THE MANAGEMENT OF DIAMONDBACK MOTH, *PLUTELLA XYLOSTELLA* (LINNAEUS) (LEPIDOPTERA: PLUTELLIDAE), POPULATION DENSITY ON CABBAGE USING CHEMICAL AND BIOLOGICAL CONTROL METHODS

By

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Declaration

I, Malesela Jonas Bopape, declare that the thesis, which I hereby submit for the degree of *Master of Science* (Agriculture) at the University of South Africa, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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Dedication

I dedicate this thesis to my late younger brother Dr. Elias Bopape for having encouraged and motivated me to further my studies.

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ABSTRACT

The diamondback moth, *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae), is a cosmopolitan insect pest of *Brassica* crops. In South Africa, there are no action thresholds for its chemical control which makes it difficult for growers to make informed decisions on when to apply insecticides and how frequently to apply them in order to achieve optimal crop yield. To contribute towards optimum application of insecticides against *P. xylostella*, this study compared the impact of weekly and bi-weekly applications of a selective insecticide Dipel® (*Bacillus thuringiensis* Berliner var. *kurstaki*) applied at 250 g/ha, and a broad-spectrum insecticide Dichlorvos (an organophosphate) applied at 1 ml/L against biological control (Control) on the pest population density on cabbage during October–December 2011 and March–May 2012. The use of both selective and broad-spectrum insecticides for experiments enables us to understand if efforts to optimise cabbage yield depend mainly on effective suppression of *P. xylostella* densities. Furthermore, investigations were carried out to determine the impact of these chemicals on parasitism rates of *P. xylostella* and species richness of its primary parasitoids.

During the October–December 2011 growing season, the lowest infestation of *P. xylostella* occurred on cabbage plots that received weekly application of Dipel and the highest on untreated control plots. Cabbage weights were negatively related to infestation levels, implying that weekly application of Dipel yielded bigger cabbage heads. During March–May 2012, *P. xylostella* infestations were again higher on the control followed by weekly and bi-weekly treatments of Dichlorvos, then weekly and bi-weekly applications of Dipel. Despite the significant differences observed, infestation levels were much lower (< 1 *P. xylostella* per plant on average) in all treatments during this season. Consequently no significant differences in cabbage weights were observed among the treatments. The lower infestation levels were attributed to higher parasitism levels (≥50 %), especially during the early stages of crop development.

A total of four parasitic Hymenoptera species were recorded from *P. xylostella* larvae and pupae during October–December 2011, while three species were recorded during March–May 2012. However, *Cotesia vestalis* (Haliday) (Braconidae) accounted for >80 % of total

parasitism levels in all treatments. Parasitism levels were not significantly different among the treatments in both seasons. Parasitoid species richness was highest on the control. Although two parasitoid species were recorded in all Dipel and Dichlorvos treatments during October–December 2011, only one parasitoid species was recorded in the Dipel treatments during March–May 2012 compared to two species in Dichlorvos treatments.

Although weekly applications of Dipel ensured good yield and crop quality during October–December, weekly applications of the chemical did not lead to better quality crop during March–May crop growing season. Thus, it is not necessary to apply insecticides during periods in which natural mortality of *P. xylostella* is high due to parasitoids. Since *P. xylostella* abundance was a determining factor of crop quality, these results imply that insect pest management should focus mainly on suppressing its numbers. Furthermore, there was no evidence that application of either insecticide type had a negative impact on parasitism rates of *P. xylostella.* The lower parasitoid species richness on Dipel treated plots was the consequence of its higher efficiency in suppressing the pest population which substantially reduced availability of potential hosts for parasitoids, hence only the efficient *C. vestalis* was recorded at low host densities.

1 General introduction

1.1 Literature review

Cabbage, *Brassica oleracea* L. var. *capitata*, is one of the most important vegetable crops in South Africa, particularly in rural and peri-urban areas where consumption is increasing (Kfir, 1997). This crop is mooted to have cancer-preventing properties (Brooks *et al*., 2001), and is rich in Vitamin C, β-carotene, lutein, DL-α-tocopherol and phenolics (Singh *et al*., 2006). It can be eaten raw in a coleslaw salad or cooked prior to consumption. Commercially, it is estimated that 2,600 ha were planted in 2010 resulting in a harvest of 150,845 tonnes (FAO STAT, 2012). This figure can be misleading as cabbage is also sold at the farm gates and in street markets whose sales are not incorporated into the national statistics. Kfir (1997) suggested that about 9,000 ha were planted annually resulting in a harvest of about 450,000 tonnes.

However, successful production of cabbage and other *Brassica* crops is threatened by a variety of insect pests, of which the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) (Plate 1.1), is considered the most damaging throughout the world (Talekar and Shelton, 1993; Furlong *et al*., 2013). The larvae affect the yield and crop quality by direct feeding on the leaves (Plate 1.2) and also reduce their marketability by contaminating the produce. The annual cost of chemical control of *P. xylostella* and yield losses on *Brassica* crops throughout the world are now estimated at US$4-5 billion (Zalucki *et al*., 2012), which is a substantial departure from the previous estimate of US$1 billion (Talekar and Shelton, 1993) that is widely cited in the literature.

Plate 1.1 Adult *Plutella xylostella*

Plutella xylostella was first reported in South Africa in the early 1900s by Gunn (1917), who also studied its biology. However, it was only in the 1930s that serious interest was developed in its pest status. Ullyett (1947) studied its natural mortality factors, and cited parasitoids as the most important mortality factor acting in a density-depended manner. However, growers continued to view insecticides as an easier option, and no attempt was made to exploit the use of natural enemies against *P. xylostella*. For a long time, *P. xylostella* was not considered an economic pest in South Africa, as insecticides appeared to provide effective control (Nofemela and Kfir, 2005). However, the pest was again brought back into the national research agenda in the early 1990s, as solutions were urgently needed to curb the insecticide resistant populations that were causing serious economic losses in different parts of the country (Dennill and Pretorius, 1995; Kfir, 1997).

It was subsequently established that *P. xylostella* had developed multiple resistance to carbamates, synthetic pyrethroids and organophosphates (Sereda *et al*., 1997), yet these chemicals are still on the list of recommended insecticides for use against it (Anonymous, 2007). Currently, *P. xylostella* resistance to insecticides is so serious that farmers spray their crops at least twice a week using high doses and/or cocktails of insecticides in an attempt to suppress its population density (Dennill and Pretorius, 1995; Sereda *et al*., 1997). Furthermore, it remained undetermined if all *Brassica* growers adhere to recommendations for reduction of residue levels for each class of insecticide before harvest of the crop as given in Anonymous (2007), as to the best of my knowledge there is no statutory body that inspects produce for insecticide residue levels on produce sold locally. This practice clearly has serious implications for the health of consumers and the environment.

Plate 1.2 *Plutella xylostella* larvae feeding on a cabbage leaf

Following the reports of insecticide resistance in *P. xylostella*, there was renewed interest in biological control, particularly in the use of parasitoids against *P. xylostella* (Kfir, 1997). This was prompted by the fact that *P. xylostella* had seized to be an economic pest in some countries where parasitoids had been introduced, and insecticide applications reduced. Lim (1986) suggested that countries that continue to be plagued by it appear to lack effective parasitoids. Since most of the insecticides used by farmers are broad-spectrum (Sereda *et al*., 1997), it was speculated that their indiscriminate use by growers possibly led to decimation of its natural enemies. Thus, *P. xylostella* outbreaks were believed to be the result of failure of insecticides to provide effective control and the absence of its natural enemies (Nofemela and Kfir, 2005). Comparison of parasitoid species richness and abundance when insecticides are intensively used (Dennill and Pretorius, 1995) and where no insecticides were used (Kfir, 1997) near Pretoria, showed that insecticides had a negative effect on parasitoids, as Kfir recorded 21 parasitoid species compared to only one parasitoid species in the Dennill and Pretorius study. Kfir (2004) further demonstrated that the indiscriminate application of insecticides can be detrimental to parasitoids, as *P. xylostella* occurred in much higher densities in sprayed than in insecticides free cabbage fields, when using an insecticide check method. The insecticide check method makes use of the selective toxicity of an insecticide to kill a large proportion of natural enemies while leaving the pest population unaffected (De Bach and Huffaker, 1971). Luck *et al*. (1999) deemed this to be a good experimental technique for evaluating the efficacy of natural enemies. Nevertheless, there is a general paucity of large-scale (> 1 ha) and long-term (> 2 years) studies that have investigated the impact of insecticides on natural enemies of insect pests (Macfadyen and Zalucki, 2012).

1.2 Motivation for the study

In many parts of the world, the pest status of *P. xylostella* began to increase in the 1950s, and by the 1970s it had become an economic pest. Although resistance to insecticides was long suspected to be the cause for its high pest status, it was only in the 1980s that studies confirmed that *P. xylostella* had developed resistance to commonly used insecticides of the day (Talekar and Shelton, 1993). Since then, Talekar and Shelton (1993) and Zhao *et al*. (2006) have affirmed that *P. xylostella* has an ability to develop resistance to all insecticide classes used against it. The use of synthetic insecticides has often led to serious environmental problems besides affecting the health of users and consumers (Carson, 1962). Thus, reduction in application frequency may deliver significant socio-economic and environmental benefits in the form of safe, healthy, and affordable food. The extensive indiscriminate use of organophosphates, pyrethroids and carbamates which also eliminate natural enemies creates the need for more insecticides usage (i.e., the so called insecticide treadmill), increase production costs, and leads to development of insecticide resistance (Saxena *et al*., 1989; Rabindra *et al*., 1995; Joia *et al*., 1996; Renuka and Regupathy, 1996).

Ullyett (1947) suggested that biological control is an important alternative insect pest control method to synthetic insecticides. Several other researchers such as Kfir (1997) and Waladde *et al.* (2001) showed that parasitoids are an important mortality factor of *P. xylostella* during November–May. Thus, the ability of parasitoids to suppress pest population density in subsequent generations can reduce crop damage (Monnerat *et al*., 2002). Nofemela (2013a) remarked that the impact of parasitoids on *P. xylostella* infestation levels is quantified using percentage parasitism level. The precision with which such a method estimates parasitoid impact on the host population density depends on the sampling method used, but several factors (e.g., sampling host stages other than those that are actually attacked by the parasitoid(s), and failure to refer to the density of the host population sampled), can lead to serious errors in estimation of parasitism levels (Van Driesche, 1983; Van Driesche *et al*., 1991). For integrated pest management, parasitism level is used as a tool to decide whether or not insecticides should be applied in reference to the predetermined economic threshold of the pest (Dent, 1991; Nofemela, 2013a).

Since parasitoids may not always provide effective suppression of insect pest populations due to influence of abiotic or biotic factors (Castle and Naranjo, 2009; Zalucki *et al*., 2009; Nofemela, 2013b), an often advocated approach for sustainable management for *P. xylostella* involves application of insecticides only when the impact of biological control agents is low, a form of integrated pest management (IPM) (Beck *et al*., 1992; Talekar and Shelton, 1993; Heisswolf *et al*., 1997; Walker *et al*., 2002). However, the integration of insecticides and biological control agents has proven difficult to practice in many crop systems (Higley and Peterson, 2009; Nofemela, 2013a). Trumble (1998) attributes the low adoption of IPM to occurrence of multiple insect pest species on a single crop such that they may require frequent application of insecticides. In such cases, it may be advantageous to use broad-spectrum insecticides with a short residual period. Thus, it is imperative to determine if broad-spectrum insecticides with a short residual period indeed have a little disturbance on population densities of the biological control agents. However, there is paucity of studies that have directly contrasted effects of selective and broad-spectrum insecticides on biological control agents in the field.

