range of tomato spotted wilt virus. *Journal of Plant Pathology* 85: 227-264.

PARRY-JONES, E. (1936) Investigations on the cotton bollworm – *Heliothis obsoleta* Fabr. *Publication, Mazoe Citrus Experimental Station* 4a: 21-82.

PEARSON, E.O. & MAXWELL-DARLING, R.C. (1958) *The Insect Pests of Cotton in Tropical Africa*. Empire Cotton Growing Corporation and Commonwealth Institute of Entomology, London.

PEDIGO, L.P. & RICE, M.E. (2006) *Entomology and Pest Management,* Pearson Education Incorporated, Upper Saddle River, New Jersey.

PELL, J.K., MaCAULAY, E.D.M., WILDING, N. (1993) A pheromone trap for dispersal of the pathogen *Zoophthora radicans* Brefeld. (Zygomycetes: Entomophthorales) amongst populations of the diamondback moth, *Plutella xylostella* L. (Lepidoptera: Yponomeutidae). *Biocontrol Science and Technology* 3: 315-320.

PETERS, D.K, WIJKAMP, I., VAN DE WETERING, F. & GOLDBACH, R. (1995) Vector relations in the transmission and epidemiology of tospoviruses. In: Kuo C. (Ed.) *International Symposium on Tospoviruses and Thrips of Floral and Vegetable Crops*. *Acta Horticulturae* No. 431, pp. 29-43.

PETTY, G.J. (2001) Order Thysanoptera. Family Thripidae. *Frankliniella schultzei* (Trybom). In: van den Berg, M.A., de Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa.* ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 228.

PICKERSGILL, B. (1971) Relationships between weedy and cultivated forms in some species of chili peppers (genus *Capsicum*), *Evolution* 25: 683-691.

PICKERSGILL, B., HEISER, C.B. Jr. & McNEILL, J. (1979) Numerical taxonomic studies on variation and domestication in some species of *Capsicum*, In: Hawkes, J.G., Lester, R.N. & Skelding, A.D. (Eds.) *The Biology and Taxonomy of the Solanaceae*. Academic Press, London, pp. 679-700.

PROKOPY, R.J. & HENDRICHS, J. (1979) Mating behaviour of *Ceratitis capitata* on a field-caged host tree. *Annals of the Entomological Society of America* 72: 642-648.

QUINN, G. & KEOUGH, M. (2002) *Experimental Design and Data Analysis for Biologists*. Cambridge University Press, Cambridge, pp 393-400.

REED, W. (1965) *Heliothis armigera* (HB.) (Noctuidae) in western Tanganyika. I. Biology, with special reference to the pupal stage. *Bulletin of Entomological Research* 56: 177-125.

REED, W. (1974) The false codling moth, *Cryptophlebia leucotreta* Mayr. (Lepidoptera: Olethreutidae) as a pest of cotton in Uganda. *Cotton Growing Review* 51: 213-225.

RIPLEY, L.B. & HEPBURN, G.A. (1930) A menace to the fruit industry: "Bug-tree" harbours fruit-fly. *Farming in South Africa* 72: 1-2.

RIPLEY, L.B., HEPBURN, G.A. & ANDERSSEN, E.E. (1940) Union of South Africa, Department of Agriculture Science Bulletin No. 204.

RIPLEY, L.B., HEPBURN, G.A. & DICK, J. (1939) Mass breeding of false codling moth, *Argyroploce leucotreta* Meyrick, in artificial media. Plant Industry Series No. 53. Entomology. *Department of Agriculture and Forestry, South Africa, Science Bulletin* 207: p. 18.

ROOME, R.E. (1975) Field trials with a nuclear polyhedrosis virus and *Bacillus thuringiensis* against larvae of *Heliothis armigera* (Hb.) (Lepidoptera, Noctuidae) on sorghum and cotton in Botswana. *Bulletin of Entomological Research* 65: 507-514.

SCHWARTZ, A. (1981) *'n Bydrae tot die biologie en beheer van die valskodlingmot* Cryptophlebia leucotreta (*Meyr*.)(*Lepidoptera: Eucosmidae*) *op nawels*. Unpublished Ph.D. Thesis, University of Stellenbosch.

SCHWARTZ, A., MARAIS, A. & VAN DER KOOIJ, R (1982) Beheer van valskodlingmot in Citrusdal deur grootskaalse vrylating van 'n eierparasiet. *Citrus and Subtropical Fruit Research Institute, Information Bulletin* 113: 17-20.

SEARLE, C.M. St. L. (1964) A list of the insect enemies of citrus pests in Southern Africa. *Department of Agricultural Technical Services, South Africa, Technical Communication* 30: p. 18.

SHEA, K. & CHESSON, P. (2002) Community ecology theory as a framework for biological invasions. *Trends in Ecological Evolution* 17: 170-176.

SHELTON, A.M. & BADENES-PEREZ, F.R. (2006) Concepts and applications of trap cropping in pest management. *Annual Review of Entomology* 51: 285-308.

SHELTON, A.M., NAULT, B.A., PLATE, J. & ZHAO, J-Z. (2003) Regional and temporal variation in susceptibility to lambda-cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae), in onion fields in New York. *Journal of Economic Entomology* 96: 1843-1848.

SHELTON, A.M., WILSEY, W.T. & SCHMAEDICK, M.A. (1998) Management of onion thrips (Thysanoptera: Thripidae) on cabbage by using plant resistance and insecticides. *Journal of Economic Entomology* 91: 329-333.

SILVERSTEIN, R.M. (1981) Pheromones: background and potential for use in insect pest control, Science 213: 1326-1332.

SILVERSTEIN, R.M. (1990) Practical use of pheromones and other behavior-modifying compounds: overview. In: Ridgway R.L., Silverstein R.M. & Inscoe M.N. (Eds.), *Behavior Modifying Chemicals for Insect Management*, Marcel Dekker, New York, pp. 1-8.

SIMON, J.E., CHADWICK, A.F. & CRAKER, L.E. (1984) *Herbs: An Indexed Bibliography. (1971-1980). The Scientific Literature on Selected Herbs and Aromatic and Medicinal Plants of the Temperate Zone.* Archon Books, Hamden, Connecticut.

SIVINSKI, J.M. (1996) The past and potential of biological control of fruit flies. In: McPheron, B.A. & Steck, G.J. (Eds.) *Fruit Fly Pests: A World Assessment of Their Biology and Management.* St. Lucie Press, Delray Beach, Florida, pp. 369-375.

SIVINSKI, J.M. & CALKINS, C. (1986) Pheromones and parapheromones in the control of tephritids. *Florida Entomologist* 69: 157-168.

SNYMAN, D.E. (1981) *Solanum* in Australia. *Journal of the Adelaide Botanic Gardens*, 4: 1-367.

SOIL CLASSIFICATION WORKING GROUP (1991) *Soil Classification a Taxonomic System for South Africa.* Department of Agricultural Development, Republic of South Africa, Pretoria.

STEYN, J.J. (1954) The pugnacious ant (*Anoplolepis custodiens* Smith) and its relation to the control of citrus scales at Letaba. *Memoirs of the Entomological Society of Southern Africa* 3: pp. 96.

THOMAS, M.C., HEPPNER, J.B., WOODRUFF, R.E., WEEMS, H.V., STECK, G.J. & FASULO, T.R. (2001) Mediterranean Fruit Fly, *Ceratitis capitata* (Wiedemann) (Insecta: Diptera: Tephritidae). Entomology and Nematology Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Document EENY-214.

TOPPER, C.P. (1987) Nocturnal behaviour of adults of *Heliothis armigera* (Hübner) (Lepidoptera: Noctuidae) in the Sudan Gezira and pest control implications. *Bulletin of Entomological Research* 77: 541-554.

TORCHIN, M.E., LAFFERTY, K.D., DOBSON, A.P., McKENZIE, V.J. & KURIS, A.M. (2003) Introduced species and their missing parasites. *Nature* 421: 628-630.

TRICHILO, P.J. & LEIGH, T.F. (1986) Predation on spider mite eggs by the western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae), an opportunist in a cotton agroecosystem. *Ecological Entomology* 15: 821-825.

ULLMAN, D.E., MEIDEROS, R., CAMPBELL, L.R., WHITFIELD, A.E., SHERWOOD, J.L. & GERMAN, T.L. (2002) Thrips as vectors of tospoviruses. *Advances in Botanical Research* 36: 113-140.

ULLMAN, D.E., SHERWOOD, J.L. & GERMAN, T.L. (1997) Thrips as vectors of plant pathogens. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CABI, Wallingford, United Kingdom, pp. 539-565.

ULLYETT, G.C. & BISHOP, H.J. (1938) Report on the false codling moth experiment carried out at Martindale, C.P. 1938. Unpublished report of the Parasite Laboratory, Division of Entomology, Pretoria, p. 23.

UNIVERSITY OF GEORGIA (2006) Commercial pepper production. June 2006, Bulletin 1309, pp. 1-56.

USDA (2005) Animal and plant health inspection service. Retrieved: June 22, 2005 from http://www.aphis.usda.gov/ppq/manuals

VAN DEN BERG, H. & COCK, M.J.W. (1993) Natural control of *Helicoverpa armigera* in cotton: assessment of the role of predation. *Biocontrol Science and Technology* 5: 453-463.

VAN DEN BERG, H., NYAMBO, B.T. & WAAGE, J.K. (1990) Parasitism of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Tanzania: analysis of parasitoid-crop associations. *Environmental Entomology* 19: 1141-1145.

VAN DEN BERG, H., WAAGE, J.K. & COCK, M.J.W. (1988) *Natural Enemies of* Helicoverpa armigera *in Africa: a review.* CAB International and Institute of Biological Control, Ascot, United Kingdom.

VAN DEN BERG, M.A. (2001) Order Lepidoptera: *Cryptophlebia leucotreta* (Meyrick) False codling moth. In: van den Berg, M.A., de Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 320-325.

VAN DEN BERG, M.A. (2001) Order Lepidoptera: Family Noctuidae *Helicoverpa armigera* (Hüber) American bollworm. In: van den Berg, M.A., de Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 352-353.

VAN EMDEN, H.F. & SERVICE, M.W. (2004) *Pest and Vector Control*. Cambridge University Press, Cambridge.

VAN HAMBURG, H. (1981) The inadequacy of egg counts as indicators of threshold levels for control of *Heliothis armigera* on cotton. *Journal of the Entomological Society of Southern Africa* 44: 291-297.

VAN HAMBURG, H. & GUEST, P.J. (1997) The impact of insecticides on beneficial arthropods in cotton agroecosystems in South Africa. *Archives of Environmental Contamination and Toxicology* 32: 63-68.

VAN RIJU, P.D.J., MOLLEMA, C. & STEENHUIS-BROERS, G.M. (1995) Comparative life history studies of *Frankliniella occidentalis* and *Thrips tabaci* (Thysanopera: Thripidae) on cucumber. *Bulletin of Entomological Research* 85: 285-297.

VARGAS, R.I., HARRIS, E.J. & NISHIDA, T. (1983) Distribution and seasonal occurrence of *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae) on the island of Kauai in the Hawaiian Islands. *Environmental Entomology* 12: 303-310.

VARGAS, R.I., PECK, S.L., MCQUATE, G.T., JACKSON, C.G., STARK, J.D. & ARMSTRONG, J.W. (2001) Potential for areawide integrated management of Mediterranean Fruit Fly (Diptera: Tephritidae) with a braconid parasitoid and a novel bait spray. *Biological and Microbial Control* 94: 817-825.

VERMEULEN, J.B. & BEDFORD, E.C.G. (1998) Family Noctuidae: Owlet moths. American Bollworm *Helicoverpa* (=*Heliothis*) *armigera* (Hübner). In: Bedford, E.C,G., van den Berg, M.A. & de Villiers, E.A. (Eds.) *Citrus Pests in the Republic of South Africa*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 217-221.

VLOK, J.H.J. & EUSTON-BROWN, D.I.W. (2002) The patterns within, and the ecological processes that sustain, the Subtropical Thicket Vegetation in the planning domain for the Subtropical Thicket Ecosystem Planning (STEP) Project. Terrestrial Ecology Research Unit, University of Port Elizabeth, Port Elizabeth. Report No. 40.

WALL, C. (1990) Principles of monitoring. In: Ridgway, R.L., Silverstein, R.M. & Inscoe, M.N. (Eds.) *Behavior Modifying Chemicals for Insect Management*. Marcel Dekker Inc., New York, pp. 9-23.

WALL, C. & PERRY, J.N. (1978) Interactions between pheromone traps for the pea moth, *Cydia nigricana* (F.) *Entomologia Experimentalis et Applicata* 24: 155-162.

WALL, C. & PERRY, J.N. (1987) Range of action of moth sex-attractant sources. *Entomologia Experimentalis et Applicata* 44: 5-14.

WALTER, G.H. (2003) *Insect Pest Management and Ecological Research*, Cambridge University Press, Cambridge, United Kingdom.

WARE, T., RICHARDS, G. & DANEEL, J-H (2003) The M3 bait station. A novel method of fruit fly control. *SA Fruit Journal* 1: 44-47.

WATMOUGH, R.H. (1991) Predation, an important cause of mortality in the pupae of the American bollworm. Plant Protection News, Bulletin of the Plant Protection Research Institute, Pretoria, South Africa, 26, 4.

WATMOUGH, R.H. & KFIR, R. (1995) Predation on pupae of *Helicoverpa armigera* Hbn. (Lep., Noctuidae) and its relation to stem borer numbers in summer grain crops. *Journal of Applied Entomology* 119: 679-688.

WHARTON, R.A. & GILSTRAP, F.E. (1983) Key to and status of opine braconid (Hymenoptera) parasitoids used in biological control of *Ceratitis* and *Dacus* s.l. (Diptera: Tephritidae). *Annals of the Entomological Society of America* 76: 721-742.

WHARTON, R., GILSTRAP, F., RHODE, R., FISCHEL, M. & HART, W. (1981) Hymenopterous egg-pupal and larval-pupal parasitoids of *Ceratitis capitata* and *Anastrepha* spp. (Diptera: Tephritidae) in Costa Rica. *Entomophaga* 26: 285-290.

WHARTON, R., TROSTLE, M., MESSING, R., COPELAND, R., KIMIANI-NJOGU, S., LUX, S., OVERHOLT, W., MOHAMED, S. & SIVINSKI, J. (2000) Parasitoids of medfly, *Ceratitis capitata*, and related tephritids in Kenyan coffee: a predominantly koinobiont assemblage. *Bulletin of Entomological Research* 90: 517-526.

WHITE, I.M. & ELSON-HARRIS, M.M. (1992) *Fruit Flies of Economic Significance: Their Identification and Bionomics.* C.A.B. International, Wallingford.

WHITFIELD, A.E., ULLMAN, D.E., GERMAN, T.L. (2005) Tospovirus-thrips interactions. *Annuual Review of Phytopathology* 43: 459-489.

WILLIERS, P. (1979) Suitability of *Harpephyllum caffrum* (kaffir [*sic*] plum) as host for Mediterranean fruit fly and false codling moth. *Citrus and Subtropical Fruit Journal* 543: 5-6.

WONG, T.T.Y., McINNIS, D.O., NASHIMOTO, J.I., OTA, A.K. & CHANG, V.C.S. (1984) Predation of the Mediterranean fruit fly (Diptera: Tephritidae) by the Argentine ant (Hymenoptera: Formicidae) in Hawaii. *Journal of Economic Entomology* 77: 1454-1458.

WORNER, S.P. (2002) Predicting the invasion potential of exotic insects. In: Hallman, G.J. & Schwable, C.P. (Eds.) *Invasive Arthropods in Agriculture: Problems and Solutions*. Science Publishers Inc., Enfield, pp. 119-137.

APPENDIX 1 Soil classification of each of the study sites by Mr Loddie Greyling (Chicory SA Ltd, Alexandria), based on "Soil Classification a Taxonomic System for South Africa" (Soil Classification Working Group 1991).