1.3 Problem statement

Long-term data sets exist on influence of parasitoids on population dynamics of *P. xylostella* in South Africa (Kfir, 1997; Waladde *et al.*, 2001; Nofemela 2013c). Although these studies show that parasitoids play an important role in suppressing pest population densities during November–May, but it remained undetermined if this impact is equivalent to that of application of an effective insecticide. In addition, it remained undetermined if insecticides need to be applied on a weekly basis during periods of low parasitoid impact in order to achieve optimal crop yield. Furthermore, previous studies comparing the relative efficacy of parasitoids or other natural enemies of insect pests and chemical control either investigated their impact in only one season and in small non-replicated plots, and only one insecticide was used (DeBach and Huffaker, 1971; Luck *et al*., 1999; Kfir, 2004; Macfadyen and Zalucki, 2012). Documentation of field differences is necessary because laboratory bioassays may not be directly extrapolated to field conditions. For example, if adult parasitoids die as a result of insecticide applications, but the progeny survive when they are developing inside insecticide-resistant *P. xylostella* immature stages (Iqbal and Wright, 1996), then we should expect parasitoid population densities to be greater in large than in smaller fields. Similarly, if inadequate spray coverage on the crop is one mechanism by which adult and immature parasitoids survive insecticide application, then we should expect more parasitoids to survive in a large field better than in a small plot. Both scenarios may lead to different outcomes in fields of different sizes. Clearly, these questions suggest a strong need to perform replicated experiments in larger fields for results to be applicable to cabbage growers.

1.4 Introduction to study insects

Plutella xylostella is believed to have originated from Europe (Hardy, 1938; Carter, 1984), but on the basis of high diversity of its wild host plants and a rich guild of parasitoid species associated with it, Kfir (1998) is of the view that it may have originated from Southern Africa. This pest is now present wherever *Brassica* species occur, and it is considered the most universally distributed of all Lepidoptera (Meyrick, 1928). *Plutella xylostella* has high net reproductive potential and each female can lay about 200 eggs mainly on upper leaf surface or on the stem bases near the soil-stem interface (Sarfraz *et al.*, 2007). Although it feeds and oviposits in nearly all *Brassica* species, it has demonstrated preference for some species over others (Sarfraz *et al.*, 2007).

Eggs hatch after 4–8 days depending on temperature and larvae feed on leaves, buds, flowers, siliques, the green outer layer of stems and also developing seeds within the older siliques (Anonymous, 2000). Depending on food supply, the moth has a short life cycle (averaging 14 to 21 days at 25 ºC and is capable of migrating long distances using trajectory winds (Harcourt, 1957). In many areas with snow during winter, the moths do not survive and these areas are reinvaded each spring by populations carried by the winds. It is multi-voltine with up to 20 overlapping generations a year in tropical and temperate warm countries (Harcourt, 1986; Vickers *et al.*, 2004) including South Africa (Nofemela, 2010).

Parasitoids are free living as adults, and have immature life stages that develop to maturity or at least to the pupal stage on or within a single host, and ultimately killing the host (Nofemela and Kfir, 2008). Most insect parasitoids attack only a particular life stage of their host species. The immature parasitoids can regulate the developmental rate of their hosts to maximise acquisition of nutrients (Hoffmann and Frodsham, 1993). Female parasitoids use a variety of olfactory, visual, tactile, and gustatory cues to recognize suitable host species and to distinguish between different sizes and/or developmental stages of the same host (Vinson, 1984; Godfray, 1994; van Alphen and Jervis 1996). It completes host-selection process by inserting its ovipositor into the host to further evaluate its suitability and nutritive quality, and if acceptable, it lays an egg (Vinson, 1984; Godfray, 1994). Adult parasitoids are often more susceptible to chemical insecticides than their hosts. Hoffmann and Frodsham (1993) conceded that immature parasitoids, especially if protected within the egg of their host or in their own cocoon, may survive pesticides better than the free-living adults, but immature parasitoids die if their host are killed by insecticide poisoning.

1.5 Hypotheses

1) If insecticides are not applied every week until crop harvest, the crop is of low quality.

2) Parasitism rates and parasitoid diversity are higher on plots sprayed with selective insecticides than broad-spectrum insecticides.

1.6 Aims and specific objectives of the study

The specific objectives for this study are:

1) To compare the influence of season on efficacy of chemical and biological control methods in suppressing *P. xylostella,*

2) To compare cabbage yield and quality on plants sprayed with different insecticide regimes against those that were not sprayed,

3) To assess whether the broad-spectrum insecticide has a greater negative effect on parasitism rates of *P. xylostella*, and

4) To determine whether parasitoids species richness differs depending on the insecticide type used.

2 General materials and methods

2.1 The study site and experimental plots

The experiments were conducted at Baviaanspoort Correctional Services Centre (25º38’S 28º30’E, altitude 1164 m) in Pretoria, South Africa, during October–December 2011, and March–May 2012. In both seasons, cabbage (*B. oleracea* L. var. *capitata*) seedlings, cultivar Green Star (Starke Ayres, Centurion, South Africa), were transplanted on 28 plots of 10 m × 16.6 m each with a spacing of 2 m between plots. In each plot, 10 raised-bed ridges of approximately 1.2 m wide and 10 m in length each were made. The spacing between ridge beds was 60 cm, and three rows were made on each ridge bed with plant spacing of 40 cm. Thus, a total of 750 cabbage seedlings were transplanted in each plot. At any given time at the landscape level, there were other cabbage fields that may have served as reservoirs for *P. xylostella* and its natural enemies. Since experimental plots were not contained in insect exclusion cages, *P. xylostella* and its parasitoids were free to move between plots and this movement is assumed to have been proportionately the same in all plots.

2.2 Treatments and experimental design

Seven treatments were used in this study: a) the untreated Control; b) Dipel^1 (Dipel® DF, a *Bacillus thuringiensis* Berliner var. *kurstaki*, Valent Biosciences, Somerset West, South Africa) applied at supplier’s recommended low dose of 250 g/ha at weekly intervals; c) Dipel^2 applied at 250 g/ha at bi-weekly intervals (i.e., every second week); d) Dipel^3 applied at 250 g/ha every week until cabbage heads developed, which was eight weeks after transplanting the plants; e) Dichlorvos^1 (Dichlorvos EC, an organophosphate, Villa Crop, Kempton Park, South Africa) applied at supplier's recommended dose of 1 ml/L at weekly intervals; f) Dichlorvos^{2} applied at 1 ml/L at bi-weekly intervals; g) Dichlorvos^{3} applied at 1 ml/L every week until cabbage heads developed. These insecticides had not been used against *P. xylostella* at the study site prior to this study. Complement® Super (A non-ionic wetter/ spreader/ penetrant surfactant, Syngenta SA, Halfway House, South Africa) was added to each insecticide treatment at supplier's recommended dose of 100 ml per ha. All chemical solutions were applied using 16 litre hand-operated knapsack sprayers with flat fan nozzles at 4.8-5.5 bar, and the quantities used were adjusted accordingly.

The seven treatments were allocated among the 28 plots in a complete randomized block design making 4 replicates for each treatment. All chemical applications commenced 3 weeks after transplanting cabbage seedlings, and were stopped 1 week before harvest for weekly (Dipel^{1} and Dichlorvos^{1}) and bi-weekly (Dipel^{2} and Dichlorvos^{2}) treatments. Standard cultivation practices that included fertilizer application, irrigation and weeding were followed. The plots were irrigated using overhead sprinklers twice a week, but irrigation was withheld for 2 days after each insecticide application.

2.3 *Plutella xylostella* infestations and data collection

Plutella xylostella larvae and pupae were monitored on each treatment plot at weekly intervals from 3 weeks after transplanting cabbage seedlings until 1 week before harvest of cabbage heads. In each treatment plot, 10 randomly selected plants (excluding outer 2 rows in each plot) were thoroughly inspected every week and the numbers of *P. xylostella* larvae and pupae (i.e., infestation levels) found on the leaf surface in each plant were recorded. All insecticide applications were on the day following crop monitoring events.

2.4 Crop quality and yield

On the day before crop harvest, the total plant population, numbers of plants with multiple heads and marketable heads were counted and recorded on each plot. Multiple heads are defined here as cabbage plants whose apical meristem was damaged by herbivory in the early stages of plant development such that several small cabbage heads are formed from the same stem. Cabbages were regarded as marketable when the head size exceeded 30 cm in diameter from base across the circumference to the other size of the base using a flexible measuring tape. At harvest, 100 marketable cabbage heads were randomly selected from each treatment (i.e., 25 cabbage heads per plot), and each was cut at the interface between the head and the stem. To facilitate bagging, the 4 outer leaves were removed from each cabbage head, and each head was weighted on a calibrated electronic scale (Digital Weighing Indicator, Model DI-20, Teraoka Weigh Systems PTE LTD, Singapore).

2.5 Determination of *P. xylostella* parasitism levels

In order to determine parasitism levels, samples of *P. xylostella* larvae (3^{rd} and 4^{th} instars) and pupae, and pupae of its parasitoids were collected during scouting at weekly intervals. The decision to estimate parasitism levels only from third and fourth instar hosts is based on the realization that parasitism rates accumulates over the larval instars, as all known *P. xylostella* larval parasitoids complete their larval development once the host has reached the fourth instar (Nofemela and Kfir, 2005). Sample sizes ranged from 12 – 206 individuals depending on infestation levels. The samples were taken to the insectary (ARC–Plant Protection Research Institute, Rietondale campus (25°44’S 28°13’E) in Pretoria) where they were maintained at 25 ± 1 °C, 65 ± 5 % r.h., and L16: D8 photoperiod. The larvae were provided with sections of fresh cabbage leaves and held individually in Petri dishes. The leaves were replaced every 2nd day until the all larvae pupated or parasitoid pupae formed. The samples of *P. xylostella* pupae and parasitoid pupae were confined individually in glass vials (2.5 × 10 cm). All emergent parasitoids were identified and their incidence determined. Parasitism rates were calculated as the percentage of emergent parasitoids out of total samples of *P. xylostella* and parasitoid pupae for each week and treatment. Thus, the impact of parasitoids on *P. xylostella* population density was determined from parasitism of corresponding infestation levels.

However, samples that died of unknown causes were excluded from calculations of parasitism.

3 The influence of season on comparative efficacy of chemical and biological control methods in suppressing *Plutella xylostella* infestation levels on cabbage

3.1 Abstract

This study compared the efficacy of two insecticide types (Dipel® applied at 250 g/ha, and Dichlorvos applied at 1 ml/L) against biological control in suppressing *Plutella xylostella* population density on cabbage during October–December 2011 and March–May 2012. Biological control impact was evaluated by monitoring parasitism rates of the pest. The insecticides were applied in three regimes: weekly until crop harvest, bi-weekly, and weekly until cabbage head formation. During the October–December season, *P. xylostella* infestations were lowest on cabbages that had weekly application of Dipel followed by the bi-weekly application, then weekly applications of Dichlorvos and higher on bi-weekly Dichlorvos and the control. It was also established that plant infestation increased linearly with infestation levels up to four *P. xylostella* per plant. Cabbage head weights were higher on plots that received weekly applications of Dipel and lower on control plants, and those that received bi-weekly Dichlorvos application. During the March–May season, *P. xylostella* infestations were higher on control plants followed by weekly and bi-weekly treatments of Dichlorvos, then weekly and bi-weekly applications of Dipel. However, infestation levels were very low in all treatments during this season. Consequently, no significant differences in cabbage head weights were observed among the treatments. The lower infestation levels during the second season on the control were due to higher parasitism levels (>50 %) during the early stages of crop development compared to the first season. The results of this study suggest that Dipel is better than Dichlorvos in suppressing pest density, especially during October–December, a high infestation season. Although weekly applications of Dipel maximized yield during October–November, this regime had no economic benefit when natural mortality of *P. xylostella* due to parasitoids was high

during March–May. Thus, this study provides baseline data for optimising insecticide applications against *P. xylostella* in South Africa.

Keywords: diamondback moth; infestation levels; proportion of plants infested; Dipel; Dichlorvos; parasitoids; cabbage yield; weather; monitoring; economic threshold

3.2 Introduction

Effective suppression of *Plutella xylostella* population density is vital to successful production of *Brassica* crops in many parts of the world (Talekar and Shelton, 1993; Furlong *et al.*, 2013). Currently, this pest is estimated to cost *Brassica* growers worldwide US$ 4-5 billion annually in direct crop losses and management costs (Zalucki *et al.*, 2012). Its high pest status in many countries stems from its extreme ability to develop resistance to all insecticide classes (Zhao *et al.*, 2006). This is particularly acute in Southeast Asia where insecticides lose their efficiency within a few years due to continuous exposure of the pest to insecticides (Talekar and Shelton, 1993; Zhao *et al.*, 2006). Thus, it is imperative that use of insecticides be optimised in order to delay development of insecticide resistance (Sarfraz and Keddie, 2005). Integration of insecticides with biological control, particularly use of parasitoids, is seen as a promising alterative to only chemical control.

Where biological control programmes were initiated against *P. xylostella* mainly relying on parasitoid introductions (Talekar and Shelton, 1993; Sarfraz *et al.*, 2005) the frequency of insecticide applications was significantly reduced due to effective suppression of the pest density by the introduced parasitoids (Kfir and Thomas, 2001; Löhr *et al.*, 2007). Despite many researchers appreciating the role of parasitoids in suppressing *P. xylostella* populations (Poelking, 1986; Sastrosiswojo and Sastrodihardjo, 1986; Talekar *et al.*, 1986; Ooi, 1992; Nofemela and Kfir, 2005), growers continue to apply insecticides indiscriminately often without any regard for levels of natural suppression of the pest by its natural enemies (Sarfraz *et al.*, 2005; Nofemela, 2013a). Because growers mainly use broad-spectrum insecticides, it is believed that over-reliance on insecticides has not only led *P. xylostella* to develop resistance, but also resulted in widespread decimation of its natural enemies in many areas (Grzywacz *et al*., 2010; Upanisakorn *et al*., 2011). Therefore, it is vital for proponents of biological control to convince growers that parasitoids, when effective, can suppress *P. xylostella* populations and lead to quality crop as good as application of any effective insecticide. That will not only help conserve efficacy of insecticides and parasitoid populations, but it will also pave a way for effective integration of biological and chemical control methods in areas where efficacy of parasitoids varies within and between seasons.

In South Africa, detailed studies on influence of parasitoids on population dynamics of *P. xylostella* were conducted on unsprayed cabbage fields during February 1992–January 2008, and the patterns as influenced by field temperatures are now well-established. Parasitoid-inflicted *P. xylostella* mortality is very high (≥50 %) during November–May, which maintains infestation levels mostly <1 *P. xylostella* per plant. Due to low parasitism levels (<50 %) during winter (June–August) and early spring (September–October), population density of the pest is very high (usually >10 *P. xylostella* per plant) in spring (Kfir, 1997; Waladde *et al*., 2001; Smith, 2004; Nofemela and Kfir, 2005; Nofemela, 2010). However, low winter temperatures (<13 °C average) also keep the pest population densities low (Nofemela, 2010). Since no action and economic thresholds have been developed for *P. xylostella* in South Africa, growers apply insecticides indiscriminately which has led the pest to develop resistance to carbamates, pyrethroids and organophosphates in some areas (Dennill and Pretorius, 1995; Sereda *et al*., 1997). Although it is necessary for insecticides to be applied during spring to reduce high infestation levels (Nofemela and Kfir, 2005; Nofemela, 2010), it has remained undetermined if they need to be applied every week and throughout the season in order to achieve good yield. Furthermore, it was never quantified if parasitoid-inflicted mortality during periods of high parasitism is similar to that of an effective insecticide in suppressing the pest densities, and if it leads to similar crop yield. To answer these questions, the study reported here compared the impact of Dipel and Dichlorvos against biological control in suppressing *P. xylostella* infestation levels during October–December and March–May. The cropping season October–December was selected for it coincides with high *P. xylostella* infestation levels according to the established patterns, whereas March-May season coincides with low pest densities. Since this study also compared crop yield from the different insecticide application regimes and biological control treatments, it provides important baseline data for understanding infestation levels that can be tolerated without application of insecticides, which is useful for determination of action and economic thresholds in the future.

3.3 Material and Methods

The details about the experimental site, experimental design, treatments and the application regime of insecticides are provided in Chapter 2.

3.3.1 Data analysis

As only 10 plants were scouted every week (and sampled in control plants) out of 750 plants in each plot, it is reasoned that *P. xylostella* infestations per plant could not be influenced by the 1.33 % of the sampled plants per week. Therefore, Analysis of Variance (ANOVA) was chosen as an appropriate method of analysis. Prior to ANOVA the data were checked for normality using Shapiro-Wilks' test and for homogeneity of variance using Levene's test. As data for % of multiple heads and % marketable plants were not normally distributed, the data were square-root transformed prior to analysis. One-way (ANOVA) were performed to compare 1) *P. xylostella* infestation levels within a week, and 2) across the season; 3) % multiple heads; and 4) cabbage weights between treatments. Where significant differences were detected, the means were compared using Fisher's protected least significant difference (LSD) test. Linear regression was used to determine the relationship between infestation levels and the proportion of plants infested. Prior to analysis, the data were square-root transformed. The statistical analyses were performed at 5 % level of significance (Statistica, 2013).

3.4 Results

3.4.1. Infestation levels during October–December 2011

During the October–December season (Table 3.1), *P. xylostella* infestation levels were similar across the treatments ($F_{6, 273} = 1.1617$; $P = 0.3271$) in week 1 of the experiments. However, after application of insecticides in week 1, infestation levels were significantly ($F_{6, 273} = 8.4329$; $P < 0.001$) high only on the control treatment in week 2. But, in week 3, *P. xylostella* infestation levels were significantly high ($F_{6, 273} = 49.201$; $P < 0.001$) on Dichlorovos[2] followed by Dipel[2], then control and weekly applications of Dichlorvos (Dichlorvos[1] and Dichlorvos[3]), and least on weekly applications of Dipel (Dipel[1] and Dipel[3]). Again after application of insecticides in week 3, infestation levels were significantly high ($F_{6, 273} = 31.306$; $P < 0.001$) on the control in week 4, followed by Dichlorvos[2], then Dichlorvos[1] and Dichlorvos[3], and least on the three Dipel treatments. Although infestation levels declined sharply in the control treatment in week 5, they remained significantly high ($F_{6, 273} = 23.974$; $P < 0.001$) relative to Dichlorvos[2] and the rest of the treatments. Despite the application of insecticides in week 5, infestation levels from plots that were sprayed with Dichlorvos at bi-weekly intervals were not significantly different from the untreated control (Table 3.1), which declined significantly after week 6. Infestation levels recorded from control and bi-weekly application of Dichlorvos were however significantly higher ($F_{6, 273} = 24.992$; $P < 0.001$) than the rest of the treatments during week 6. In week 7, infestation levels were significantly high ($F_{6, 273} = 20.463$; $P < 0.001$) in all the Dichlorvos treatments followed by the control, and least on all Dipel treatments. In week 8, infestation levels were significantly high ($F_{6, 273} = 16.266$; $P < 0.001$) in Dichlorvos[1] and Dichlorvos[3] followed by control, Dichlorvos[2] and Dipel[2], and least on Dipel[1] and Dipel[3]. Despite infestation levels dropping to 0.88 *P. xylostella* per plant in the control treatment in week 9, infestations were not significantly different to Dichlorvos treatments, but were significantly high ($F_{6, 273)} = 7.8941$; $P < 0.001$) compared Dipel treatments. However, infestation levels were not significantly different ($F_{6, 273} = 1.8740$; $P = 0.0854$) among all treatments in week 10.

Table 3.1: Mean (± S.E.) numbers of *Plutella xylostella* larvae and pupae at weekly intervals collected cabbage plants not treated with insecticide (Control) and from plants subjected to insecticidal applications of Dipel or Dichlorvos at various treatment intervals during October–December 2011.

Time (in weeks)	Control	Dipel[1]	Dichlorvos[1]	Dipel[2]	Dichlorvos[2]	Dipel[3]	Dichlorvos[3]
1	0.78 ± 0.16a	1.53 ± 0.27ab	1.03 ± 0.19ab	1.3 ± 0.22ab	1.38 ± 0.17ab	1.33 ± 0.36ab	1.3 ± 0.18ab
2	2.15 ± 0.42a	0.53 ± 0.15b	0.83 ± 0.13b	0.35 ± 0.08b	0.48 ± 0.09b	0.85 ± 0.24b	0.65 ± 0.14b
3	12.55 ± 1.77bc	0.7 ± 0.22d	11.38 ± 1.16c	15.58 ± 0.95b	22.5 ± 1.6a	0.45 ± 0.13d	10.88 ± 0.9c
4	14.5 ± 1.5a	0.85 ± 0.23d	5.1 ± 0.47c	1.43 ± 0.58d	9.2 ± 1.71b	0.48 ± 0.18d	4.48 ± 0.32c
5	5.55 ± 0.77a	0.75 ± 0.31cde	1.7 ± 0.21cd	0.65 ± 0.19de	3.8 ± 0.45b	0.4 ± 0.26e	1.8 ± 0.22c
6	4.33 ± 0.69a	0.08 ± 0.04c	2.38 ± 0.35b	0.38 ± 0.15c	4.78 ± 0.62a	0.15 ± 0.07c	1.95 ± 0.26b
7	2.0 ± 0.26b	0.25 ± 0.09c	4.5 ± 0.93a	0.55 ± 0.16c	4.1 ± 0.36a	0.13 ± 0.06c	4.03 ± 0.46a
8	2.05 ± 0.51b	0.18 ± 0.08c	3.83 ± 0.66a	0.88 ± 0.22bc	1.7 ± 0.33b	0.00 ± 0.00c	4.85 ± 0.77a
9	0.88 ± 0.26a	0.38 ± 0.12b	1.23 ± 0.17a	0.38 ± 0.09b	1.03 ± 0.21a	0.10 ± 0.05b	1.33 ± 0.19a
10	0.53 ± 0.20	0.18 ± 0.07	0.18 ± 0.11	0.05 ± 0.03	0.25 ± 0.14	0.13 ± 0.06	0.30 ± 0.10

Means in a row with the same letter are not significantly different at P = 0.05 Fisher's LSD.

[1]Weekly insecticide applications until one week before harvest.

[2]Bi-weekly insecticide applications until one week before harvest.

[3]Weekly insecticide applications until cabbage heads formed.

3.4.2 Parasitism of *Plutella xylostella* during October–December 2011

Four species of indigenous primary parasitic Hymenoptera were recorded from collected samples of *P. xylostella* larvae and pupae during October–December 2011. There were two larval parasitoids – *Cotesia vestalis* (Haliday) and *Apanteles halfordi* (Ullyett, 1947), both Braconidae; a larval-pupal parasitoid – *Oomyzus sokolowskii* (Kurdjumov) (Eulophidae); and a pupal parasitoid – *Diadromus collaris* (Gravenhorst) (Ichneumonidae). The substantial increase in infestation levels during the early stages of crop development during October–December 2011 corresponded with lower parasitism levels (<50 %) of *P. xylostella* in the control treatment (Fig. 3.1). The increase in parasitism levels above 50 % during week 4 corresponded with a sharp decline in infestations levels in week 5 (Fig. 3.1), and their sustenance at high levels thereafter regulated *P. xylostella* infestation at lower levels such that by week 10, infestations per plant dropped to 0.53 (Table 3.1).

3.4.3 Effects of infestations on cabbage quality during October–December 2011

On average, *P. xylostella* infestation levels were significantly high ($F_{6, 2793} = 47.296$; $P < 0.001$) on Dichlorvos^{2} and control treatments followed by Dichlorvos^{1} and Dichlorvos^{3}, then Dipel^{2} and least on Dipel^{1} and Dipel^{3} during October–December 2011 (Table 3.2). However, multiple heads were significantly high ($F_{6, 21} = 2.8512$; $P = 0.0343$) on control treatment compared to the rest of the treatments. Similarly, the percentage of marketable cabbage heads was significantly low ($F_{6, 21} = 3.5929$; $P = 0.0131$) on control treatment compared to the rest of the treatments. Cabbage head weights were significantly different ($F_{6, 723} = 44.545$; $P < 0.001$) among treatments; they were higher on Dipel^{1} and Dipel^{3} followed by Dipel^{2}, then Dichlorvos^{1} and Dichlorvos^{3} and least on Dichlorvos^{2} and control.