Farm Name and Land	Soil Form	Soil Discription	Subsoil	Soil Family
Varnam Seedling 1	Good soil. Dug to a depth of 45 cm.	Horizon A = Orthic A, on Neocutanic B. Less than 10% clay.	Unspecified - Oakleaf.	2000 A horizon bleached. 2100 Non-red B horizon. Luvic B1 horizon # 2120 Patrysdal.
Varnam Seedling 2	Good soil. Dug to a depth of 50 cm.	Horizon A = Orthic A, 7-10% clay. Horizon B = Yellow-brown Apedal B 15-20% clay.	Unspecified - Clovelly.	1000 Dystrophic B1 horizon. Non-luvic B1 horizon # 1100 Twyfelaar.
Varnam Ratooned	Very good soil. Dug to a depth of 40 cm.	Horizon A = Orthic A, on Neocutanic B. Horizon A less than 10% clay. Horizon B = 10-15% clay.	Unspecified - Oakleaf.	1000 A horizon not bleached. 1200 Red B horizon. Luvic B1 horizon # 1220 Dipene.
Imjabulo Ratooned and Seedling*	Good soil. Dug to a depth of slightly more than 50 cm.	Horizon A = Orthic A, on Neocutanic B. Horizon A shallow 10 – 15 cm. 15-18% clay. Unspecified horizon at 500 cm+.	Unspecified material with signs of wetness - Tukulu.	1000 A horizon not bleached. 1100 Non-red B horizon. Luvic B1 horizon # 1120 Olivedale.
Lower Melrose Seedling	Good soil. Dug to a depth of 50 cm.	Horizon A = Orthic A, 12-15% clay. Horizon B = Neocutanic B, not homogenous in colour, has some structure.	Unspecified material with signs of wetness - Tukulu.	1000 A horizon not bleached. 1100 Non-red B horizon. Luvic B1 horizon # 1120 Olivedale.
Brenthoek Ratooned	Good soil. Dug to a depth of 35 cm.	Horizon A = Orthic A, on Neocutanic B, unspecified. 20% clay.	Oakleaf.	1000 A horizon not bleached. 1200 Red B horizon. Luvic B1horizon # 1220 Dipene.
Brenthoek Seedling	Good, well-drained soil. Dug to a depth of 55 cm.	Horizon A = Orthic A, on Red Apedal B. Less than 6% clay. Homogenous in colour.	Apedal - unspecified, very sandy, leachable soil - Hutton.	1000 Dystrophic B1 horizon. Non-luvic B1 horizon # 1100 Lillieburn.

***** Imjabulo Ratooned and Seedling lands were classified as the same type of soil as these two lands are directly adjacent to one another.

APPENDIX 2 Dates when fungicides, herbicides and insecticides were applied in each of the study sites.

Farm, Site and Date	Insecticide	Herbicide	Fungicide
Varnam Seedling 1			
October 2005		Ronstar	
October 2005		Lasso Micro Tech	
Oct/Nov 2005	Bulldock		
20/11/2005	Bulldock		
20/11/2005			Copflo
06/01/06	Bulldock		
12/01/06	Bulldock		
12/01/06			Copflo
15/01/06		Agil	
22/01/06		Agil	
03/02/06	Bulldock		
03/02/06	Methomex		
03/02/06			Folicur
25/02/06		Roundup	
25/02/06	Bulldock		
25/02/06			Copper Oxychloride
16/03/06	Methomex		
16/03/06	Bulldock		
04/04/06	Dipterex		
20/08/06		Gramoxone	
05/11/06	Bulldock		
Varnam Seedling 2			
October 2005		Ronstar	
October 2005		Lasso Micro Tech	
Oct/Nov 2005	Bulldock		
20/11/2005	Bulldock		

Farm, Site and Date	Insecticide	Herbicide	Fungicide
20/11/2005			Copflo
06/01/06	Bulldock		
12/01/06	Bulldock		
12/01/06			Copflo
15/01/06		Agil	
22/01/06		Agil	
03/02/06	Bulldock		
03/02/06	Methomex		
03/02/06			Folicur
25/02/06		Roundup	
25/02/06	Bulldock		
25/02/06			Copper Oxychloride
16/03/06	Methomex		
16/03/06	Bulldock		
04/04/06	Dipterex		
20/08/06		Gramoxone	
05/11/06	Bulldock		
Varnam Ratooned			
Dec 2005	Thioflo		
Dec 2005	Bulldock		
Dec 2005			Copstar
12/01/06	Bulldock		
12/01/06			Dithane
12/01/06	Biomectin		
31/01/06	Bulldock		
31/01/06			Dithane
03/02/06		Roundup	
10/03/06	Dipterex		
Imjabulo Seedling			
No data available			

Farm, Site and Date	Insecticide	Herbicide	Fungicide
Imjabulo Ratooned			
No data available			
Lower Melrose Seedling			
During fruiting	Bulldock		
During fruiting	Bulldock		
During fruiting	Bulldock		
Brenthoek Seedling			
07/11/05		Ronstar	
07/11/05		Alachlor	
07/11/05	Bulldock		
10/01/06	Bulldock		
03/03/06	Bulldock		
03/03/06	Dipterex		
10/03/06	Dipterex		
24/03/06	Dipterex		
08/04/06	Dipterex		
21/04/06	Dipterex		
Brenthoek Ratooned			
10/01/06	Bulldock		
03/03/06	Bulldock		
03/03/06	Dipterex		
10/03/06	Dipterex		
24/03/06	Dipterex		

APPENDIX 3 Record of pheromone lures and bait dispenser replacement in traps throughout the study period.

DATE	EGO PheroLure™	Lorelei®	Questlure®	Texas Volatile™
21/11/05	Set Up	Set Up		Set Up
30/01/06	10 wks		Set Up	10 wks
20/02/06			3 wks	
20/03/06			4 wks	
03/04/06	9 wks		2 wks	9 wks
10/04/06			1 wk	
17/04/06			1 wk	
02/05/06			2 wks	
08/05/06			1 wk	
15/05/06	6 wks		1 wk	6 wks
22/05/06			1 wk	
05/06/06			2 wks	
19/06/06			2 wks	
03/07/06	7 wks	32 wks	2 wks	7 wks
24/07/06			3 wks	
07/08/06			2 wks	
21/08/06	7 wks		2 wks	7 wks
04/09/06			2 wks	
18/09/06			2 wks	
25/09/06	5 wks		1 wk	5 wks
02/10/06			1 wk	
09/10/06			1 wk	
23/10/06			2 wk	
30/10/06	5 wks		1 wk	5 wks
06/11/06			1 wk	

* Set Up = date traps set up. N.B. Yellow Card Traps are not shown as no pheromone is used with it. YCT's were replaced weekly.

APPENDIX 4 Insect fauna collected from all lands between the 21st of November 2005 and the 19th of November 2006.

ORDER	FAMILY	GENUS	SPECIES
Coleoptera			
	Anthicidae	*Anthicus*	
		Formicomus	
		Notoxus	
		genus indeterminate	
	Apionidae	*Perapion*	
		genus indeterminate	
	Bruchidae	*Bruchidius*	
		Spermophagus	
	Buprestidae	genus indeterminate	
	Cantharidae	genus indeterminate	
	Carabidae	genus indeterminate	
	Cerambycidae	*Chlorophorus*	
		Litopus	
		genus indeterminate	
	Chrysomelidae	*Afrorestia*	
		Altica	
		Aphthona	
		Dibolia	
		Decaria	
		Gabonia	
		Hespera	
		Monomacra	
		Phyllotreta	
		Sphaeroderma	
		Chrysolina	
		Afrophthalma	
		Lema	

ORDER	FAMILY	GENUS	SPECIES
		Afroeurydemus	
		Colasposoma	
		Macrocoma	
		Pseudomalegia	
		Afromaculepta	
		Exosoma	
		Leptaulaca	
		Monolepta	
		genus indeterminate	
	Cicindelidae	*Lophyra*	
	Cleridae	genus indeterminate	
	Coccinellidae	*Cheilomenes*	
		Lioadalia	
		Scymnus	
		genus indeterminate	
	Corylophidae	genus indeterminate	
	Cryptophagidae	?*Ephistemus*	
		Micrambe	
		genus indeterminate	
	Curculionidae	*Barius*	
		Cleopomiarus	
		Lobotrachelus	
		Cionus	
		genus indeterminate	
	Dermestidae	genus indeterminate	
	Dytiscidae	genus indeterminate	
	Elateridae	genus indeterminate	
	?Endomychidae	genus indeterminate	
	Histeridae	genus indeterminate	
	Hydrophilidae	genus indeterminate	

ORDER	FAMILY	GENUS	SPECIES
	Laemophloeidae	genus indeterminate	
	Lampyridae	genus indeterminate	
	Lycidae	genus indeterminate	
	Meloidae	*Mylabris*	
		genus indeterminate	
		genus indeterminate	
	Melyridae	*Melyris*	
		genus indeterminate	
	Mordellidae	genus indeterminate	
	Mycetophagidae	*Litargus*	
	Nitidulidae	*Brachypeplus*	
		Carpophilus	
		Haptoncus	
		near *Haptoncus* sp.	
		Lordites	
		Meligethes	
		Pria	
		Urophorus	
	Oedemeridae	*Melananthia*	
	Paussidae	genus indeterminate	
	Phalacridae	genus indeterminate	
	Pselaphidae	genus indeterminate	
		genus indeterminate	
	Ptiliidae	genus indeterminate	
	Scarabaeidae	*Aphodius*	
		Campolimpus	
		Leucocelius	
		?Leucocelius	
		Onthophagus	
		genus indeterminate	

ORDER	FAMILY	GENUS	SPECIES
	Scraptiidae	genus indeterminate	
	Silvanidae	genus indeterminate	
	Staphylinidae	genus indeterminate	
	Tenebrionidae	*Gonocephalum*	
		genus indeterminate	
	Urodontidae	genus indeterminate	
Diptera			
	Agromyzidae	genus indeterminate	
	Anthomyidae	genus indeterminate	
	Bibionidae	genus indeterminate	
	Bombyliidae	genus indeterminate	
	Calliphoridae	genus indeterminate	
	Cecidomyiidae	genus indeterminate	
	Ceratopogonidae	genus indeterminate	
	Chamaemyiidae?	genus indeterminate	
	Chironomidae	genus indeterminate	
	Chloropidae	genus indeterminate	
	Chryomyidae	genus indeterminate	
	Clusiidae?	genus indeterminate	
	Conopidae	genus indeterminate	
	Culicidae	genus indeterminate	
	Drosophlidae	genus indeterminate	
	Empididae	genus indeterminate	
	Ephydridae?	genus indeterminate	
	Lonchaeidae	genus indeterminate	
	Milichiidae	genus indeterminate	
	Muscidae	genus indeterminate	
	Phoridae	genus indeterminate	
	Playstomatidae	genus indeterminate	

ORDER	FAMILY	GENUS	SPECIES
	Psychodidae	genus indeterminate	
	Sarcophagidae	genus indeterminate	
	Scatopsidae	genus indeterminate	
	Sciaridae	genus indeterminate	
	Sepsidae	genus indeterminate	
	Stratiomyidae	genus indeterminate	
	Syrphidae	genus indeterminate	
	Tachinidae	genus indeterminate	
	Tephritidae	*Ceratitis*	*capitata*
		Ceratitis	*rosa*
		genus indeterminate	
Hemiptera			
	Aleyrodidae	genus indeterminate	
	Anthocoridae	*Orius*	sp.
	Aphididae	*Macrosiphum*	*euphorbiae*
		Myzus	*persicae*
	Cercopidae	*Locris*	*aenea*
	Cicadellidae	*Austroagallia*	
		Balclutha	*fumigata*
		Batracomorphus	*danae*
		Cicadulina	*anestaea*
		Empoasca	
		Empoascanara	
		Epignoma	*natalensis*
		Exitianus	*taeniaticeps*
		Macropsis	*turneri*
		Naevus	*subparalleus*
		Neoaliturus	*karrooensis*
		Neoaliturus	*struthiola*

ORDER	FAMILY	GENUS	SPECIES
		Peragallia	*caboverdensis*
		Recilia	
		Rhusopus	
		Scaphoideus	
		Xestocephalus	*aethiopicus*
		genus indeterminate	
	Cixiidae	*Afroreptalus*	sp.
		Oliarus	sp.
		Pentastridius	sp.
	Coreidae	*Cletus*	sp.
	Corixidae	genus indeterminate	
	Cydnidae	*Aethus*	*lautipennis*
		Geotomus	*difficilis*
	Delphacidae	*Nycheuma*	
		Scotoeurysa	
		Toya	
	Lygaeidae	*Caprochromus*	*moerens*
		Cymodema	*tabidum*
		Elasmolomus	*consocialis*
		Geocoris	
		Haemobaphus	*concinuus*
		Horridipamera	*inconspicuus*
		Lasiosomus	
		Lethaeus	*guttulatus*
		Lethaeus	*setulatus*
		Nysius	
		Oxycarenus	
		Pachybrchius	*inconspicuus*
		Plinthisus	*rudebecki*
		Rhyparochroms	*moerens*

ORDER	FAMILY	GENUS	SPECIES
		Spilostethus	*pandurus*
		Spilostethus	*trilineatus*
		Sweetocoris	
	Membracidae	*Oxyrhachis*	*delalandei*
	Miridae	genus indeterminate	
	Nabidae	*Nabis*	*capsiformis*
	Pentatomidae	*Bagrada*	*hilaris*
		Carbula	
		Eysarcoris	*inconspicuus*
		Mecidaea	*prolixa*
		Nezara	*viridula*
	Psyllidae	*Diaphorina*	
		genus indeterminate	
	Reduviidae	*Rhinocoris*	*segmentarius*
	Rhopalidae	*Liorhyssus*	*hyalinus*
		Peliochrous	*nigromaculatus*
Hymenoptera			
	Agaonidae	genus indeterminate	
	Ampulicidae	*Dolichurus*	sp.
	Aphelinidae	*Aphelinus*	sp.
	Apidae	*Allodape*	*pernix*
			quadrilineata
		Allodapula	*dichroa*
			variegata
		Amegilla	*kaimosica*
			obscuriceps
		Apis	*mellifera*
		Braunsapis	*leptozonia*
		Ceratina	*nigriceps*

ORDER	FAMILY	GENUS	SPECIES
		Xylocopa	*caffra*
			flavorufa
			scioensis
	Bethylidae	genus indeterminate	
	Braconidae	*Opius*	sp.
		genus indeterminate	
	Ceraphronidae	genus indeterminate	
	Chalcididae	*Dirhinus*	sp.
	Chrysididae	*Chrysis*	sp.
	Colletidae	*Colletes*	sp.
		Hylaeus (Nothylaeus)	*heraldicus*
		Hylaeus	sp.
		Hylaeus (Deranchylaeuis)	sp.
	Crabronidae	*Dasyproctus*	sp.
		Liris	sp.
		Oxybelus	sp.
	Diapriidae	genus indeterminate	
	Encyrtidae	*Cerchysiella*	sp.
		Coelopencyrtis	sp.
		Habrolepis	
		Tachinaephagus	sp.
		genus indeterminate	
	Eucharitidae	*Aperilampus*	sp.
	Eucoilidae	genus indeterminate	
	Eulophidae	*?Aprostocetus*	sp.
		Entedon	sp.
		Euplectrus	sp.
		Pediobius	sp.
		Systasis	sp.
		genus indeterminate	

ORDER	FAMILY	GENUS	SPECIES
	Eurytomidae	*Eurytoma*	sp.
		Tetramesa	sp.
		genus indeterminate	
	Formicidae	*Camponotus*	*niveosetosis*
			maculatus
			sp.
		Crematogaster	sp.
		genus indeterminate	
	Halictidae	*Ceylalictus*	sp.
		?Halictus	sp.
		Lasioglossum	sp.
		Lipotriches	sp.
		Nomia	sp.
		Nomioides	sp.
		Patellapis	sp.
	Ichneumonidae	genus indeterminate	
	Megachilidae	*Lithurgus pullatus*	
		Megachile (Eutricharaea)	sp.
		Megachile (Paracella)	
		?Stenoheriades	sp.
		genus indeterminate	
	Melittidae	*Melitta*	*arrogans*
	Mymaridae	genus indeterminate	
	Philanthidae	*Cerceris*	*erythrosoma*
			sp.
		Philanthus	*fuscipennis*
			loefflingi
	Pompilidae	*Hemipepsis*	sp.
		genus indeterminate	
	Pteromalidae	*Spalangia*	

ORDER	FAMILY	GENUS	SPECIES
		genus indeterminate	
	Platygasteridae	genus indeterminate	
	Sapygidae	*Sapyga*	simillima
	Scelionidae	genus indeterminate	
	Scoliidae	*Campsomeriella*	*caelebs*
			madonensis
		Scolia	sp.
		genus indeterminate	
	Sphecidae	*Ammophila*	*beniniensis*
			ferrugineipes
			vulcania
		Prionyx	*kirbii*
		Sphex	sp.
	Tenthredinidae	genus indeterminate	
	Tiphiidae	genus indeterminate	
	Torymidae	genus indeterminate	
	Vespidae	*Anterhynchium*	*natalense*
		Belonogaster	sp.
		Polistes	sp.
		Ropalidia	sp.
		Rhynchium	*marginellum*
		Synagris	*abyssinica*
		genus indeterminate	
Lepidoptera			
	Adelidae	genus indeterminate	
	Arctiidae	*Amerila*	*vitrea*
		Eilema	*colon*
		Eucreagra	*arculifera*
		Phryganopsis	sp.
		Sommeria	sp.