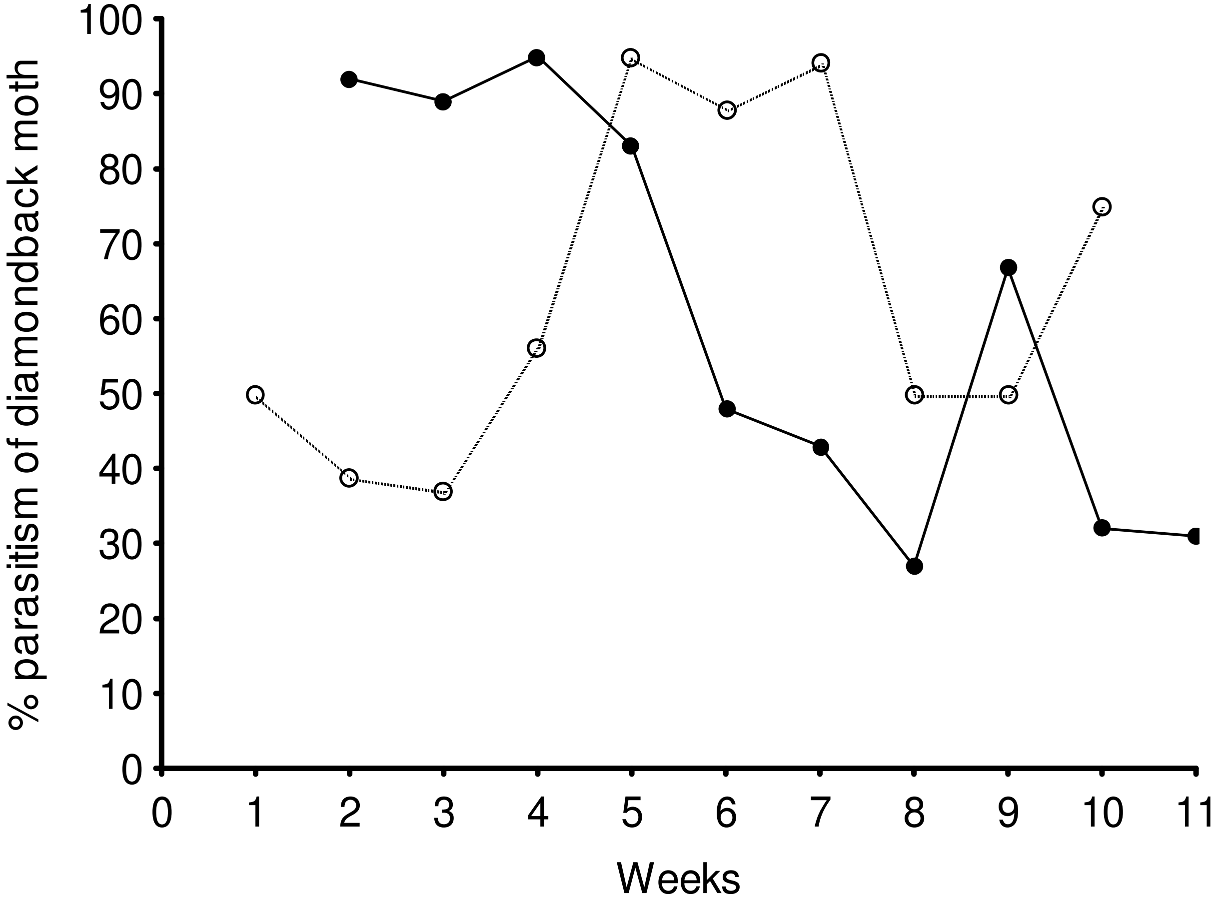

Figure 3.1: Parasitism of *Plutella xylostella* larvae and pupae at weekly intervals during October–December 2011 (dotted line) and March–May 2012 (solid line).

Table 3.2: The influence of Dipel and Dichlorvos insecticides applied at different regimes compared to the untreated cabbage plants (Control) on mean (± S.E.) number of *Plutella xylostella* larvae and pupae and cabbage quality (i.e., % multiple heads, % marketable heads and cabbage weight) during October–December 2011 and March–May 2012.

	October–December 2011				**March–May 2012**			
Treatments	Infestation per plant	% multiple heads	% marketable Heads	Cabbage weight	Infestation per plant	% multiple heads	% marketable heads	Cabbage weight
Control	4.53 ± 0.36a	16.19 ± 2.12a	78.29 ± 1.87a	2.00 ± 0.06d	0.86 ± 0.08a	13.2 ± 0.92a	76.82 ± 2.7a	3.51 ± 0.06a
Dipel[1]	0.54 ± 0.06d	9.21 ± 1.23b	86.69 ± 1.64b	3.24 ± 0.08a	0.03 ± 0.01c	9.82 ± 1.46a	79.97 ± 3.9a	3.67 ± 0.04a
Dipel[2]	2.22 ± 0.25c	10.97 ± 1.71b	86.09 ± 1.91b	2.49 ± 0.07b	0.09 ± 0.02c	11.15 ± 1.39a	75.05 ± 3.17a	3.53 ± 0.07a
Dichlorovos[1]	3.21 ± 0.24b	11.4 ± 0.98b	85.38 ± 1.13b	2.46 ± 0.10c	0.21 ± 0.03b	13.23 ± 2.18a	67.57 ± 4.04a	3.59 ± 0.06a
Dichlorovos[2]	4.86 ± 0.41a	10.55 ± 1.14b	87.09 ± 0.91b	2.18 ± 0.05d	0.25 ± 0.03b	11.61 ± 0.95a	71.88 ± 3.67a	3.57 ± 0.06a
Dichlorovos[3]	3.2 ± 0.20b	8.96 ± 1.29b	86.84 ± 1.64b	2.85 ± 0.07c	0.25 ± 0.03b	13.73 ± 1.87a	72.73 ± 4.39a	3.6 ± 0.04a
Dipel[3]	0.4 ± 0.06d	10.03 ± 1.3b	86.57 ± 2.12b	3.45 ± 0.10a	0.01 ± 0.01c	10.1 ± 1.17a	73.71 ± 3.4a	3.64 ± 0.07a

Means in a column with the same letter are not significantly different at P = 0.05 Fisher's LSD.

[1]Weekly insecticide applications until one week before harvest.

[2]Bi-weekly insecticide applications until one week before harvest.

[3]Weekly insecticide applications until cabbage heads formed.

3.4.4 Infestation levels during March–May 2012

During March–May 2012 (Table 3.3), the trial began with significantly low ($F_{6, 273}$ = 2.2026; P = 0.04304) infestation levels on control plants and Dipel^{3} treatment and highest on Dipel^{1} and Dipel^{2} and intermediate in the rest of the other treatments (week 1). However, after application of insecticides in week 1 infestation levels were significantly high ($F_{6, 273}$ = 10.885; P < 0.001) on control compared to the rest of the treatments in week 2. In week 3, infestation levels were significantly high ($F_{6, 273}$ = 4.7822; P < 0.001) on control and Dichlorvos^{2}, and least on Dipel^{1}, Dipel^{3} and Dichlorvos^{3}. After application of insecticides in week 3 infestation levels were only significantly high ($F_{6, 273}$ = 4.1742; P < 0.001) on the control treatment in week 4. In week 5 infestation levels were significantly high ($F_{6, 273}$ = 3.4198; P = 0.0029) on control and Dichlorvos^{3} and least on Dipel^{1}, Dipel^{2} and Dipel^{3}. In week 6, infestation levels were significantly high ($F_{6, 273}$ = 6.4388; P < 0.001) on control, Dichlorvos^{2} and Dichlorvos^{3}, and least on Dipel^{1}, Dipel^{2} and Dipel^{3}. Infestation levels were significantly high ($F_{6, 273}$ = 10.984; P < 0.001) on control plants in week 7, which was the first time this season infestation levels on control surpassed 1 *P. xylostella* per plant, and were least on Dipel^{1} and Dipel^{3}. In week 8 infestation levels remained significantly high ($F_{6, 273}$ = 10.664; P < 0.001) on the control treatment and were absent on Dipel^{1} and Dipel^{3}. While infestation levels remained significantly high ($F_{6, 273}$ = 6.1873; P < 0.001) on control treatment in week 9, they were comparable among the rest of the treatments. Similarly, infestation levels remained significantly high in weeks 10 ($F_{6, 273}$ = 13.743; P < 0.001) and 11 ($F_{6, 273}$ = 9.0385; P < 0.001) on control treatment, and they were comparable among the rest of the treatments.

Table 3.3: Mean (± S.E.) numbers of *Plutella xylostella* larvae and pupae collected on cabbage plants not treated with insecticide (Control) and from plants subjected to insecticidal applications of Dipel or Dichlorvos at various treatment intervals during March–May 2012

Time (in weeks)	Control	Dipel[1]	Dichlorvos[1]	Dipel[2]	Dichlorvos[2]	Dipel[3]	Dichlorvos[3]
1	0.03 ± 0.03b	0.30 ± 0.11a	0.20 ± 0.11ab	0.28 ± 0.09a	0.06 ± 0.04ab	0.00 ± 0.00b	0.15 ± 0.06ab
2	0.70 ± 0.18a	0.00 ± 0.00b	0.15 ± 0.07b	0.00 ± 0.00b	0.10 ± 0.05b	0.00 ± 0.00b	0.10 ± 0.05b
3	0.53 ± 0.16a	0.00 ± 0.00c	0.18 ± 0.09bc	0.18 ± 0.09bc	0.30 ± 0.11ab	0.00 ± 0.00c	0.05 ± 0.04c
4	0.45 ± 0.18a	0.00 ± 0.00b	0.13 ± 0.05b	0.13 ± 0.5b	0.13 ± 0.5b	0.00 ± 0.00b	0.03 ± 0.03b
5	0.48 ± 0.19a	0.03 ± 0.03c	0.15 ± 0.07bc	0.00 ± 0.00c	0.20 ± 0.09bc	0.05 ± 0.04c	0.33 ± 0.11ab
6	0.73 ± 0.17a	0.00 ± 0.00c	0.30 ± 0.12bc	0.05 ± 0.04c	0.48 ± 0.10ab	0.05 ± 0.04c	0.55 ± 0.18ab
7	1.55 ± 0.33a	0.05 ± 0.05c	0.40 ± 0.12bc	0.18 ± 0.06bc	0.60 ± 0.19b	0.00 ± 0.00c	0.38 ± 0.11bc
8	1.23 ± 0.28a	0.00 ± 0.00d	0.38 ± 0.13bc	0.18 ± 0.07cd	0.18 ± 0.06cd	0.00 ± 0.00d	0.55 ± 0.14b
9	0.93 ± 0.33a	0.00 ± 0.00b	0.20 ± 0.09b	0.03 ± 0.03b	0.08 ± 0.04b	0.00 ± 0.00b	0.13 ± 0.06b
10	1.15 ± 0.27a	0.03 ± 0.03b	0.05 ± 0.04b	0.03 ± 0.03b	0.10 ± 0.08b	0.05 ± 0.04b	0.10 ± 0.05b
11	1.75 ± 0.52a	0.00 ± 0.00b	0.13 ± 0.05b	0.00 ± 0.00b	0.55 ± 0.18b	0.00 ± 0.00b	0.40 ± 0.10b

Means in a row with the same letter are not significantly different at P = 0.05 Fisher's LSD.

[1]Weekly insecticide applications until one week before harvest.

[2]Bi-weekly insecticide applications until one week before harvest.

[3]Weekly insecticide applications until cabbage heads formed.

3.4.5 Parasitism of *P. xylostella* during March–May 2012

Three species of primary parasitoids – *C. vestalis*, *O. sokolowskii* and *D. collaris* were recorded on *P. xylostella* larvae and pupae during March–May 2012. However, this season started with high parasitism levels compared to the October–December 2011 season (Fig 3.1). *Plutella xylostella* infestation levels during this season were much lower compared to the previous season. There were only 4 occasions that infestation levels exceeded 1 *P. xylostella* per plant this season (Table 3.3), which was associated with parasitism levels falling below 50 %.

3.4.6 Effects of infestations on cabbage quality during March–May 2012

On average, *P. xylostella* infestation levels were significantly high ($F_{6,\ 3073} = 59.086$; $P < 0.001$) on control followed by Dichlorvos treatments then Dipel treatments during March–May 2012 (Table 3.2). However, there were no significant differences ($F_{6,\ 21} = 1.1395$; $P = 0.3761$) in the percentage of multiple heads among the treatments. Similarly, there were no significant differences ($F_{6,\ 21} = 1.1579$; $P = 0.3668$) in the percentage of marketable plants and cabbage weights ($F_{6,\ 717} = 0.8328$; $P = 0.5447$) among the treatments.