ORDER	FAMILY	GENUS	SPECIES
		Syntomini	sp.
		genus indeterminate	
	Choreutidae	genus indeterminate	
	Crambidae	*Epipagis*	*cancellalis*
		Hellula	*undalis*
		Hydriris	*ornatalis*
		Hymenia	*recurvalis*
		Loxostege	*frustalis*
		Lygropa	*quaternalis*
		Maruca	
		Nomophila	sp.
		Palpita	*indica*
		Parapoynx	sp.
		Pleuroptya	*nasonalis*
		Pyralis	*incoloralis*
		Udea	sp.
		genus indeterminate	
	Ethmiidae	*Ethmia*	sp.
		genus indeterminate	
	Gelechiidae	genus indeterminate	
	Geometridae	*Ascotis*	*reciprocaria*
		Cabera	sp.
		Chiasmia	*brongusaria*
		Drepanogynis	sp.
		Eupithecia	sp.
		Erastria	*madecassaria*
		Horisme	sp.
		Oaracta	sp.
		Orthonama	*obstipata*
		Palaeaspilates	*inoffensa*

ORDER	FAMILY	GENUS	SPECIES
		Psilocerea	sp.
		Rhodometra	*sacraria*
		Scopula	sp
		Xylopteryx	*protearia*
		Zamaroda	sp.
		genus indeterminate	
	Gracillariidae	genus indeterminate	
	Lymantriidae	*Euproctis*	sp.
	Noctuidae	*Abrostola*	sp.
		Acanthuleucania	sp.
		Achaea	sp
		Agrapha	*limbirena*
		Agrotis	*longidentifera*
			segetum
		Amyna	*axis*
		Anomis	*flava*
			sabulifera
		Apospasta	sp.
		Athetis	sp.
		Chrysodeixis	*acuta*
		Cosmophila	*flava*
		Cucullia	*terensis*
		Dicerogastia	sp.
		Earias	*cupreoviridis*
		Grammodes	*stolida*
		Hadena	*bulgeri*
		Helicoverpa	*armigera*
		Hypocala	sp.
		Hypomecis	sp.
		Hypotype	*scotomista*

ORDER	FAMILY	GENUS	SPECIES
		Memtaxya	sp.
		Nodaria	*uliginosalis*
		Ozarba	sp.
		Trichopluria	*sestertia*
		Spodoptera	*exigua*
			sp.
		Trichoplusia	*exquisita*
			orichalcea
			vittata
		Tycomarptes	*inferior*
		Ulotrichopus	*primulinus*
		Xylomania	sp.
		genus indeterminate	
	Nolidae	genus indeterminate	
	Pieridae	*Dixeia*	*pigea*
		Mylothris	sp.
	Plutellidae	genus indeterminate	
	Pterophoridae	genus indeterminate	
	Pyralidae	*Endotricha*	sp.
		genus indeterminate	
	Tineidae	genus indeterminate	
	Scythrididae	*Eretmocera*	sp.
	Sphingidae	*Hippotion*	*celerio*
	Thyatiridae	*Marplena*	sp.
	Tineidae	genus indeterminate	
	Tortricidae	*Thaumatotibia*	*leucotreta*
		genus indeterminate	
	Zygaenidae	genus indeterminate	
Thysanoptera			
	Thripidae	*Frankliniella*	*occidentalis*

ORDER	FAMILY	GENUS	SPECIES
			schultzei
		Thrips	*?emulatus*
			tabaci
		genus indeterminate	
	Aeolothripidae	*Aeolothrips*	*brevicornis*
		genus indeterminate	
	Phlaeothripidae	*Haplothrips*	*callani*
			clarisetis
			nigricornis
		genus indeterminate	
Psocoptera			
	Ectopsocidae		
Neuroptera			
	Hemerobiidae		
	Chrysopidae		
	Myrmeleontidae		

APPENDIX 5 Seasonal distribution graphs of African Bollworm, False Codling Moth, Mediterranean Fruit Fly and thrips in the eight *Capsicum* lands.

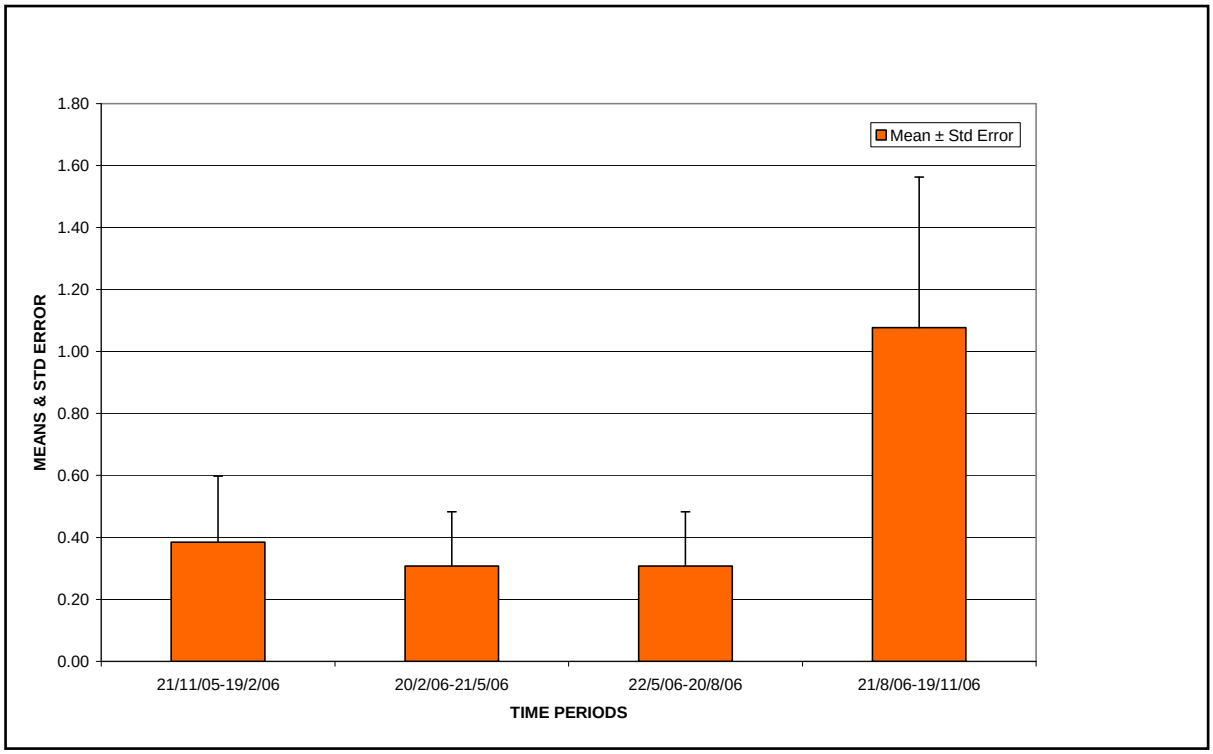


Figure 1 Brenthoek Ratooned: African Bollworm means and standard error over the four time periods.

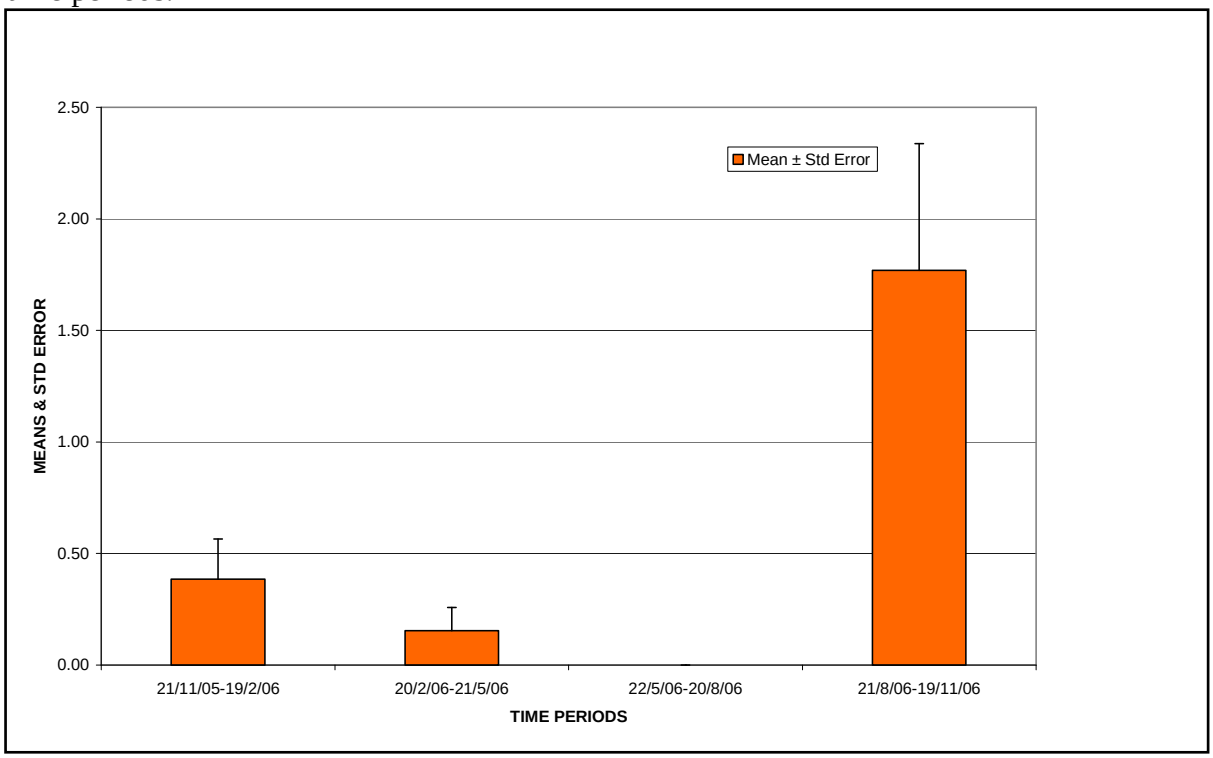


Figure 2 Imjabulo Ratooned: African Bollworm means and standard error over the four time periods.

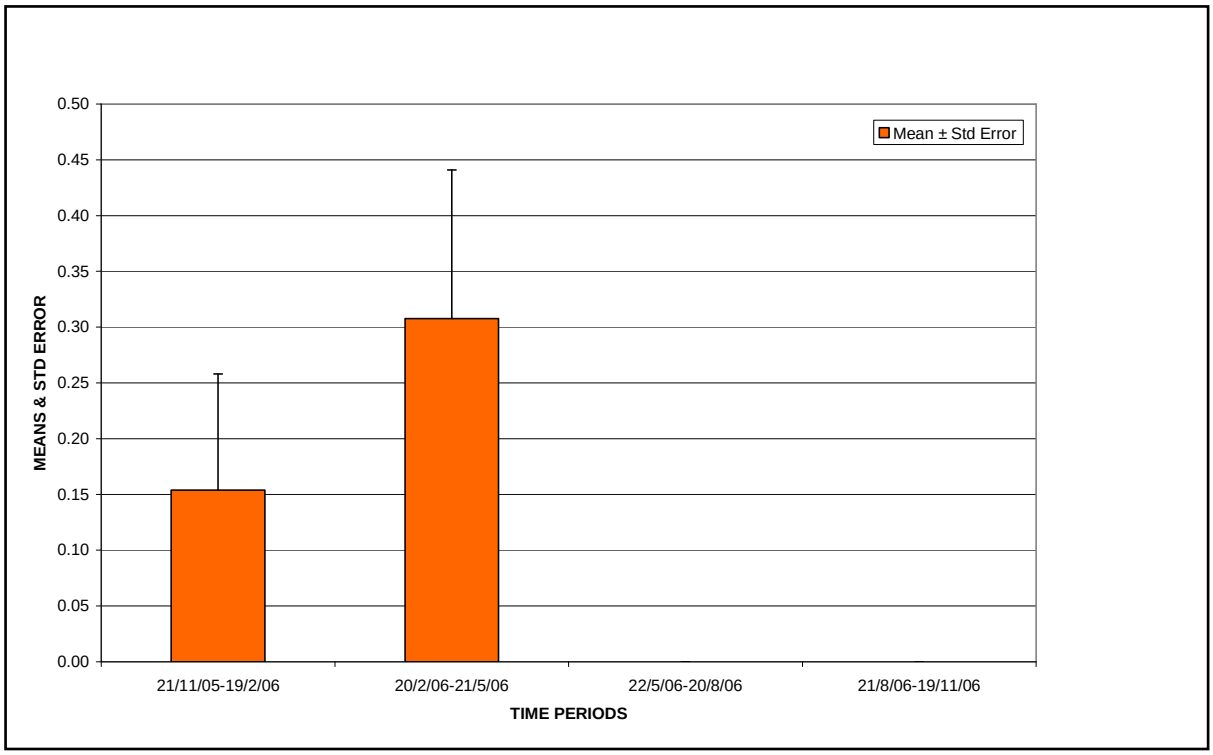


Figure 3 Varnam Ratooned: African Bollworm means and standard error over the four time periods.

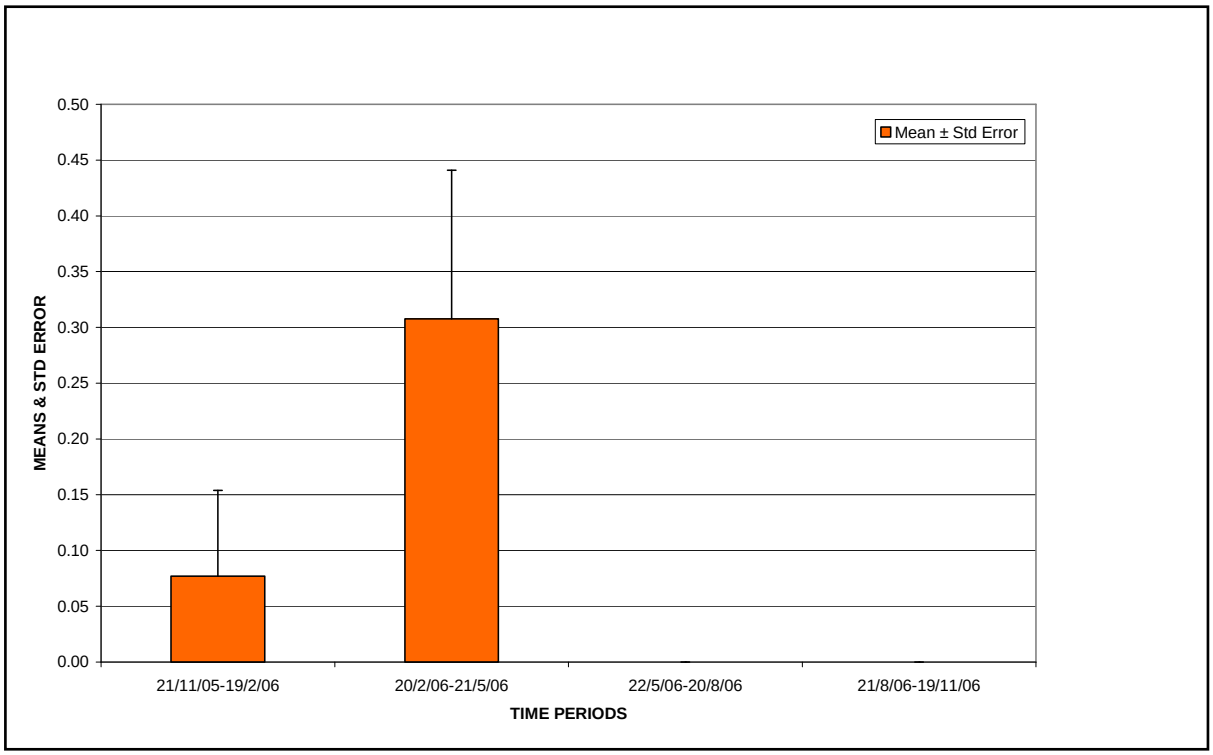


Figure 4 Brenthoek Seedling: African Bollworm means and standard error over the four time periods.

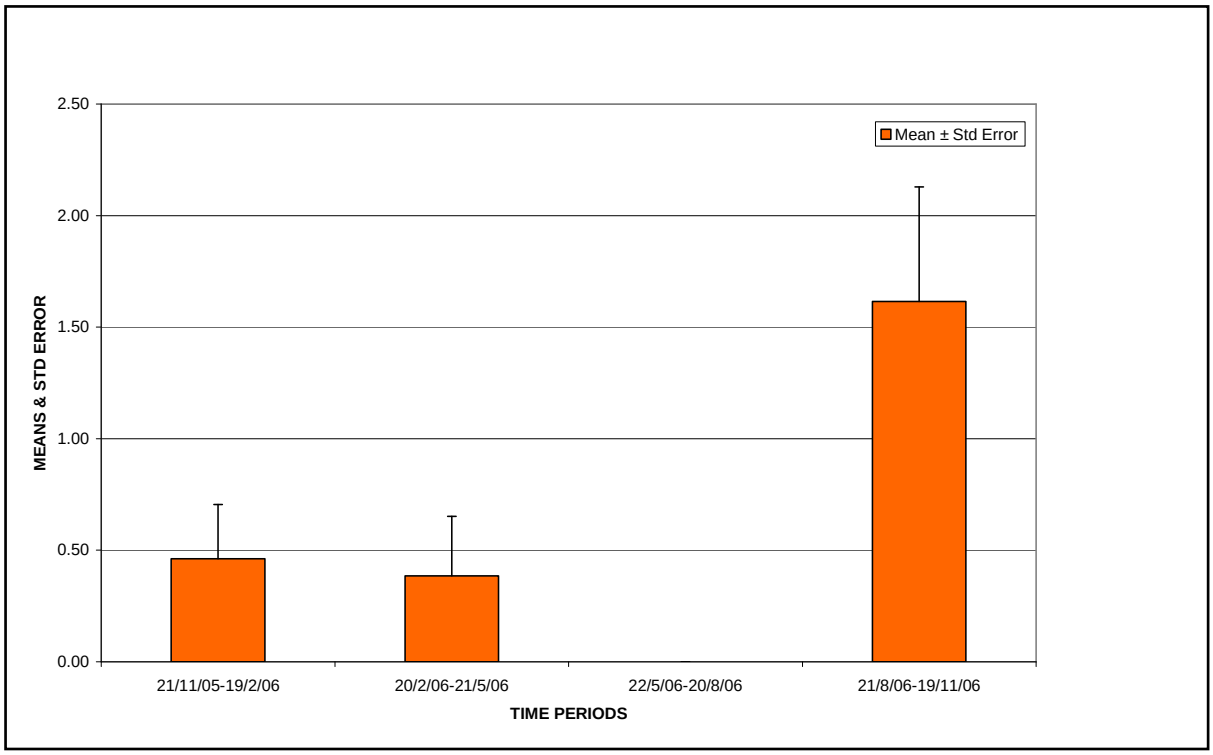


Figure 5 Imjabulo Seedling: African Bollworm means and standard error over the four time periods.

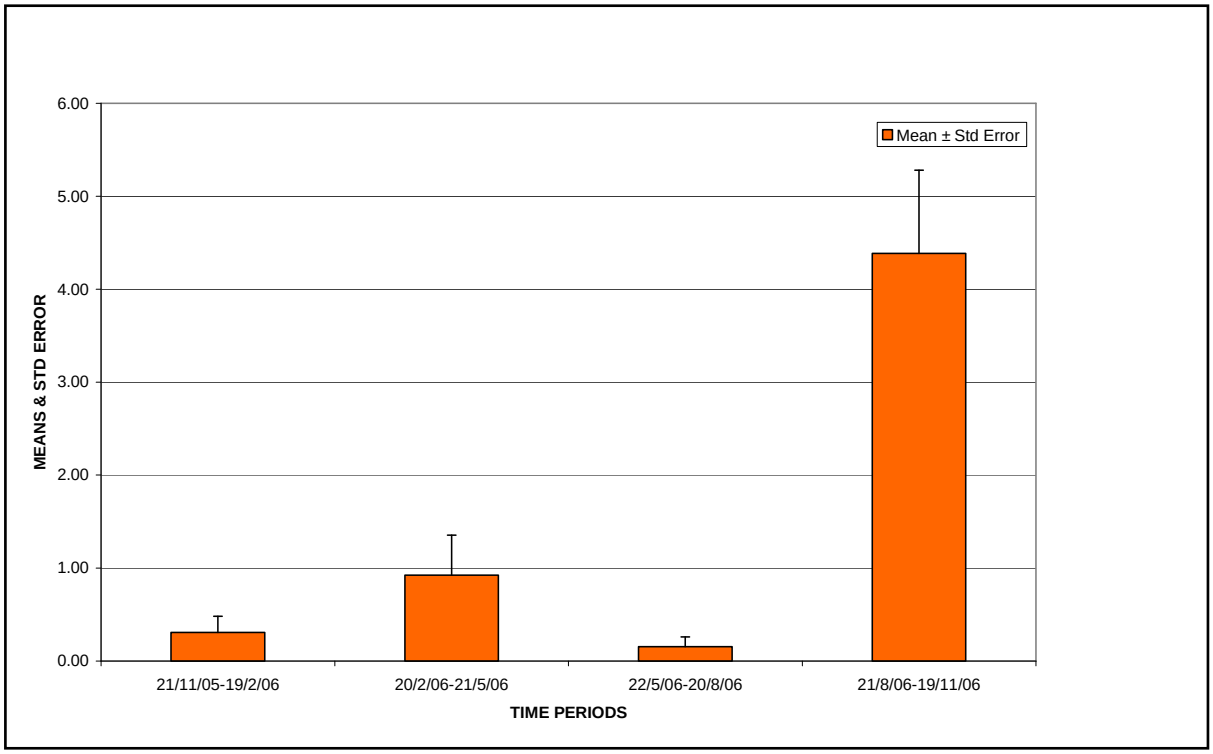


Figure 6 Varnam Seedling 1: African Bollworm means and standard error over the four time periods.

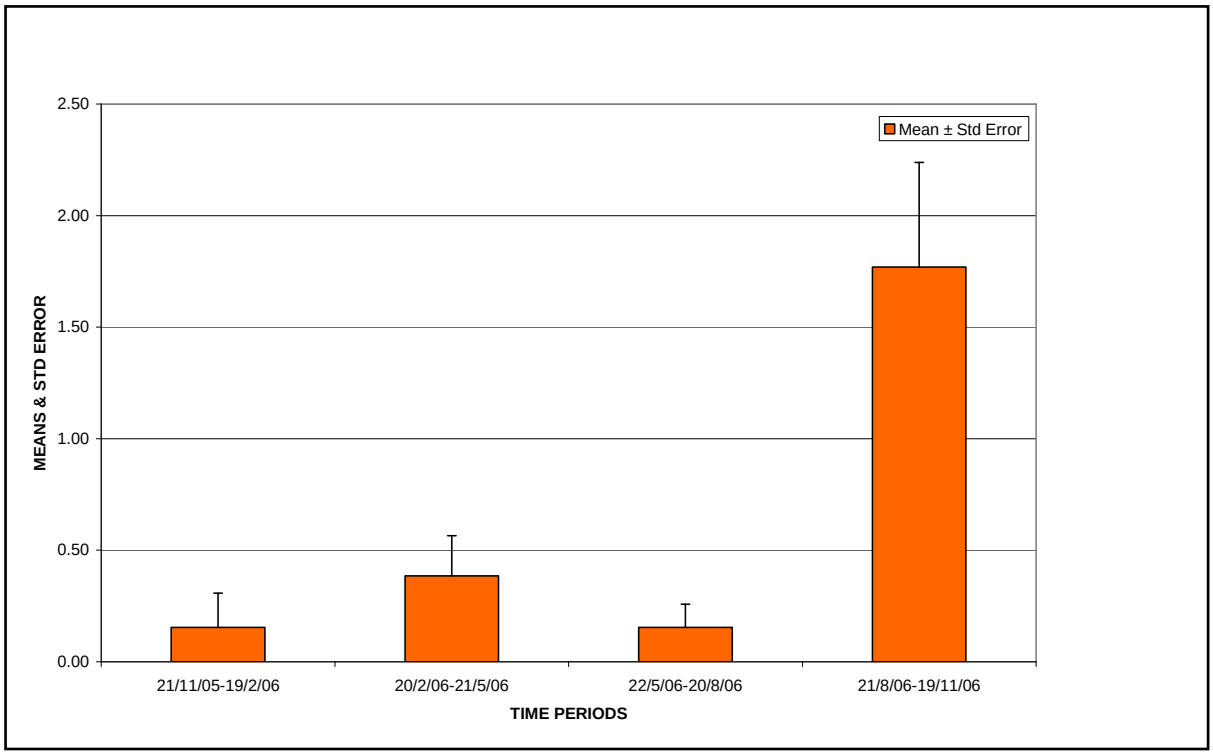


Figure 7 Varnam Seedling 2: African Bollworm means and standard error over the four time periods.

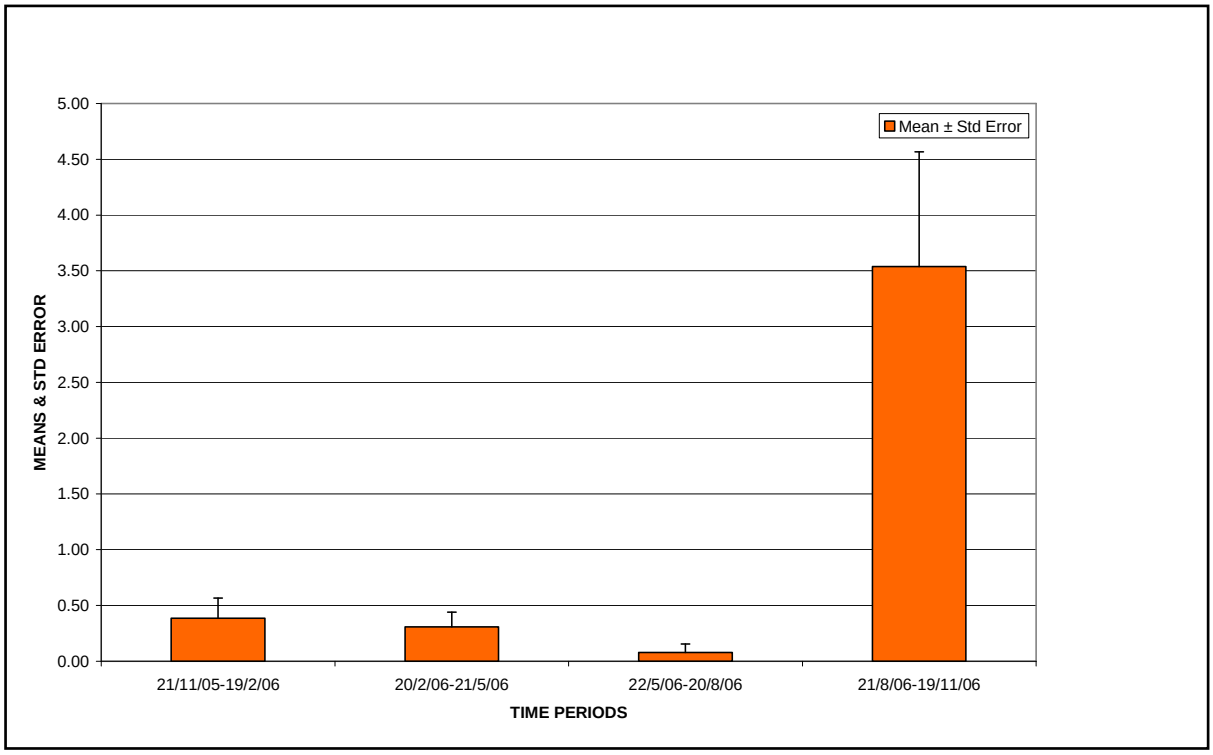


Figure 8 Lower Melrose Seedling: African Bollworm means and standard error over the four time periods.

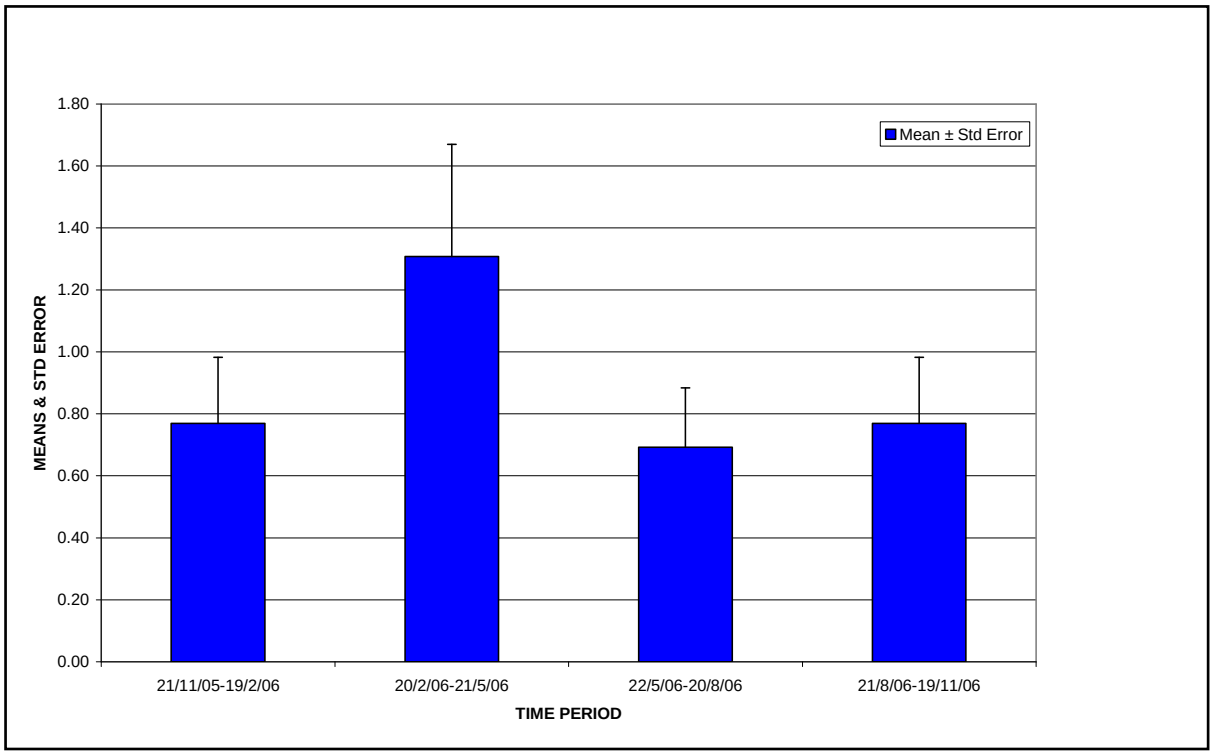


Figure 9 Brenthoek Ratooned: False Codling Moth means and standard error over the four time periods.

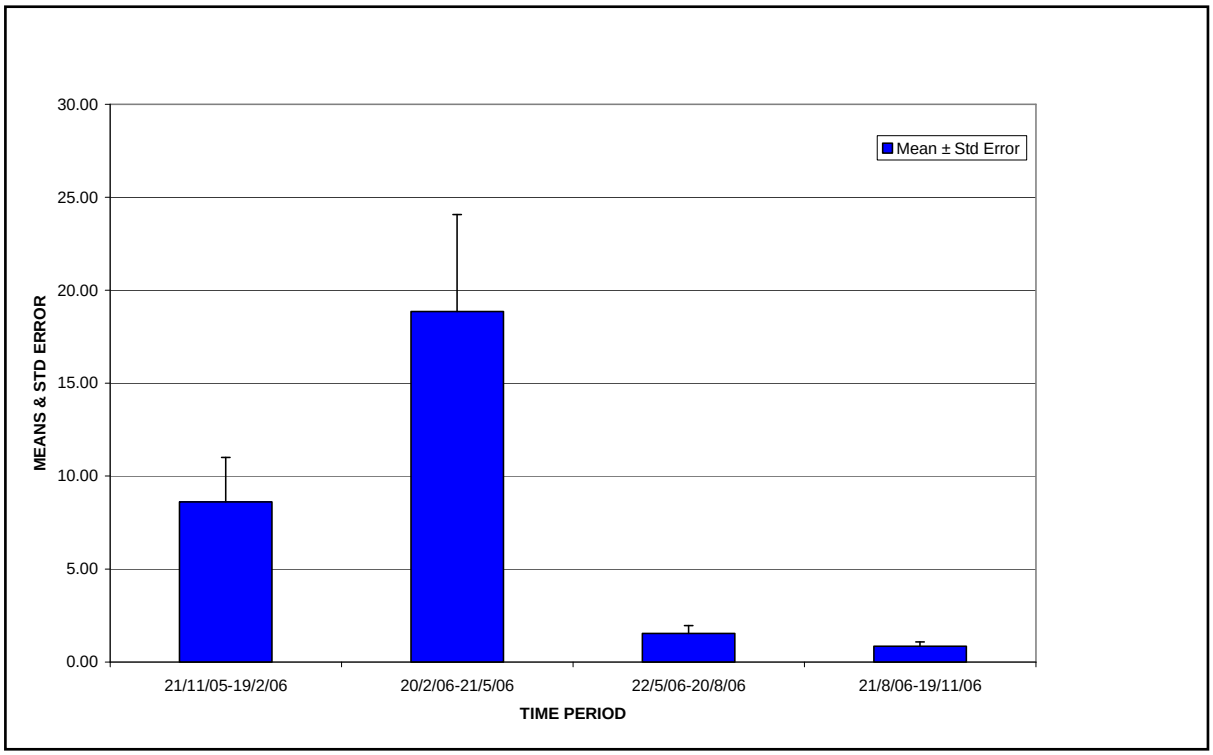


Figure 10 Imjabulo Ratooned: False Codling Moth means and standard error over the four time periods.