3.4.7 Relationship between infestation levels and proportion of plants infested

Since crop infestations by *P. xylostella* were much higher on the control treatment during October–December 2011 than during March–May 2012 (Tables 3.1 and 3.2), the relationship between infestation levels and proportion of plants infested can be clearly modelled from the data set of the former season. A significantly positive relationship ($r^2 = 0.7859$; $F_{1,\ 54} = 198.2241$; $P < 0.001$; $y = 0.192 + 0.2289x$; Fig. 2.2) was observed between proportion of plants infested and infestation levels up to 4 *P. xylostella* per plant. At all infestations levels above 4 *P xylostella* per plant, 100 % of the sampled plants were infested, hence all this data was excluded from the above analysis.

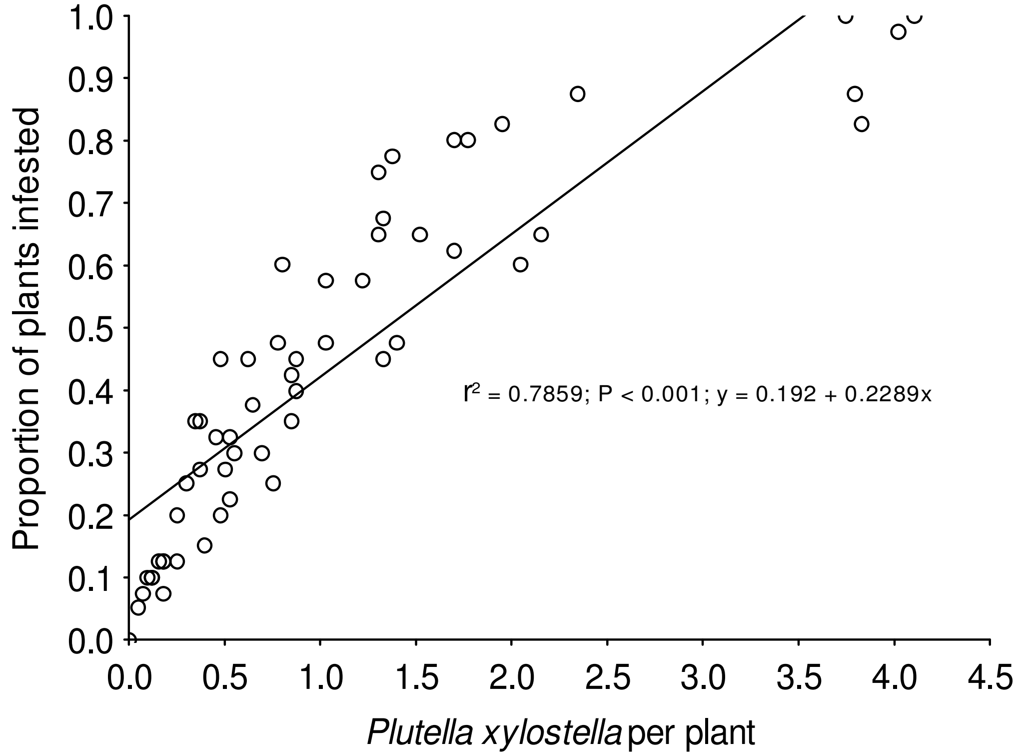

Figure 3.2: The relationship between *Plutella xylostella* infestation levels and the proportion of cabbage plants that were infested on untreated cabbage plants (Control).

3.5 Discussion

Although it is widely recognised that successful cultivation of *Brassica* crops depends in part on good suppression of *P. xylostella* population density (Talekar and Shelton, 1993; Furlong *et al*., 2013), it remained undetermined how low infestation levels need to be maintained in South Africa in order to maximise crop quality. An answer to this question is very important now that growers are under pressure to reduce insecticide inputs to prevent development of widespread insecticide resistance in *P. xylostella.* Although we did not specifically investigate action and economic thresholds for *P. xylostella*, this study provides information on the control of this pest using a combination of chemical and biological control specifically looking at infestation levels that can be tolerated, and the time during growing season can justify regular application of insecticides.

Previous studies have shown that *P. xylostella* enters a population outbreak phase every spring if insecticides are not applied, which results in severe crop damage (Nofemela and Kfir, 2005; Nofemela, 2010). In this study, we showed that weekly application of Dipel is necessary, especially in the first half of October–December season, to maximise yield. Since infestation levels and cabbage head weights were similar when Dipel was applied every week until crop harvest (Dipel^1) and when applied every week until cabbage head formation (Dipel^3), these results suggest that there is no need to apply the insecticide up to crop harvest, which can save growers a lot of money in insecticide and its application costs estimated at US$ 63.13 per 500 g and US$ 8.05 per ha (Ayalew, 2006), respectively. In addition, judicious applications of insecticides prolong their efficacy (Sarfraz and Keddie, 2005). The period November–May has been shown to correspond with low incidence of *P. xylostella* (Nofemela and Kfir, 2005; Nofemela, 2010), which explains why infestation levels did not increase when Dipel application was discontinued (Dipel^3). Further evidence for low incidence of *P. xylostella* from November is obtained in the control treatment, as infestations levels declined sharply from week 5 in association with high parasitism (>50 %) levels.

The clear-cut differences in infestation levels observed in all treatments during the first half of the crop season compared to the second half (Table 3.1) indicate the necessity to abate infestation levels early in the season during October–December. For instance, the significant differences in infestation levels observed between Dipel^2 and both Dipel^1 and Dipel^3 on weeks when the insecticide was not applied in the former treatment in the first half of the season were not observed in the second half. As a consequence of significantly higher infestations in Dipel^2 compared to both Dipel^1 and Dipel^3, crop yield in the former treatment was lower. Despite weekly application of the insecticide in Dichorvos^1 and up to cabbage head formation in Dichlorvos^3, infestation levels were consistently higher compared to the Dipel treatments, even Dipel^2, resulting in cabbage yield to rank third in these treatments. Although Dichlorvos is approved for use in *Brassica* crops against *P. xylostella* in South Africa (Anonymous, 2007), the results of this study suggest that this insecticide is less effective in suppressing the pest than Dipel. Since Dichlorvos is known to dissipate fairly quickly on the plant surface such that it is recommended to be applied up to 2 days before harvest (Anonymous, 2007), the pest is able to successfully re-infest the crop within a week after application. Thus, an inappropriate management practice is to apply Dichlorvos at bi-weekly intervals (Dichlorvos^{2}) during periods of high infestation levels. For instance, infestation levels and cabbage yield on Dichlorvos^{2} were similar to the control treatment during the October–December season.

Although peak infestation levels observed on control plants and Dichlorvos^{2} treatment during October in this study were much lower than the 74 and 54 *P. xylostella* per plant recorded in previous studies (Kfir, 1997; Nofemela and Kfir, 2005), the fact that infestation levels increased substantially during the initial stages of crop development resulted in the lowest yield compared to treatments that kept infestation levels low (i.e., <1 *P. xylostella* per plant per week). Because the proportion of plants infested increased as a function of infestation levels up to 4 *P. xylostella* per plant, treatments (e.g. Dipel^{1} and Dipel^{3}) that consistently maintained infestation levels <1 *P. xylostella* per plant had a lower (<40 %) proportion of plants infested. The emphasis on infestation levels <1 *P. xylostella* is made here because such infestation levels are regarded as too low to negatively affect cabbage quality and yield (Furlong *et al*. 2004; Ayalew 2011). Thus, weekly applications of Dipel during the first half of the cropping season during October–December protected the crop from *P. xylostella* damage, as the proportion of plants infested was low.

Although infestation levels were significantly high on control relative to other treatments during March–May, the percentage of marketable cabbage heads and yield were similar in all treatments. This is because infestation levels were <1 *P. xylostella* per plant in all treatments, except during the second half of the season on control plants when infestation levels increased >1 but remained <2 *P. xylostella* per plant. Thus, the proportion of plants infested were relatively low (<40 %) even on the control treatment in the initial stages of crop development, and the slight increase in infestation levels in the second half of the season did not cause any economic damage, as the damage caused by the pest was clearly confined to the outside leaves. The maintenance of infestation levels <1 *P. xylostella* per plant on the control during the first half of the season was evidently due to parasitism levels starting and maintained at >50 %. Even when parasitism levels fell to <50 % during the second half of the season, infestation levels did not increase as much as they did during the first half of the October–December season when parasitism levels were also low. If we consider that infestation levels also increased during the first half of the October–December season when an insecticide was either not applied (Dipel[2]) or it was ineffective in suppressing high pest densities (Dichlorvos treatments), during the March–May season no significant increases in infestation levels were observed. These findings agree with previous studies that *P. xylostella* occurs at lower densities during March–May compared to the period October–December as evidenced by synthetic sex pheromone trap catches of male moths, whereby both trap catches and infestations occurred at lower densities during November–August than during September–October (Nofemela and Kfir, 2005; Nofemela, 2010). Because parasitism levels were lower during the second half of the March–May season, the failure of pest infestation levels to increase may signal declining field temperatures such that population densities of the pest and its parasitoids were restricted (Nofemela, 2010).

In our opinion, the benefit of insecticide application should always outweigh the cost of the insecticide and its application. Thus, there is an economic benefit for applying Dipel on a weekly basis during the first half of the October–December season, as failure to do so led to *P. xylostella* population outbreak when the plants were still young which resulted in lower yield. However, when natural mortality of *P. xylostella* was high during March–May on the control treatment and as consequence infestation levels were low, there was no economic benefit derived from weekly application of Dipel. Thus, the costs of the insecticide and its application outweighed the benefit of applying the chemical. To ensure that the pest population densities remain below damaging levels, growers should monitor the pest populations by using synthetic sex pheromone traps (Nofemela, 2010) and/or scout the field for immature stages of *P. xylostella.* This study provides important baseline data for developing action and economic thresholds for *P. xylostella* in South Africa.

Because insecticides were applied 3 weeks after cabbage transplants, about 11 % (averaged across treatments and both seasons) of the plants produced multiple heads of low marketability, which can be a very large number in large fields. Therefore, future studies should investigate if early application of a systemic insecticide will substantially reduce proportion of multiple heads. In addition, while aphids [*Myzus persicae* (Sulzer), and *Brevicoryne brassicae* (L.)] and the cabbage webworm [*Hellula undalis* Fabricius] were recorded on very few occasions during this study, and when present they occurred at very low densities, they have a potential to devastate *Brassica* crops (Munthali, 2009; Nofemela and Mosiane, 2011). Thus, future studies should also focus on a holistic management approach of cabbage pest complex.

4 Effects of a selective and a broad-spectrum insecticide on parasitism rates of *Plutella xylostella* and species richness of its primary parasitoids

4.1 Abstract

The direct impact of broad-spectrum insecticides on primary parasitoids is considered a major contributing factor to the high pest status of *Plutella xylostella* in many parts of the world as mentioned above. As a result, selective insecticides are often put forward as a solution to the problem of integrating chemical and biological control methods. However, there is paucity of studies that have directly contrasted effects of selective and broad-spectrum insecticides on parasitism rates and parasitoid species richness in the field. We compared effects of weekly and bi-weekly application regimes of a selective insecticide (Dipel) and a broad-spectrum insecticide (Dichlorvos) on parasitism rates of *P. xylostella* and species richness of its primary parasitoids against unsprayed control for two cropping seasons. Parasitoids were reared from immature *P. xylostella* in all treatments, and parasitism rates were not significantly different among the treatments. During October–December 2011, four species of parasitic Hymenoptera [*Cotesia vestalis* (Haliday) (Braconidae), *Apanteles halfordi* (Ullyett 1947) (Braconidae), *Oomyzus sokolowskii* (Kurdjumov) (Eulophidae), and *Diadromus collaris* (Gravenhorst) (Ichneumonidae)] were reared from *P. xylostella* larvae and pupae, whereas three parasitoid species (*C. vestalis*, *O. sokolowskii* and *D. collaris*) were reared during March–May 2012. *Cotesia vestalis* accounted for >80 % of total parasitism rates in all treatments. In both seasons, parasitoid species richness was highest on the control treatment. Although two parasitoid species were recorded on all Dipel and Dichlorvos treatments during October–December 2011, only one parasitoid species was recorded on Dipel treatments during March–May 2012 compared to two species in Dichlorvos treatments. While insecticide application frequency had no significant impact on parasitoid species richness, insecticide type had an effect. Since *P. xylostella* infestations were significantly lower in Dipel treatments in both seasons, this

study suggests that a greater impact of a selective insecticide on the pest population density can affect parasitoid species richness more than the direct impact of a broad-spectrum insecticide with a short crop residual period.