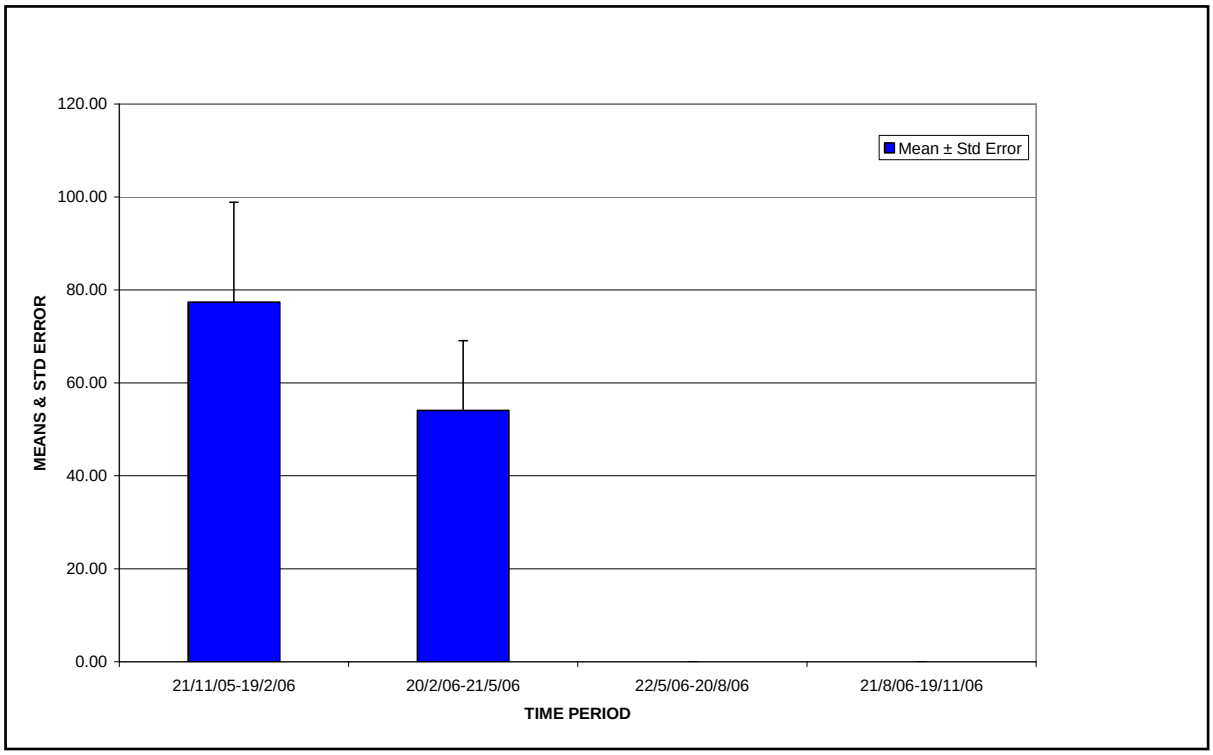


Figure 11 Varnam Ratooned: False Codling Moth means and standard error over the four time periods.

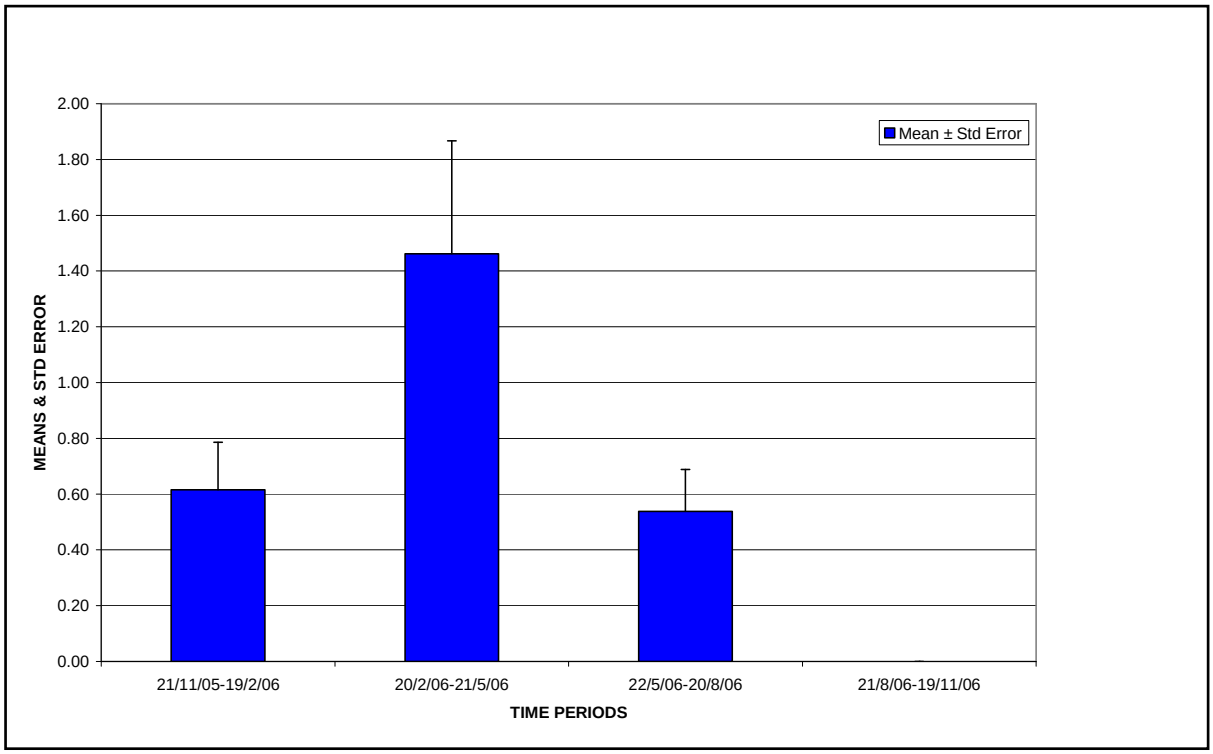


Figure 12 Brenthoek Seedling: False Codling Moth means and standard error over the four time periods.

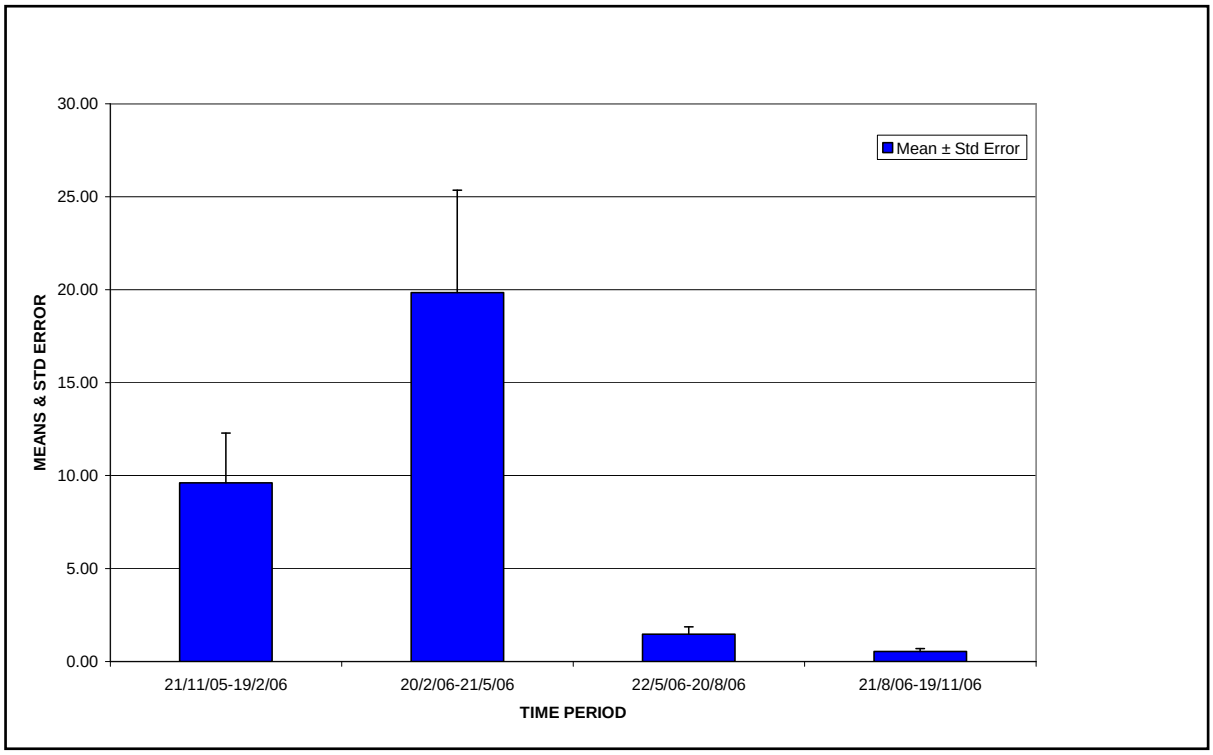


Figure 13 Imjabulo Seedling: False Codling Moth means and standard error over the four time periods.

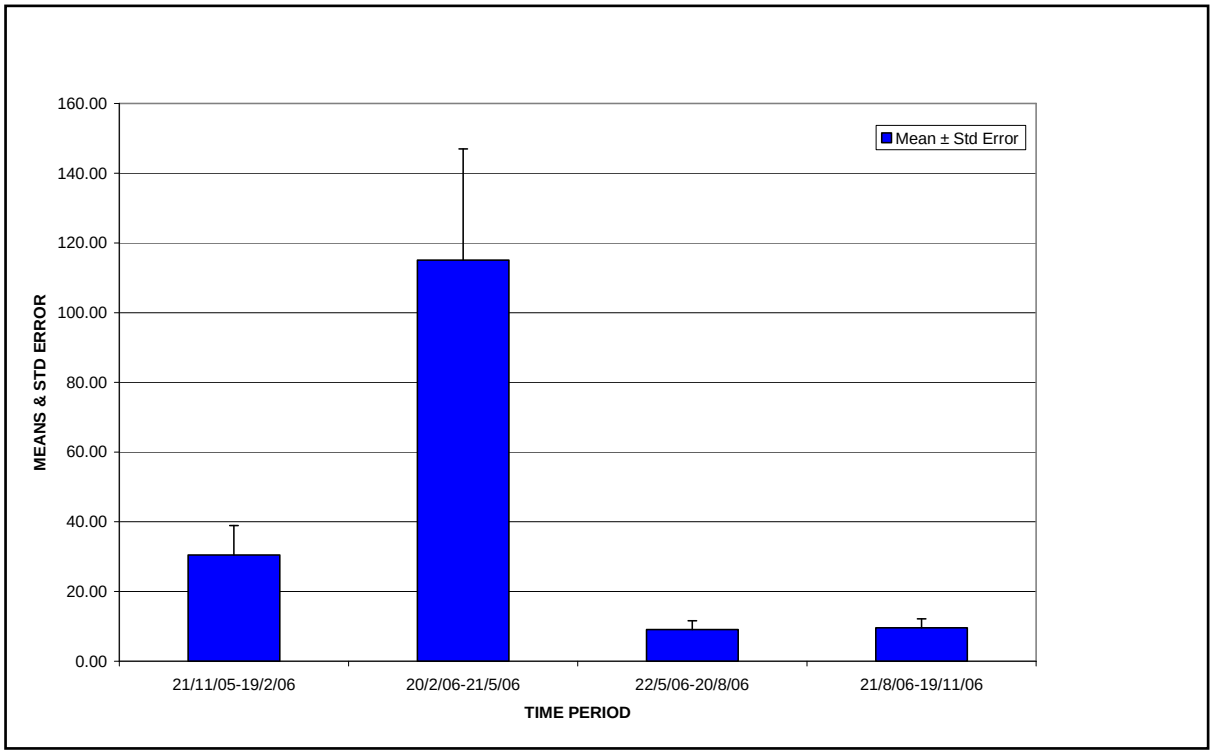


Figure 14 Varnam Seedling 1: False Codling Moth means and standard error over the four time periods.

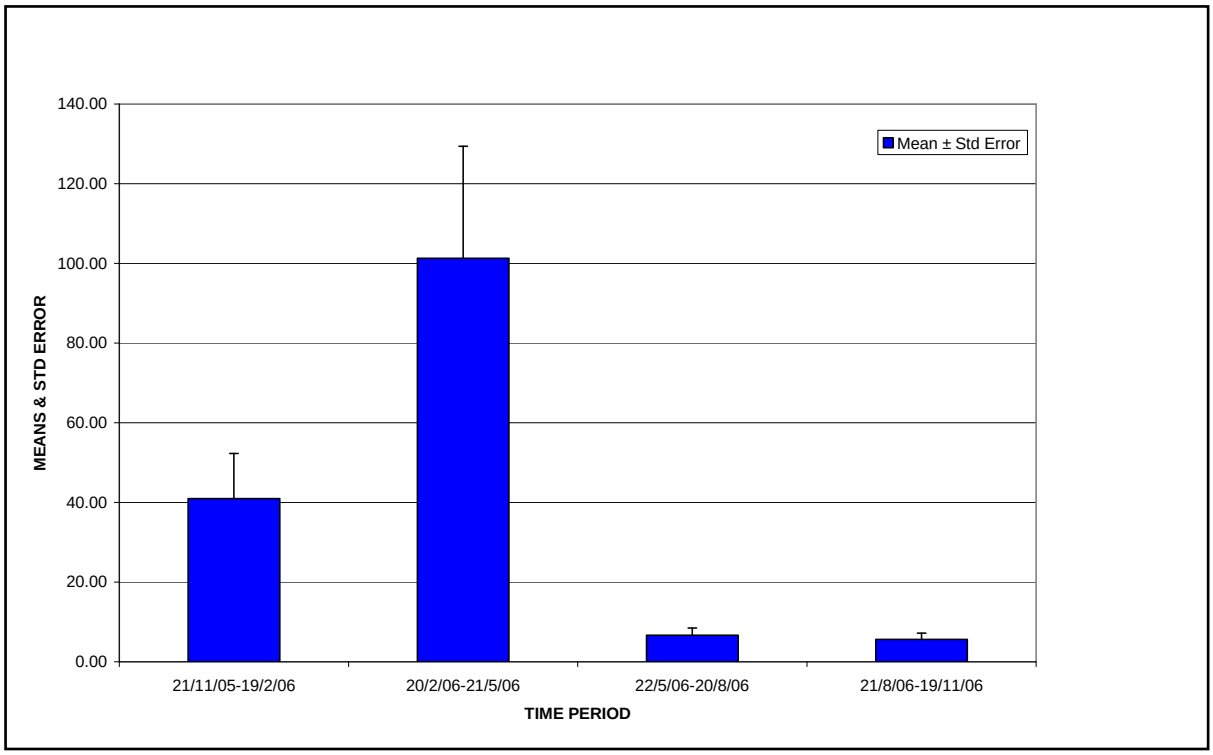


Figure 15 Varnam Seedling 2: False Codling Moth means and standard error over the four time periods.

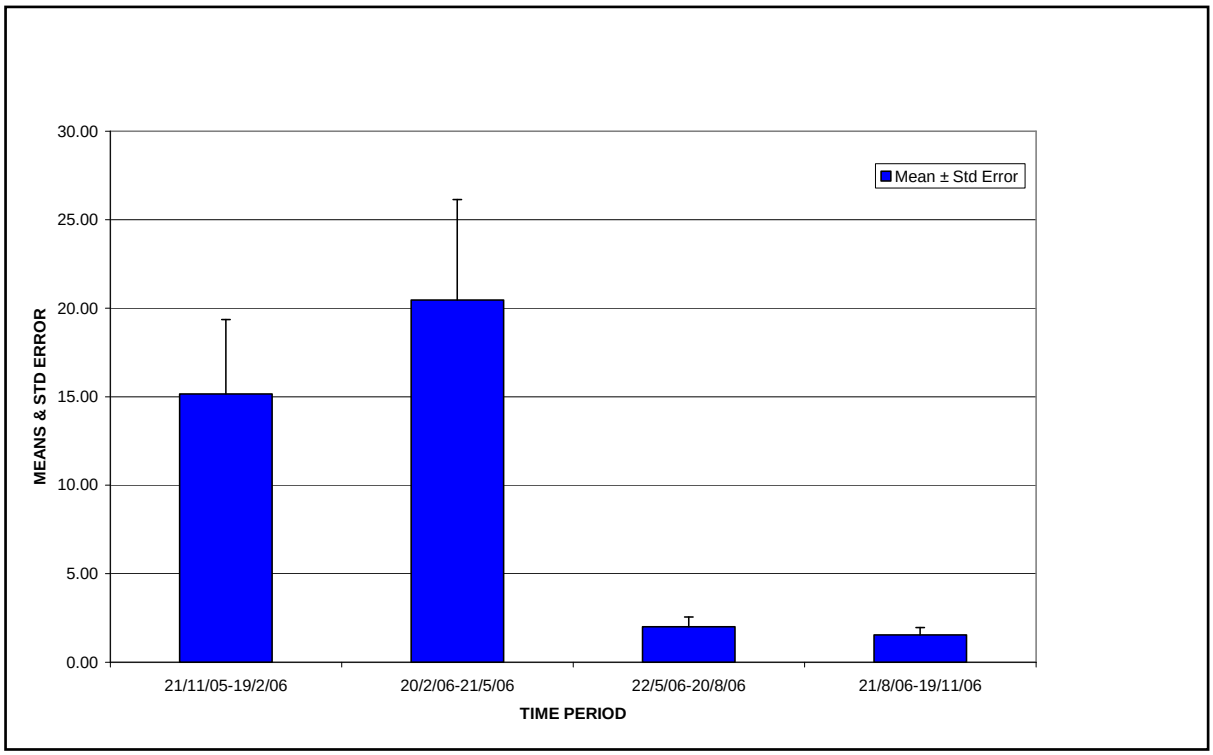


Figure 16 Lower Melrose Seedling: False Codling Moth means and standard error over the four time periods.

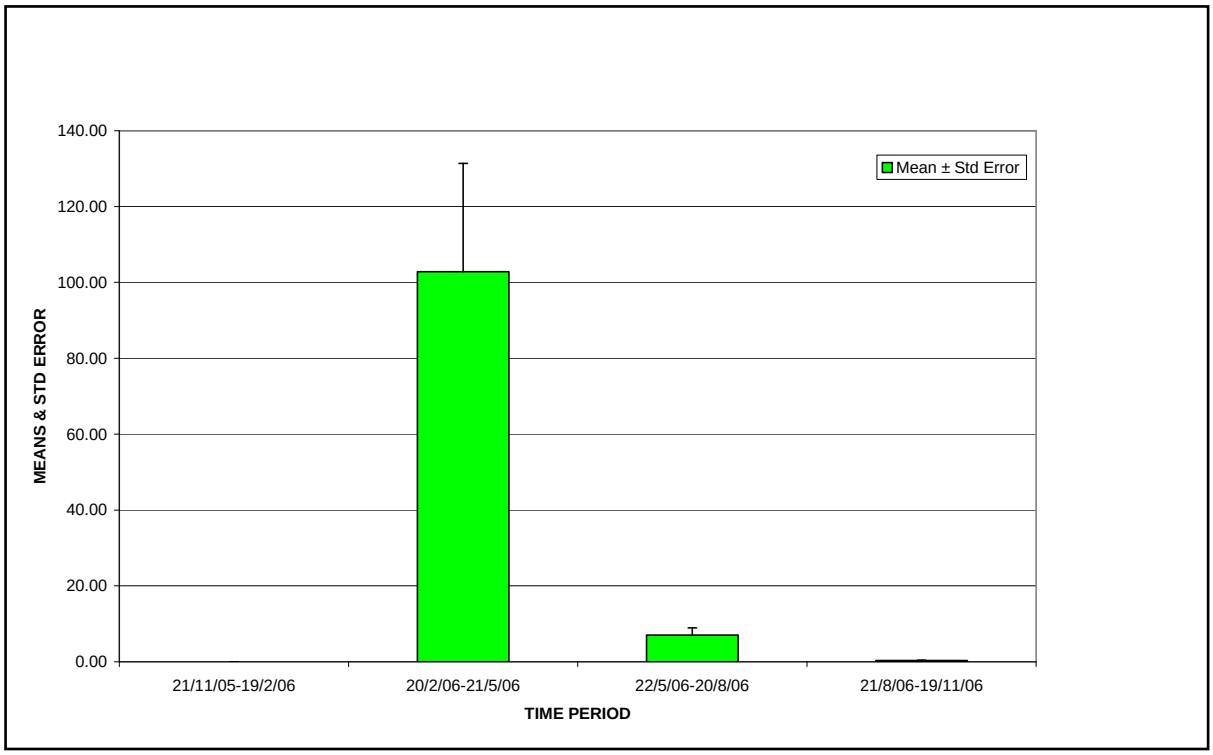


Figure 17 Brenthoek Ratooned: Mediterranean Fruit Fly means and standard error over the four time periods.

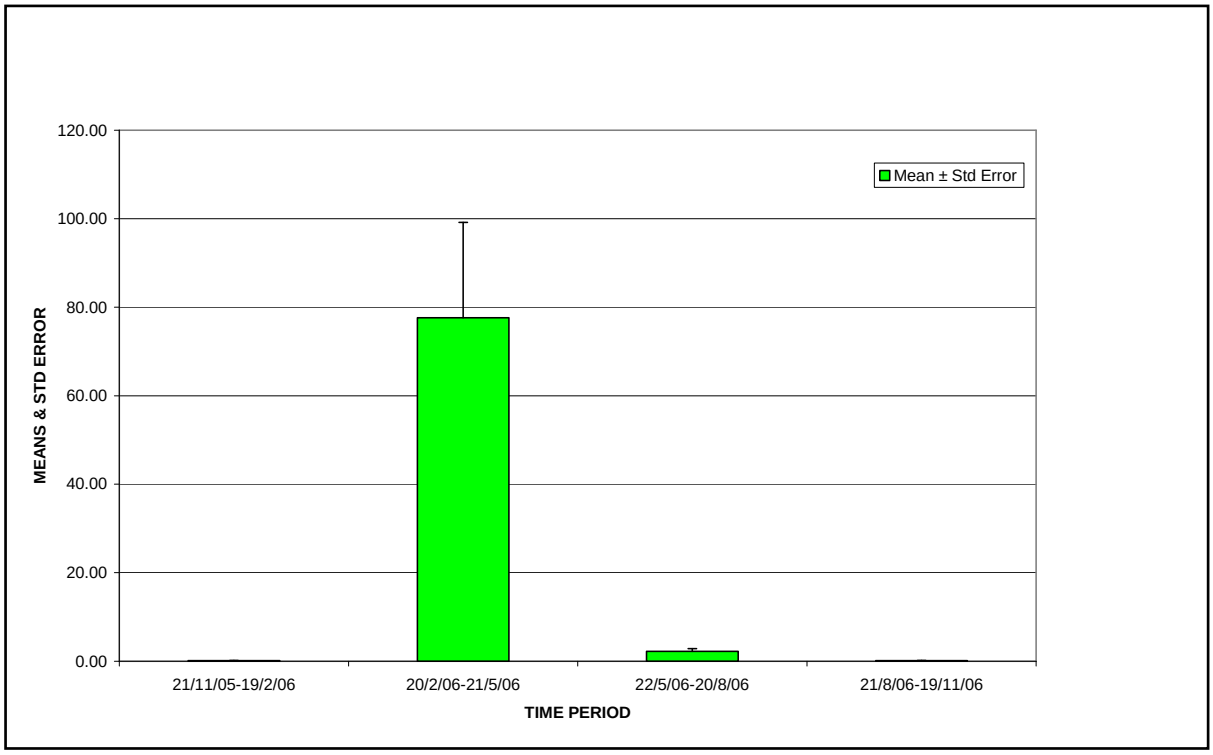


Figure 18 Imjabulo Ratooned: Mediterranean Fruit Fly means and standard error over the four time periods.

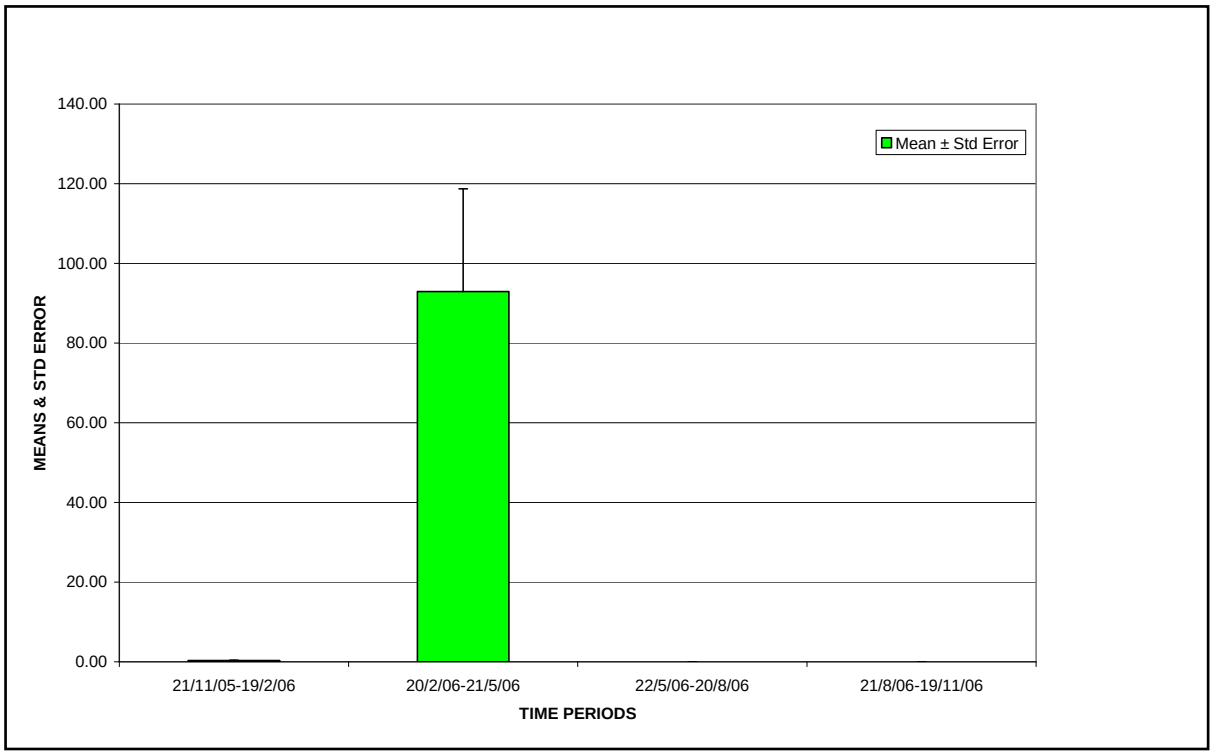


Figure 19 Varnam Ratooned: Mediterranean Fruit Fly means and standard error over the four time periods.

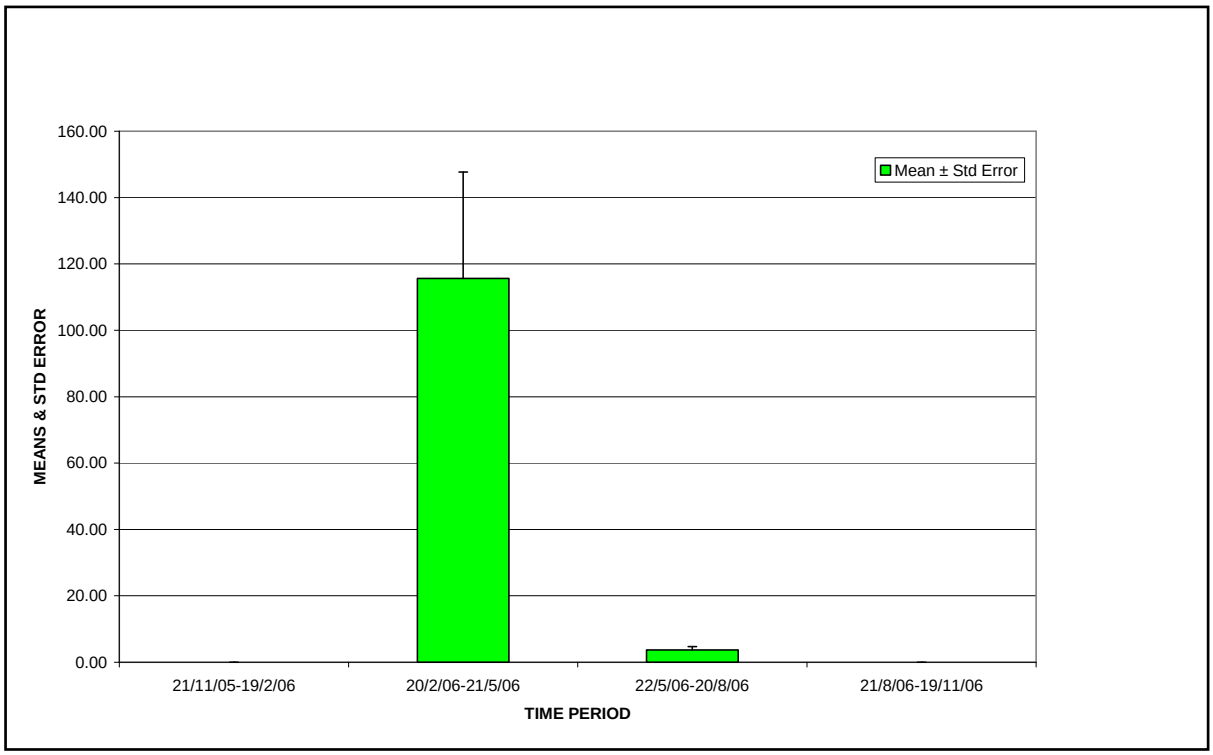


Figure 20 Brenthoek Seedling: Mediterranean Fruit Fly means and standard error over the four time periods.

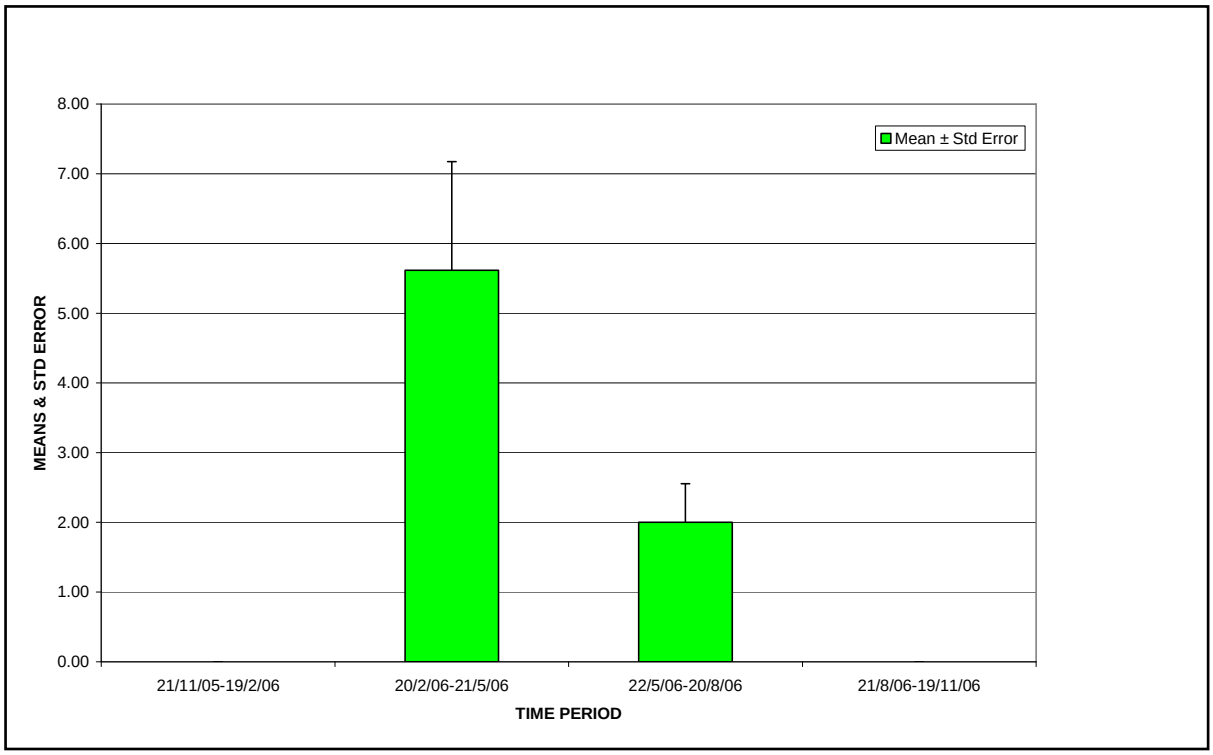


Figure 21 Imjabulo Seedling: Mediterranean Fruit Fly means and standard error over the four time periods.