Key words: diamondback moth; Dipel; Dichlorvos; residual period; natural enemies; host density; host age structure; integrated pest management

4.2 Introduction

The ecosystem service of pest control provided by natural enemies of insect pests worldwide is estimated to be worth over US$ 400 billion a year (Constanza *et al*., 1997). Primary parasitoids are a major mortality factor of insect pests in many agroecosystems (DeBach and Rosen, 1991; Hawkins *et al*., 1999). Since each life stage of a holometabolous insect pest is essentially a niche, several primary parasitoid species can be reared on an insect herbivore population at any given moment (Godfray, 1994; Hawkins 1994). Since parasitoid species that attack different life stages of their common host population, referred to as functional complementary (Wilby *et al*., 2005), do not engage in direct competition, every parasitized host adds to total parasitism and may lead to a positive relationship between primary parasitoid diversity and pest population suppression (Casula *et al*., 2006; Snyder *et al*., 2006; Straub *et al*., 2008). Thus, conservation of parasitoid guilds can enhance biological control.

However, parasitoids may not always effectively suppress insect pest populations, which makes insecticides to continue to be an important component of integrated pest management (IPM) programmes (Castle and Naranjo, 2009; Zalucki *et al*., 2009). However, the general lack of proper guidelines for integrating chemical and biological control methods (Giles *et al*., 2003; Weinzierl, 2009; Nofemela, 2013a) makes it difficult to judiciously use broad-spectrum insecticides and thus conserve parasitoid diversity (Furlong *et al*., 2008; Maalouly *et al*., 2013). Furthermore, indiscriminate application of these insecticides may elevate pest densities if a pest population is resistant or less susceptible to administered doses than the parasitoids (Kfir, 2002; Furlong *et al*., 2008; Bommarco *et al*., 2011). Although judicious application of insecticides in favour of methods that promote natural enemies is one of the central tenets of IPM (Allen and Rajotte, 1990), insecticide usage throughout the world has remained unchanged (Devine and Furlong, 2007; Bommarco *et al*., 2011). This may be due in part to increased availability over the decades of selective insecticides, i.e., chemicals that only kill target insect pests and spare natural enemies (Cross, 2012). Studies have shown that application of selective insecticides can be compatible with biological control using insect predators (Musser and Shelton, 2003; Torres and Ruberson, 2007; Nicholas *et al*., 2005; Bernardi *et al*., 2013) and parasitoids (Furlong *et al*., 2008; Liu *et al*., 2012). However, conservation of diverse assemblages of parasitoid guilds using selective insecticides can be complicated by non-target effects. For example, if the insecticide kills a large proportion of the host life stages that parasitoids depend on for reproduction or it radically reduces incidence of advanced life stages that other parasitoid species depend on (Waage *et al*., 1985; Idris and Grafius, 1993; Chilcutt and Tabashnik, 1997). Thus, indiscriminate application of selective insecticides can conflict with conservation of parasitoid diversity.

Immature stages of *Plutella xylostella* are attacked by a diverse guild of indigenous parasitoids in South Africa (Kfir, 1998). Although its pest status is low in South Africa compared to countries of similar climate (Kfir, 2011), parasitoids are unable to keep its populations in check during spring months (September and early October) which necessitates application of insecticides (Nofemela and Kfir, 2005; Nofemela, 2010). However, parasitism rates increase from late October due to numerical response of key parasitoid species to levels that are sufficiently high to maintain the pest population density largely below one *P. xylostella* per plant per week from November–May (Nofemela, 2010; 2013a). Therefore, it is imperative to determine which insecticide type (selective vs. broad-spectrum) provides the least disturbance on parasitoid abundance and diversity. In this study, we compared the effects of a selective insecticide (Dipel) and a broad-spectrum insecticide (Dichlorvos) on parasitism rates of *P. xylostella* and species richness of its primary parasitoids against a control treatment. Dipel selectively kills larvae of Lepidoptera. Furthermore, we investigated the effects of application regimes of either insecticide type on host density, and whether low host densities influences parasitoid species richness.

4.3 Material and Methods

The details about the experimental site, experimental design, treatments and the application regime of insecticides are provided in Chapter 2.

4.3.1 Data analysis

One-way analyses of variance (ANOVA) were performed to compare 1) parasitism rates % and, 2) *P. xylostella* density between treatments. Prior to ANOVA, the data were checked for normality using Shapiro-Wilks' test and for homogeneity of variance using Levene's test. The data for parasitism rates were square-root transformed prior to analysis. Where significant differences were detected, the means were compared using Fisher's protected least significant difference (LSD) test. The statistical analyses were performed on Statistica (2013) at 5 % level of significance.

4.4 Results

4.4.1 Parasitism of *P. xylostella*

Immature *P. xylostella* were parasitized in all treatments during October–December 2011 (Fig. 4.1) and March–May 2012 (Fig. 4.2). Parasitism rates followed a similar trend in all treatments during the two seasons. They were lower (<50 %) in the early stages of crop development during October–December 2011 until about 5th week when they increased above 50 % and were largely maintained above this level until the end of the season (Fig. 4.1).

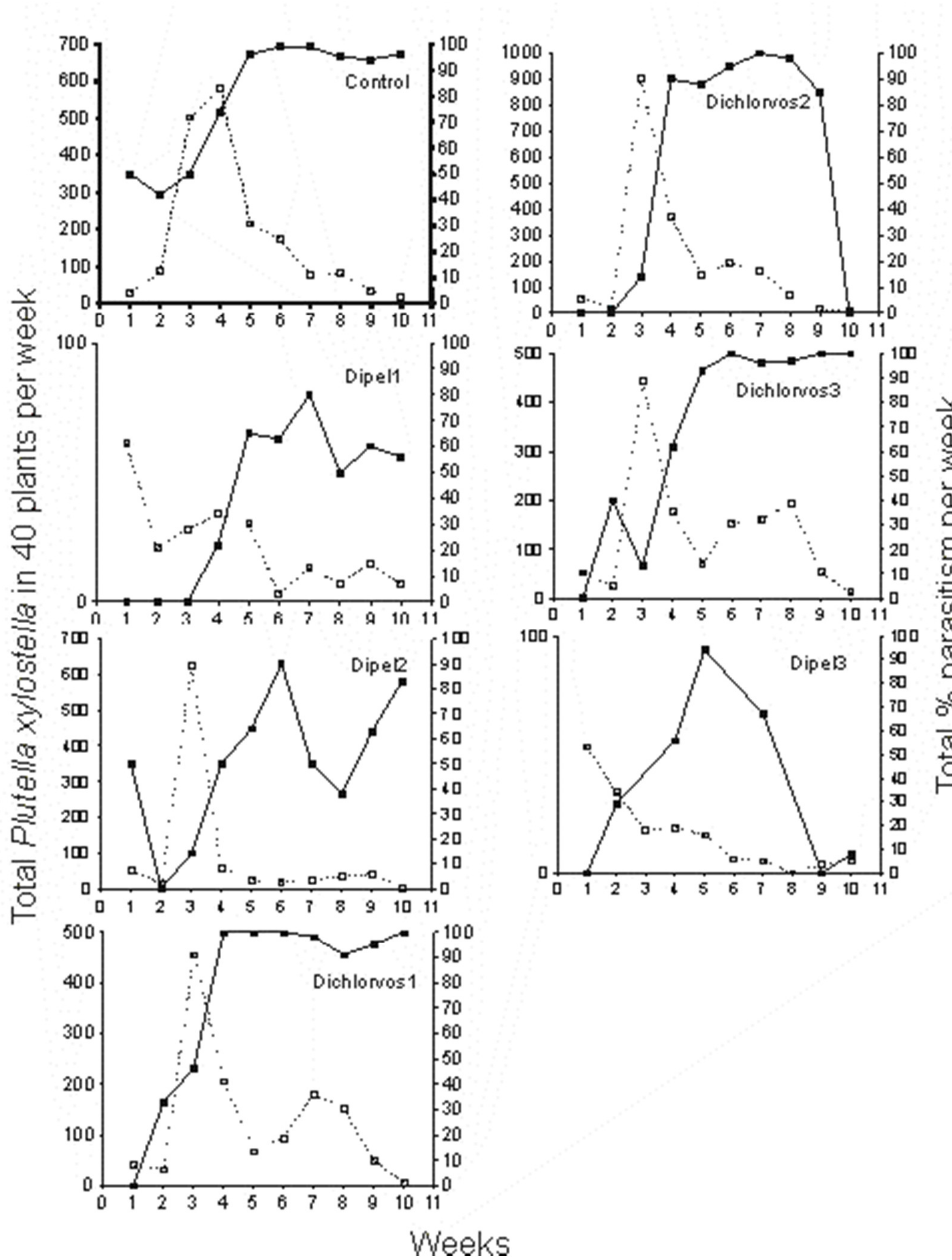

Fig. 4.1: The influence of different insecticides and spray regimes on incidence of *Plutella xylostella* immature stages (dotted line) and parasitism levels (solid line) during October–December 2011

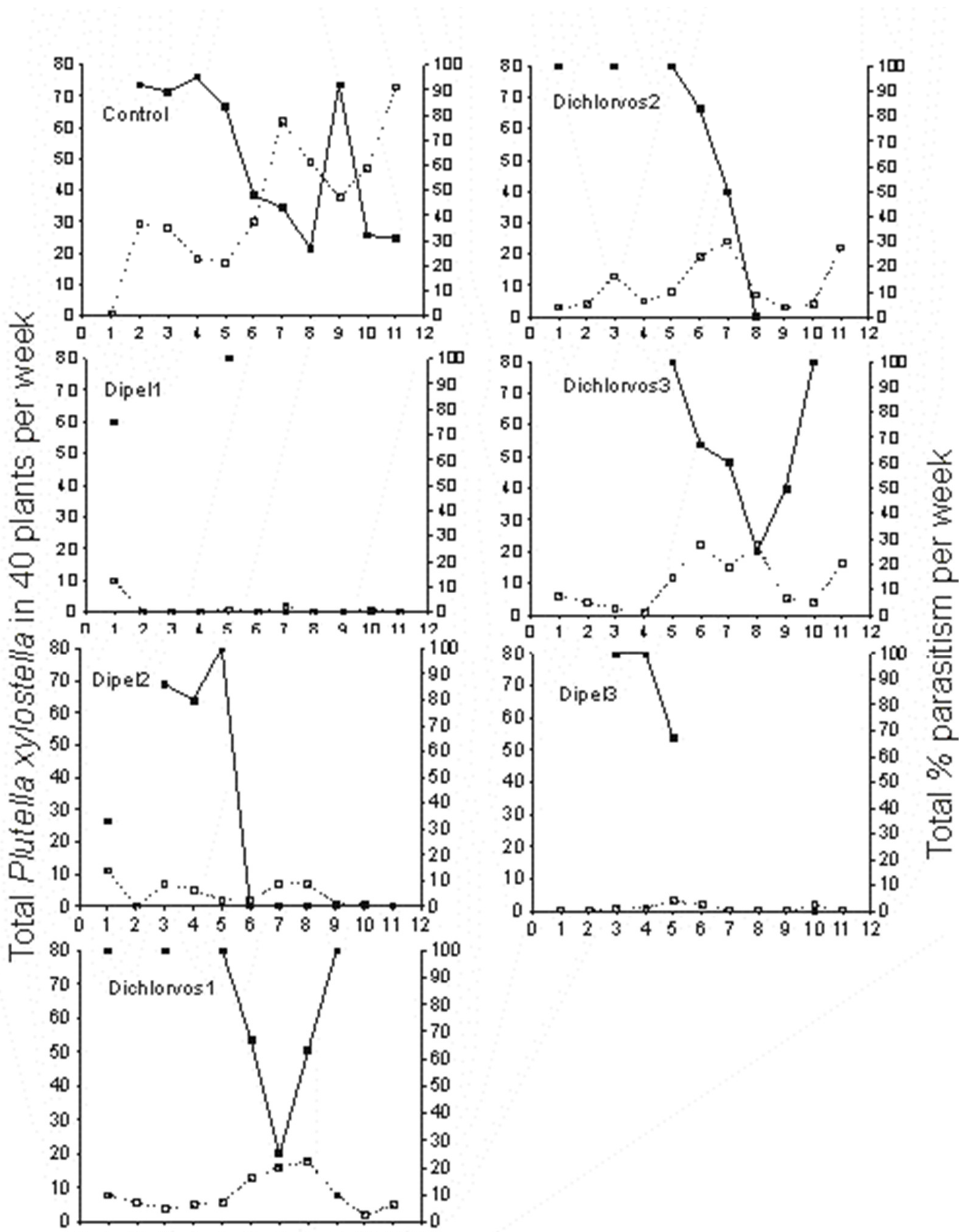

Fig. 4.2: The influence of different insecticides and spray regimes on incidence of *Plutella xylostella* immature stages (dotted line) and parasitism levels (solid line) during March–May 2012

In contrast, initial parasitism levels were high (>50 %) during March–May 2012 until about 5th week when they started to decline below 50 % (Fig. 4.2). No significant differences in parasitism levels were observed among the treatments during October–December 2011 ($F_{6, 57} = 1.59$; $P = 0.1666$) and March–May ($F_{6, 40} = 1.71$; $P = 0.1448$) seasons due to wide variation in most treatments. Thus, there is no evidence that application of either insecticide type and application regime hindered parasitism of the host.

4.4.2 <u>Parasitoid species richness</u>

Four species of indigenous primary parasitic Hymenoptera were recorded from *P. xylostella* during this study: *Cotesia vestalis* (Haliday) (Braconidae), a larval parasitoid; *Apanteles halfordi* (Ullyett, 1947) (Braconidae), a larval parasitoid; *Oomyzus sokolowskii* (Kurdjumov) (Eulophidae), a larval-pupal parasitoid; and *Diadromus collaris* (Gravenhorst) (Ichneumonidae), a pupal parasitoid. During October–December 2011, all four parasitoid species were recorded from the control treatment; only *C. vestalis* and *A. halfordi* were recorded on plants treated with Dipel^{1}; and only *C. vestalis* and *D. collaris* were recorded on plants treated with Dipel^{2}, Dipel^{3}, Dichlorvos^{1}, Dichlorvos^{2} and Dichlorvos^{3} treatments (Fig. 4.3).

During the March–May season, only *C. vestalis*, *O. sokolowskii* and *D. collaris* were recorded from *P. xylostella* larvae and pupae. However, the reason for the complete absence of *A. halfordi* during this season is not clear, as it is normally recorded albeit at low levels (Nofemela 2013b). All three parasitoid species were again recorded from the control treatment; only *C. vestalis* was recorded on plants treated with Dipel^{1}, Dipel^{2} and Dipel^{3}; and both *C. vestalis* and *O. sokolowskii* were recorded from plants treated with Dichlorvos^{1}, Dichlorvos^{2} and Dichlorvos^{3} (Fig. 4.4).

In both seasons, *C vestalis* was the dominant parasitoid species accounting for >80 % of total parasitism levels in all treatments (Figs. 4.3 & 4.4). At face value, the numerical dominance of *C. vestalis* suggests that this parasitoid species may not be negatively affected by insecticide applications than the other parasitoid species active in the system.

However, *C. vestalis* is known to be very efficient in utilizing younger *P. xylostella* instars (Kawagushi and Tanaka, 1999; Nofemela, 2004) such that at low host densities its high efficiency limits availability of hosts for those parasitoid species attacking advanced host life stages (Nofemela 2013b). Thus, it becomes vital to establish if insecticide applications altered the age-structure of the host population to the advantage of *C. vestalis* by promoting preponderance of younger *P. xylostella* life stages?

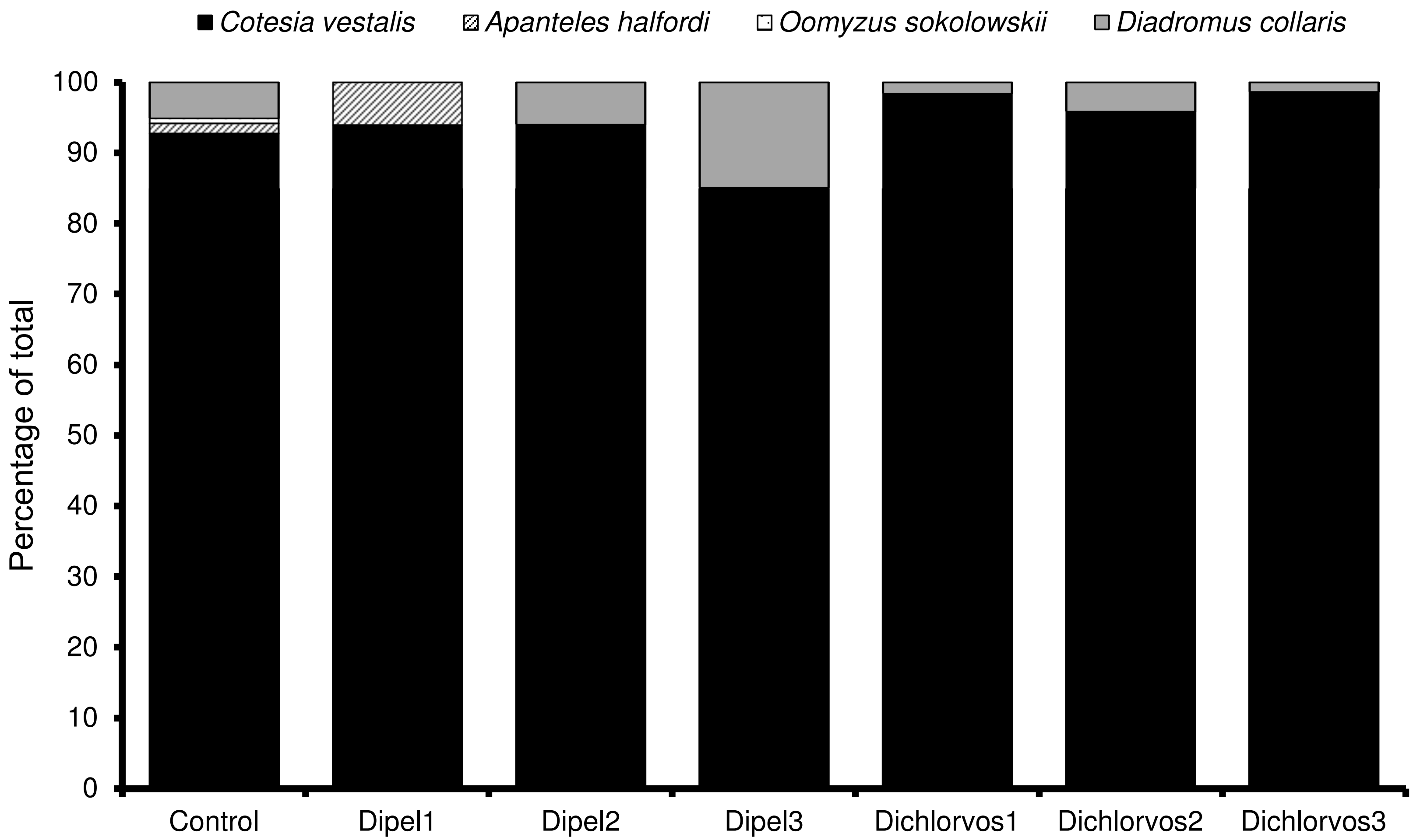

Fig. 4.3: Species composition and relative abundance of *Plutella xylostella* parasitoids in different treatments during October–December 2011

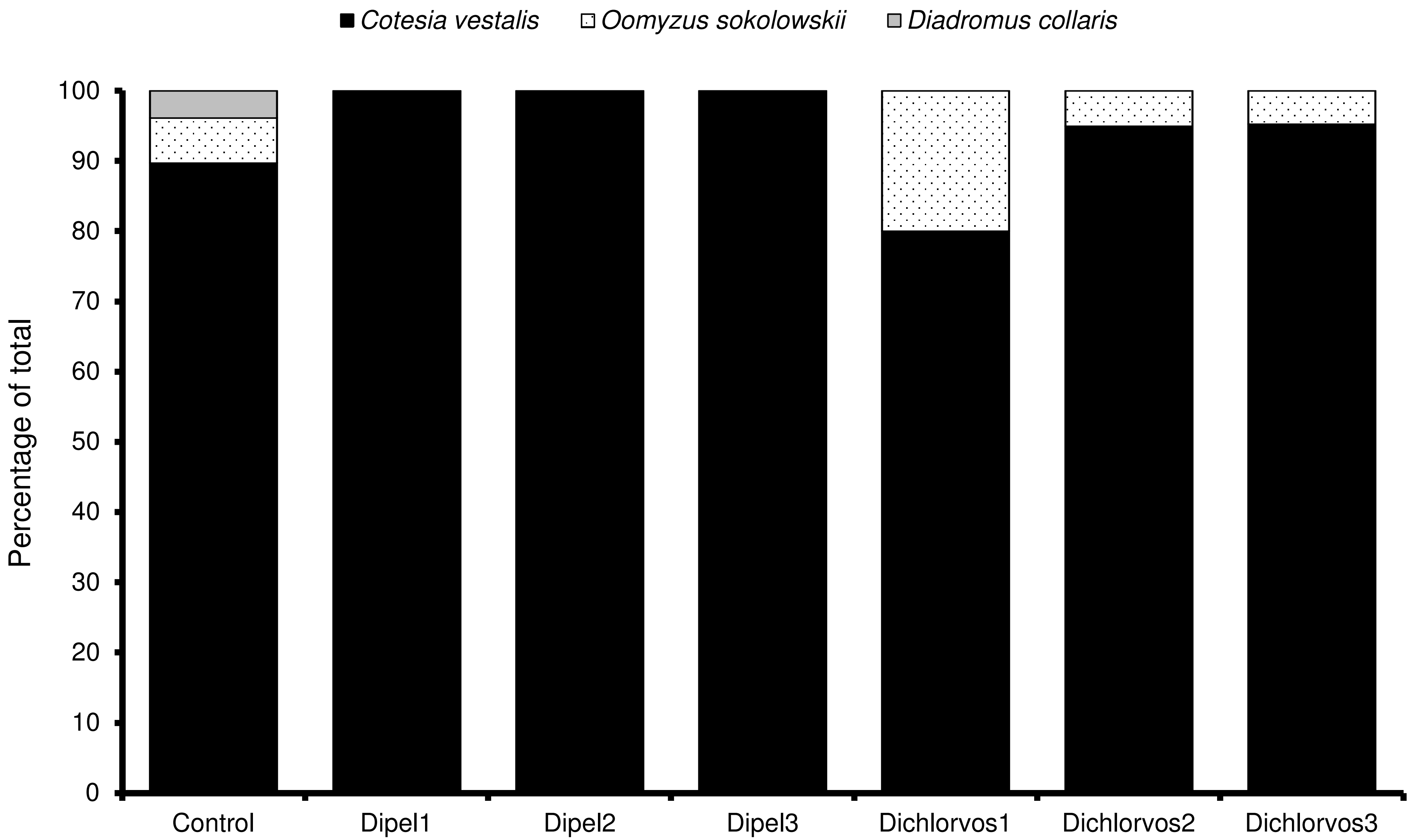

Fig. 4.4: Species composition and relative abundance of *Plutella xylostella* parasitoids in different treatments during October-December 2011

4.4.3 *Plutella xylostella* age-structure and population density

During October–December 2011, the age-structure of *P. xylostella* (Fig. 4.5) suggests that the pest occurred in overlapping generations, as 1st instar larvae and the pupae (as well as instars in-between) were recorded in all treatments nearly throughout the season. However, there was a preponderance of 1st instars in the first half of the season in most treatments, which suggests that the pest population was increasing (Fig. 4.1). As the pest population declined later in the season (Fig. 4.1), advanced life stages of *P. xylostella* became more abundant (Fig. 4.5). The continuous presence of all the pest life stages implies that insecticide applications did not alter its age structure. Thus, there is a theoretical chance that each parasitoid species active in the system can find hosts. However, infestation levels were significantly lower ($F_{6, 2793} = 47.296$; $P < 0.001$) on weekly applications of Dipel – Dipel^{3} (mean ± SE) (0.4 ± 0.06a) and Dipel^{1} (0.54 ± 0.06a) – compared to its bi-weekly application – Dipel^{2} (2.22 ± 0.25b) – and weekly applications of Dichlorvos – Dichlorvos^{1} (3.21 ± 0.24c) and Dichlorvos^{3} (3.2 ± 0.20c) – control (4.53 ± 0.36d) and Dichlorvos^{2} (4.86 ± 0.41d). Thus, despite the presence of different immature stages of *P. xylostella*, the abundance of each life stage varied greatly between treatments.