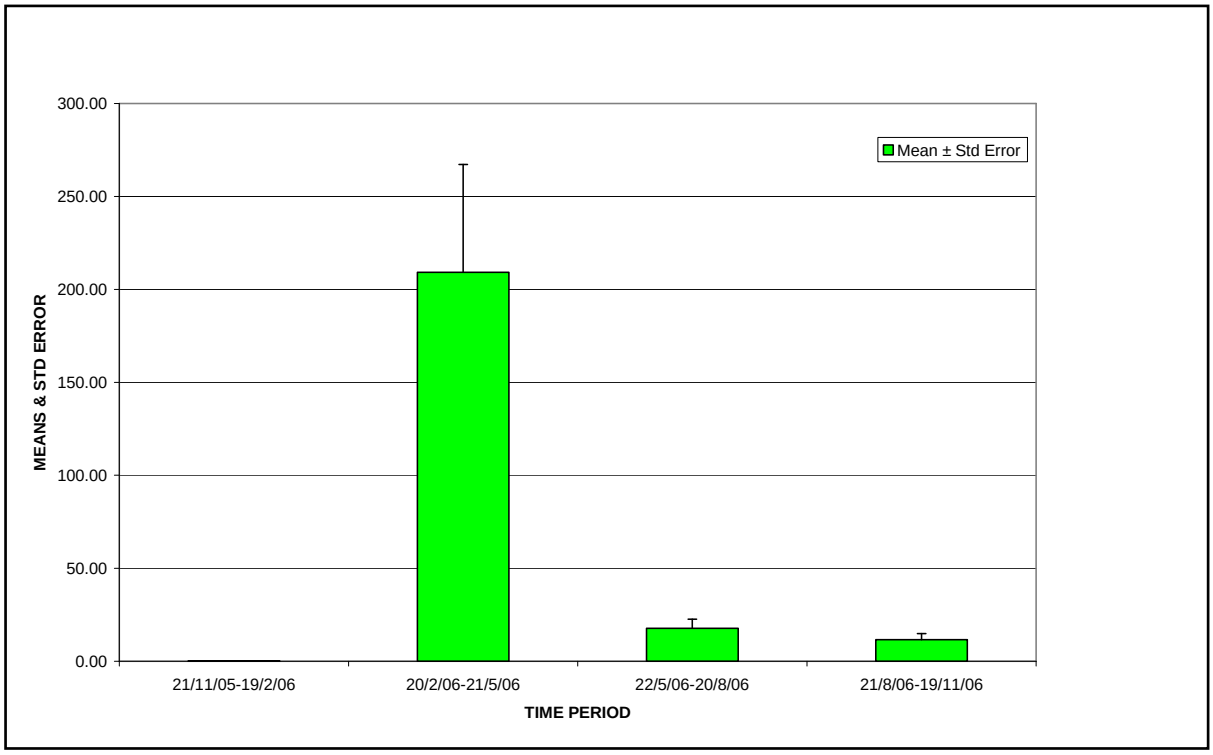


Figure 22 Varnam Seedling 1: Mediterranean Fruit Fly means and standard error over the four time periods.

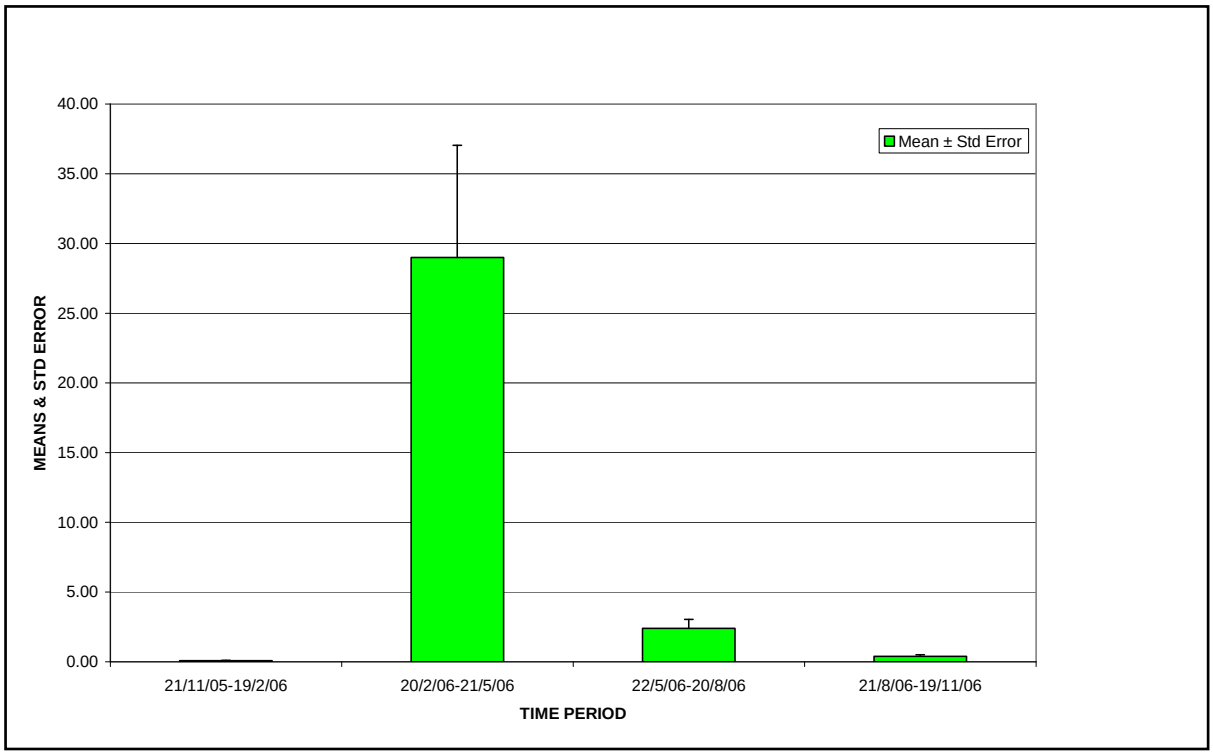


Figure 23 Varnam Seedling 2: Mediterranean Fruit Fly means and standard error over the four time periods.

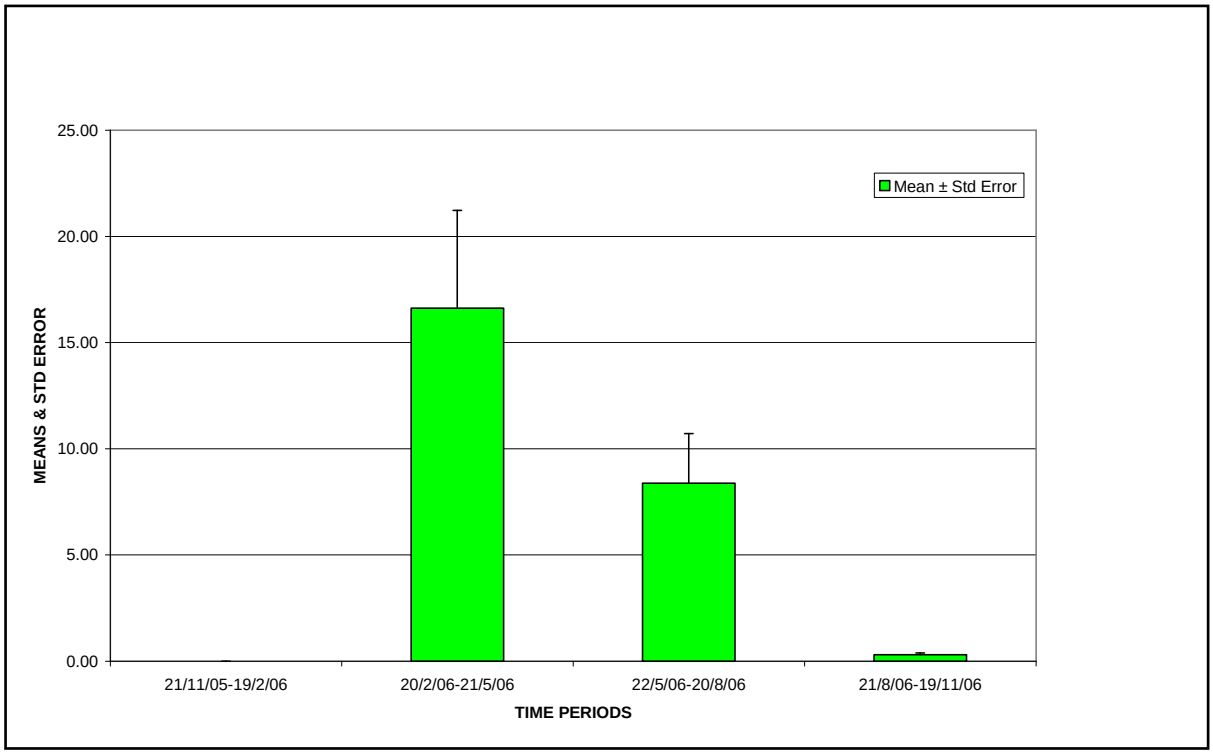


Figure 24 Lower Melrose Seedling: Mediterranean Fruit Fly means and standard error over the four time periods.

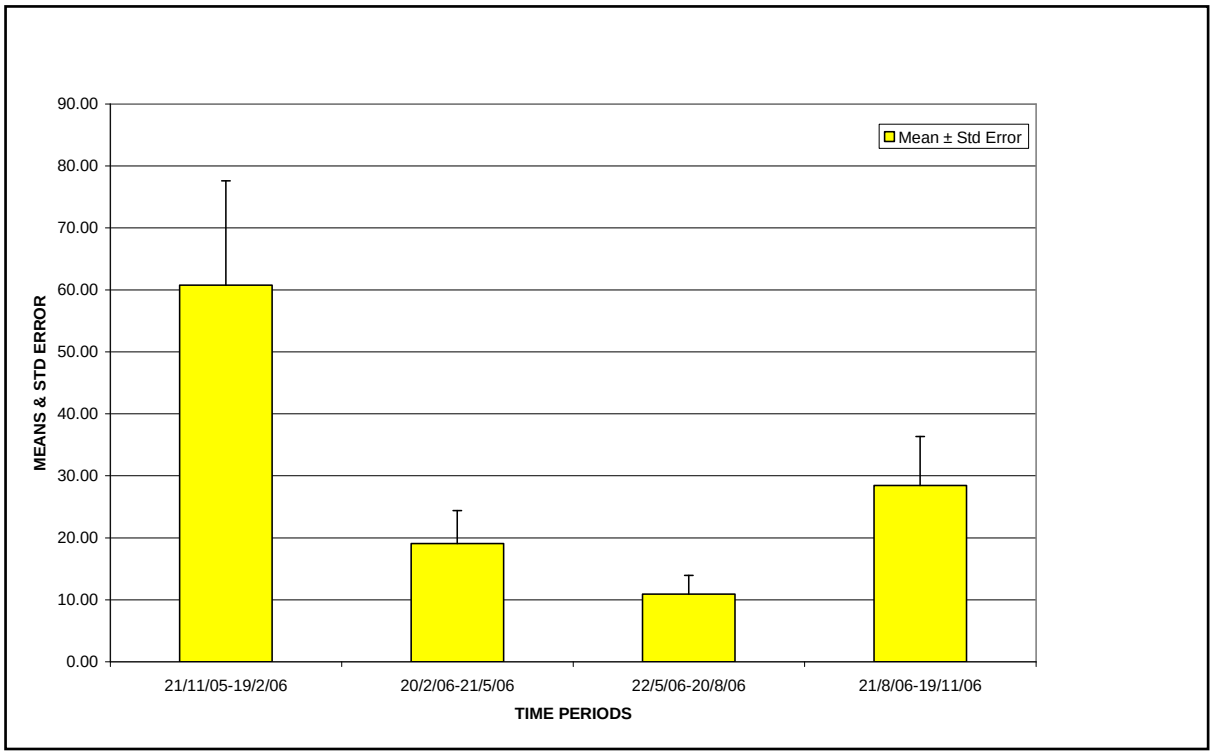


Figure 25 Brenthoek Ratooned: thrips means and standard error over the four time periods.

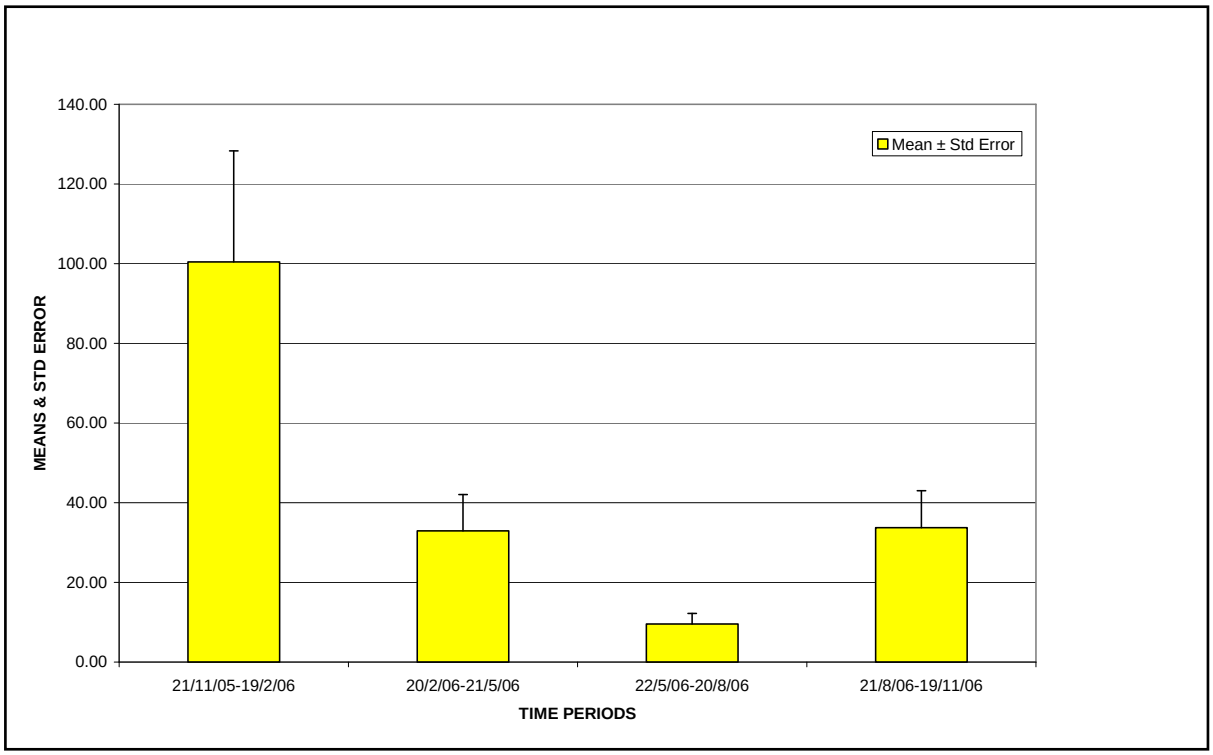


Figure 26 Imjabulo Ratooned: thrips means and standard error over the four time periods.

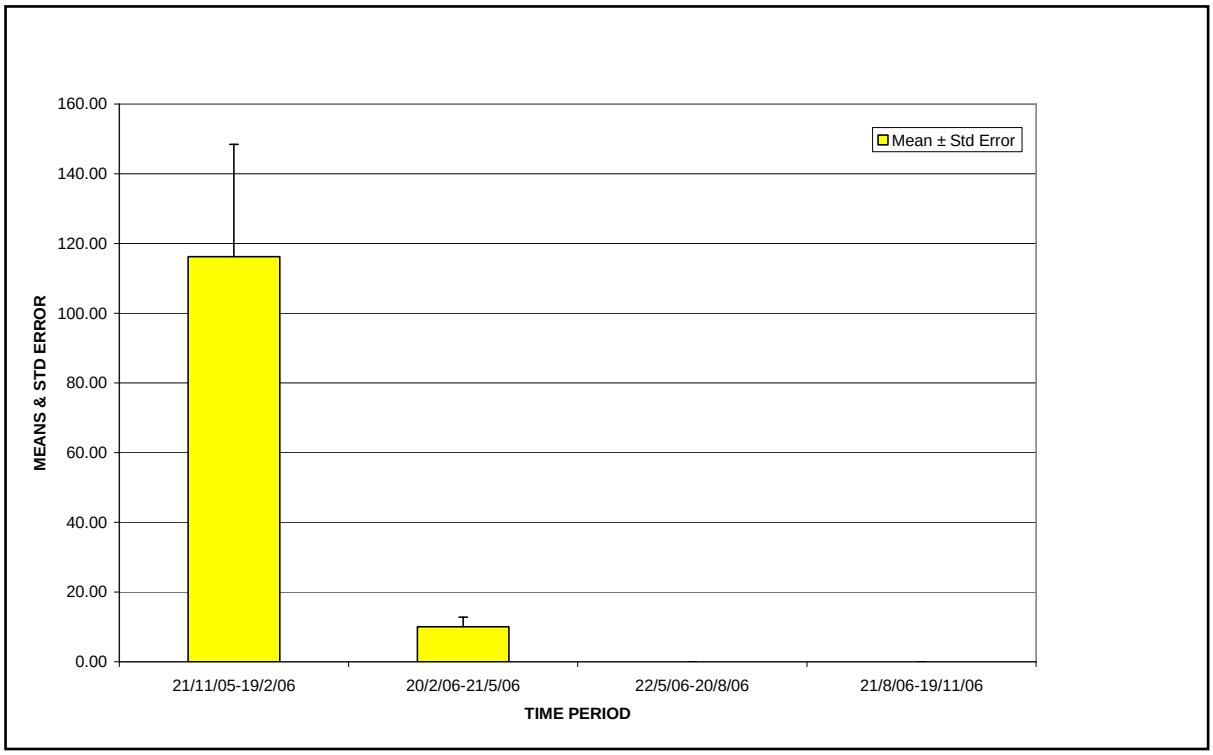


Figure 27 Varnam Ratooned: thrips means and standard error over the four time periods.

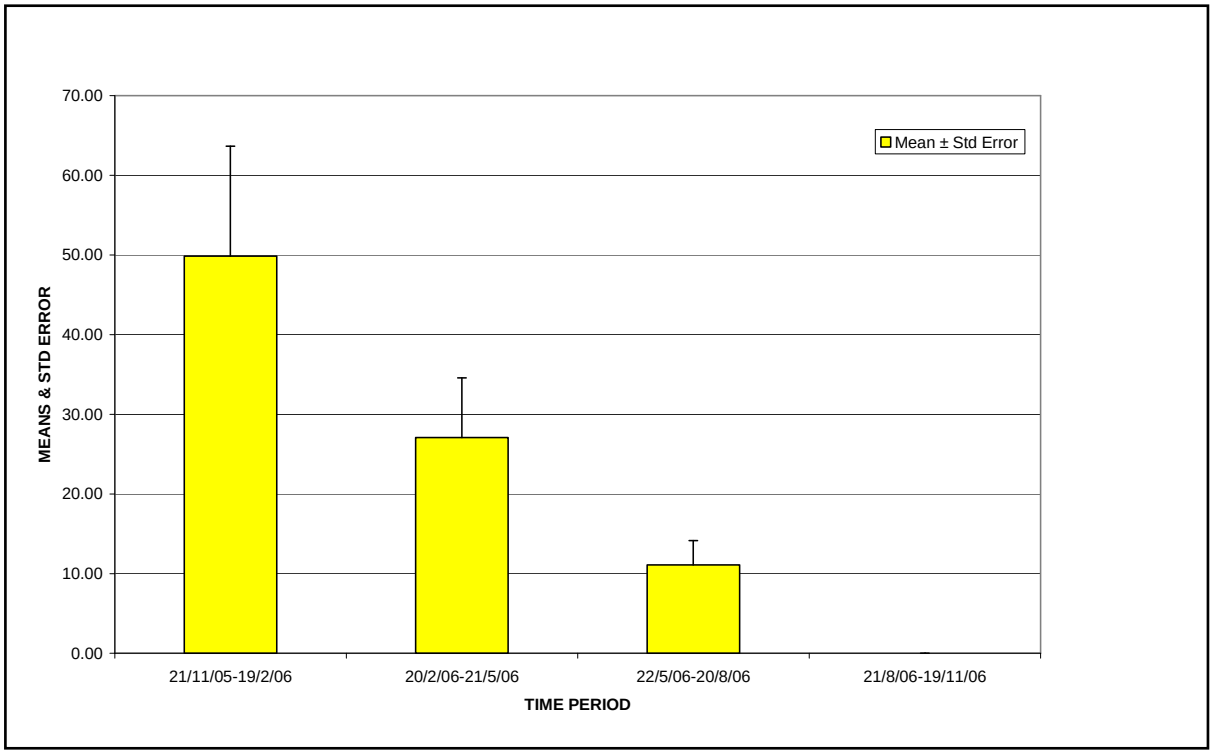


Figure 28 Brenthoek Seedling: thrips means and standard error over the four time periods.

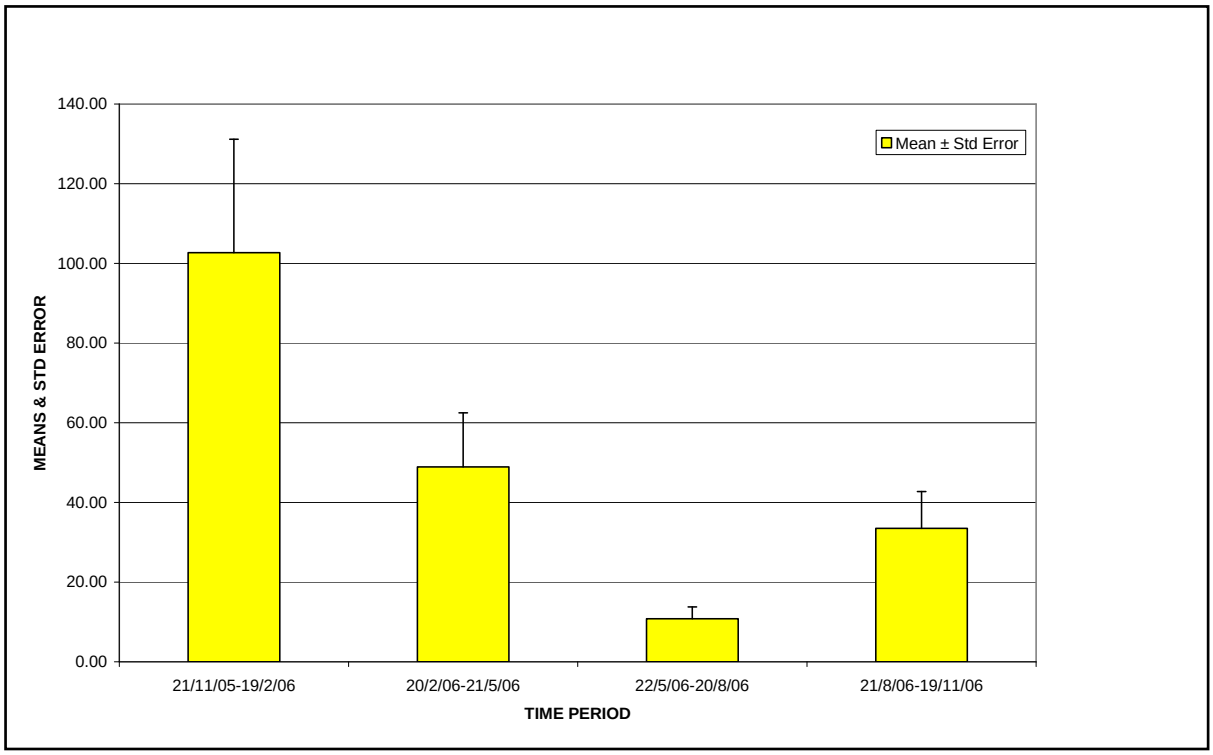


Figure 29 Imjabulo Seedling: thrips means and standard error over the four time periods.

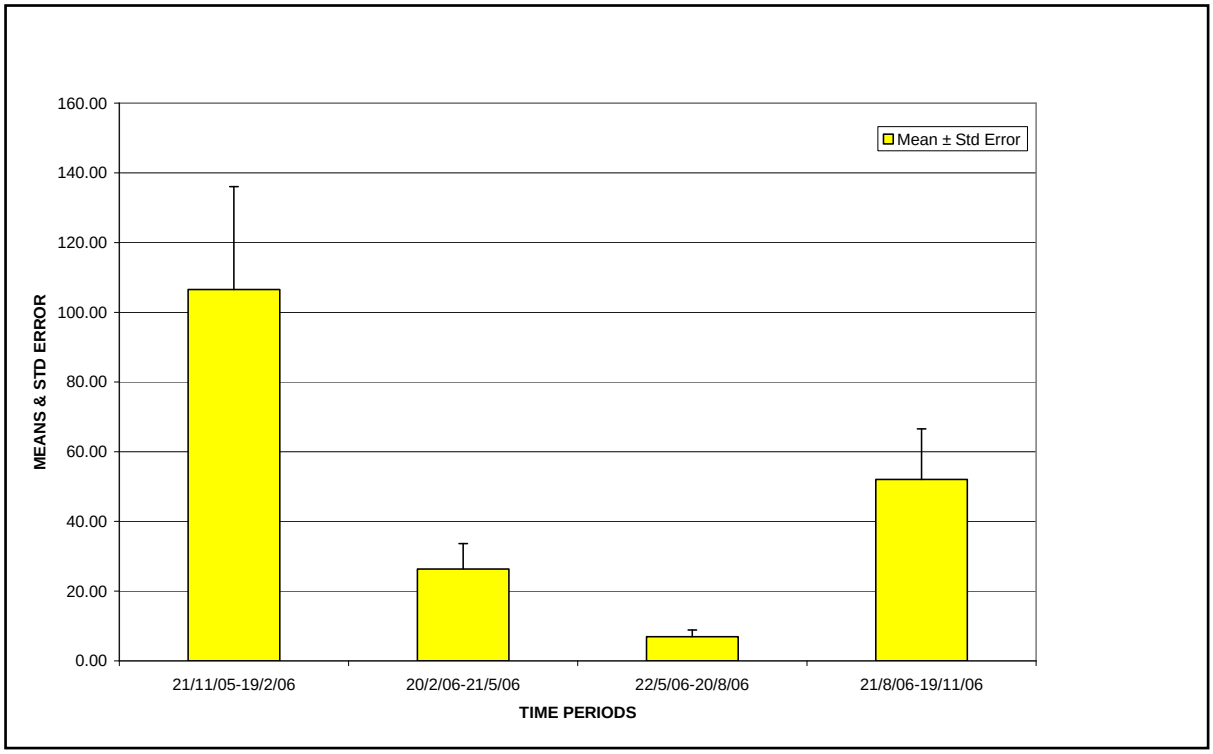


Figure 30 Varnam Seedling 1: thrips means and standard error over the four time periods.

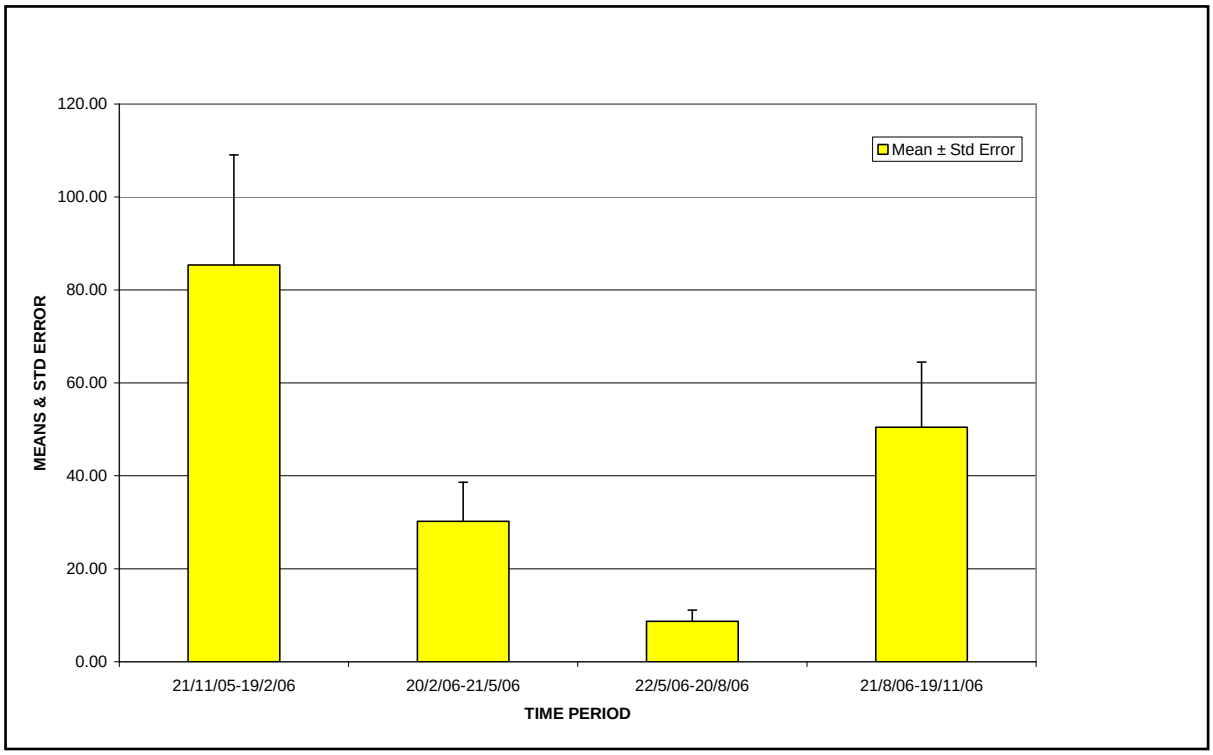


Figure 31 Varnam Seedling 2: thrips means and standard error over the four time periods.

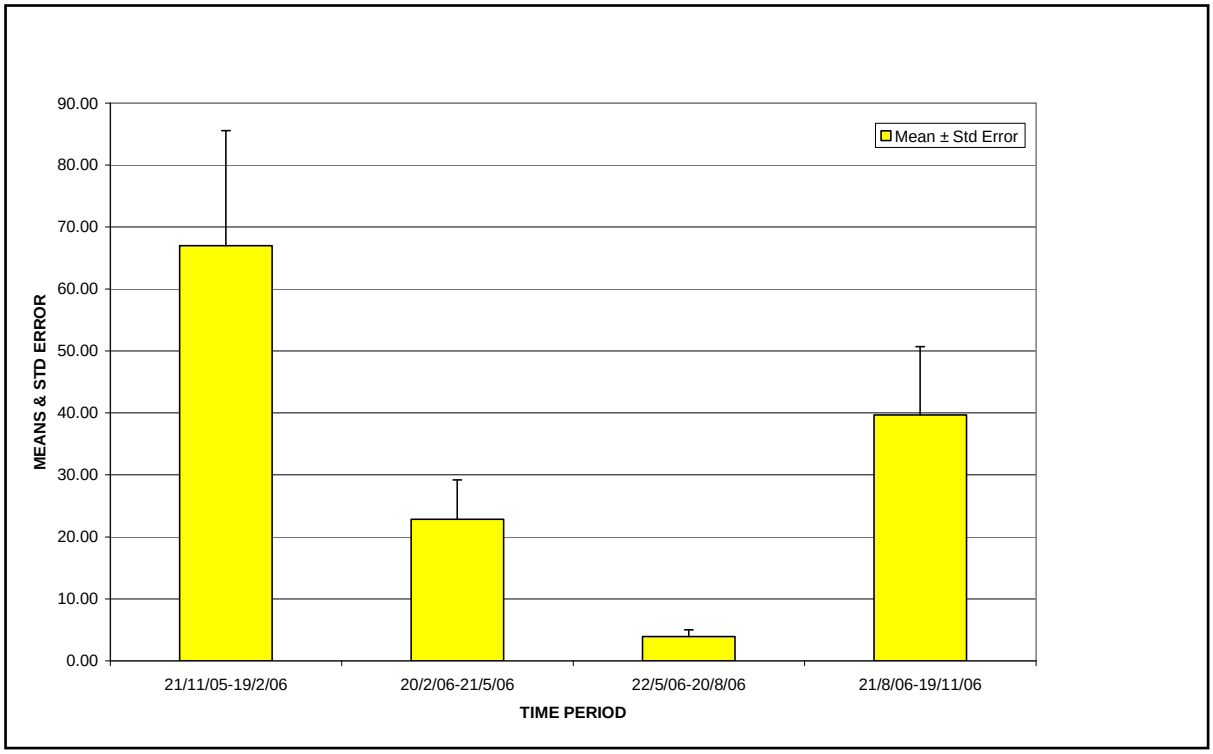


Figure 32 Lower Melrose Seedling: thrips means and standard error over the four time periods.

APPENDIX 6 Seasons, calendar dates and weeks of sampling.

Season	Dates	Week
SPRING	21/11/05-27/11/05	1
	28/11/05-4/12/05	2
SUMMER	5/12/05-11/12/05	3
	12/12/05-18/12/05	4
	19/12/05-25/12/05	5
	26/12/05-1/1/06	6
	2/1/06-8/1/06	7
	9/1/06-15/1/06	8
	16/1/06-22/1/06	9
	23/1/06-29/1/06	10
	30/1/06-5/2/06	11
	6/2/06-12/2/06	12
	13/2/06-19/2/06	13
	20/2/06-26/2/06	14
	27/2/06-5/3/06	15
AUTUMN	6/3/06-12/3/06	16
	13/3/06-19/3/06	17
	20/3/06-26/3/06	18
	27/3/06-2/4/06	19
	3/4/06-9/4/06	20
	10/4/06-17/4/06	21
	18/4/06-23/4/06	22
	24/4/06-30/4/06	23
	1/5/06-7/5/06	24
	8/5/06-14/5/06	25
	15/5/06-21/5/06	26
	22/5/06-28/5/06	27
	29/5/06-4/6/06	28

WINTER	5/6/06-11/6/06	29
	12/6/06-18/6/06	30
	19/6/06-25/6/06	31
	26/6/06-2/7/06	32
	3/7/06-9/7/06	33
	10/7/06-16/7/06	34
	17/7/06-23/7/06	35
	24/7/06-30/7/06	36
	31/7/06-6/8/06	37
	7/8/06-13/8/06	38
	14/8/06-20/8/06	39
	21/8/06-27/8/06	40
	28/8/06-3/9/06	41
SPRING	4/9/06-10/9/06	42
	11/9/06-17/9/06	43
	18/9/06-24/9/06	44
	25/9/06-1/10/06	45
	2/10/06-8/10/06	46
	9/10/06-16/10/06	47
	17/10/06-22/10/06	48
	23/10/06-29/10/06	49
	30/10/06-5/11/06	50
	6/11/06-12/11/06	51
	13/11/06-19/11/06	52