During the March–May 2012 season, there was a general abundance of older instars of the pest in all treatments (Fig. 4.6), which implies that the pest population density did not increase substantially between weeks as was observed during early part of the October–December 2011 season (Fig. 4.1). However, the incidence of *P. xylostella* pupae was very low in the other treatments (except for the control where pupae were recorded nearly throughout the season) compared to the previous season. Furthermore, there were more instances where no *P. xylostella* immature stages were recorded on Dipel^{1} and Dipel^{3} treatments. Infestation levels in all treatments were much lower during the March–May season (Fig. 4.2) compared to the October–December season (Fig. 4.1), which suggests that the pest pressure at landscape level was low. Nonetheless, infestation levels were significantly higher ($F_{6, 3073} = 59.086$; $P < 0.001$) on control (0.86 ± 0.08a) followed by Dichlorvos^{1} (0.21 ± 0.03b), Dichlorvos^{2} (0.25 ± 0.03b) and Dichlorvos^{3} (0.25 ± 0.03b) and least on Dipel^{1} (0.03 ± 0.01c), Dipel^{2} (0.09 ± 0.02c) and Dipel^{3} (0.01 ± 0.01c).

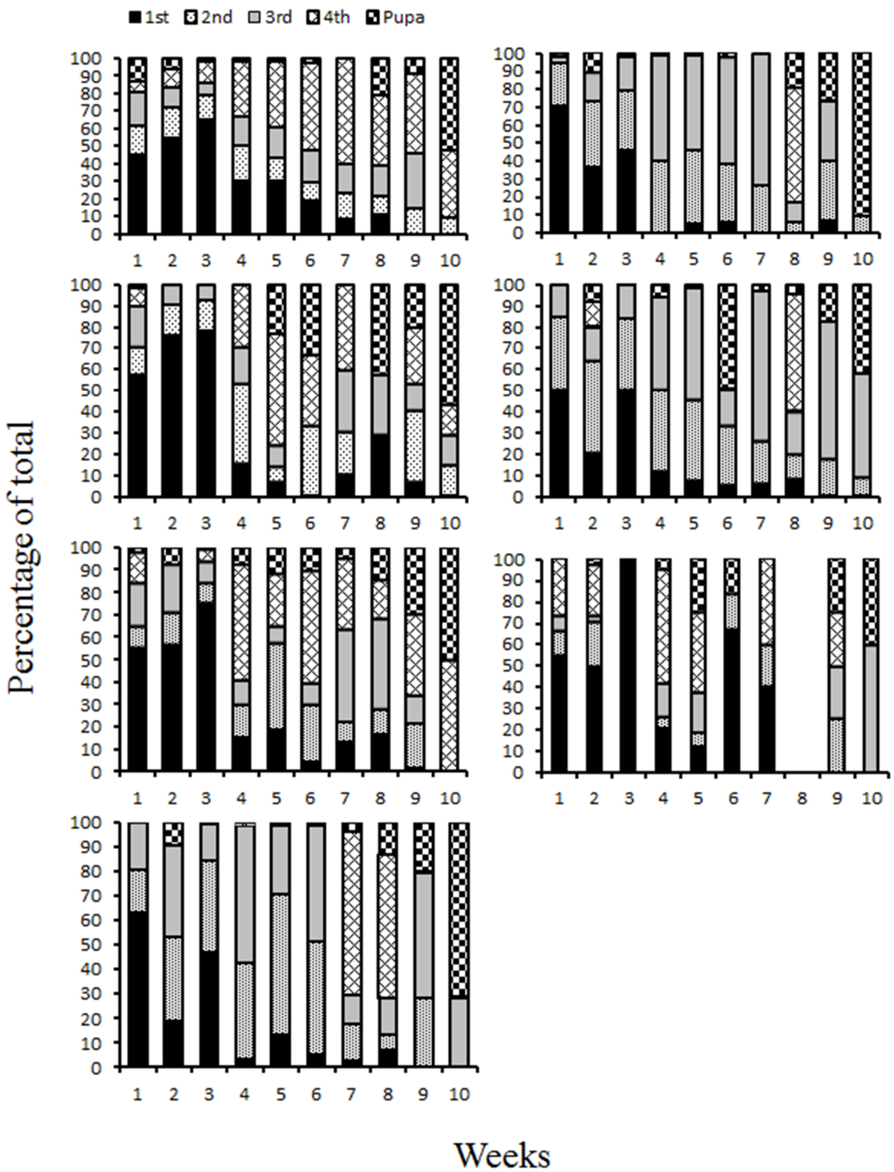

Fig. 4.5: Relative abundance of *Plutella xylostella* life stages on cabbage plants after different treatments during October–December 2011. The treatments are arranged vertically from top left as Control, Dipel[1], Dipel[2], Dichlorvos[1], Dichlorvos[2], Dichlorvos[3] and Dipel[3].

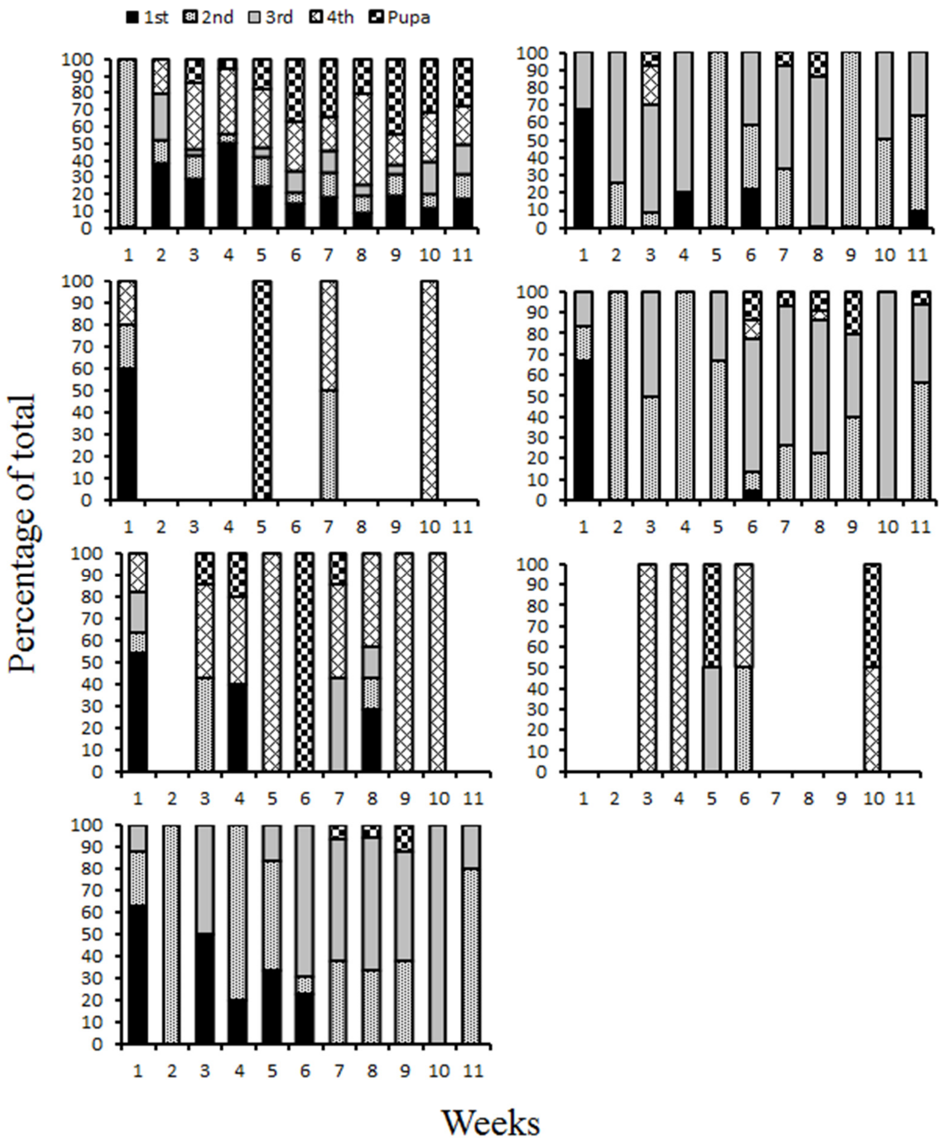

Fig. 4.6: Relative abundance of *Plutella xylostella* life stages on cabbage plants after different treatments during March–May 2012. The treatments are arranged vertically from top left as Control, Dipel^1, Dipel^2, Dichlorvos^1, Dichlorvos^2, Dichlorvos^3 and Dipel^3.

4.5 Discussion

Parasitism rates of *P. xylostella* were comparable in all treatments during both seasons. They followed a general pattern in both seasons; they started low (<50 %) and increased >50 % as the October–December season progressed, whereas initial parasitism levels were high (>50 %) and declined < 50 % towards the end of March–May season. This pattern in parasitism levels is well established in South Africa, and it has shown to be due to positive effect of temperature on developmental rates of the parasitoids (Nofemela, 2010). Although parasitoids were able to colonize all treatment plots despite insecticide applications and application regimes, *C. vestalis* was dominant in all treatments in both seasons. While lower parasitism rates of *P. xylostella* by *C. vestalis* were observed when broad-spectrum insecticides such as Deltamethrin were routinely applied (Furlong *et al*., 2008), the results of this study indicated that Dichlorvos had no significant effect on parasitism rates. Since Dichlorvos has a very short residual period of not more than two days on the crop (Anonymous, 2007), the disturbance caused by its application on the parasitoid population appears to be short-lived, as the crop is re-colonized by the pest and its parasitoids within a week of application. However, pupal stages of parasitoids are invulnerable to most insecticide applications (Shi *et al*., 2013). Furthermore, applications of Dipel did not interfere with parasitism rates of the pest, as to be expected when applications of a selective insecticide do not eliminate a pest population (Furlong *et al*., 2008; Liu *et al*., 2012). However, application of both insecticide types reduced parasitoid diversity irrespective of their application regimes.

Although all *P. xylostella* immature stages were observed in all the treatments, their incidence and thus infestation levels differed greatly between treatments. During October–December, *P. xylostella* infestation levels were significantly lower in Dipel^{1} and Dipel^{3} treatments followed by Dipel^{2}, then Dichlorvos^{1} and Dichlorvos^{3} and higher in Dichlorvos^{2} and control treatments. These results imply that parasitoids had a greater chance of encountering hosts in the control and Dichlorvos^{2} treatments and least on Dipel^{1} and Dipel^{3}. This is especially true on the incline phase of the pest population depicted by the preponderance of 1st instar host larvae. While parasitoid species richness was highest (four species) on control, only two species were recorded from the Dichlorvos^{2} treatment despite similar infestation levels. In both control and Dichlorvos^{2} treatments, *C. vestalis* accounted for more than 90 % of total parasitism rates whereas *D. collaris* was responsible for about 5 %. Since there was a similar sampling effort in both control and Dichlorvos^{2} treatments, the additional two species recorded on the control treatment may indicate lack of disturbance on parasitoid populations, in which case both *A. halfordi* and *O. sokolowskii* that occurred in low densities at the landscape level parasitized a lot more hosts. The fact that only *C. vestalis* and *D. collaris* were also recorded in both the selective (Dipel^{2} and Dipel^{3}) and the broad-spectrum (Dichlorvos^{1} and Dichlrovos^{3}), insecticide treatment illustrates that both *A. halfordi* and *O. sokolowskii* occurred at low densities at landscape level. Thus, the effects of the insecticides on the pest population density may have made it even harder to sample hosts (i.e., sampling effect) parasitized by *A. halfordi* and *O. sokolowskii*. The replacement of *D. collaris* by *A. halfordi* in the Dipel^{1} treatments cannot be immediately explained, as the age structure of the pest in that treatment was almost identical to others (Fig. 4.3), and that infestation levels were similar to the Dipel^{3} treatment.

During the March–May season, the incidence of *P. xylostella* was highest on the control treatment, followed by Dichlorvos treatments and least on the Dipel treatments. However, infestation levels were significantly low compared to the spring season across all treatments, and they were about a fifth of what they were during October–December on the control treatment. The lower infestation levels in the other treatments compared to the control indicate a strong positive interaction between parasitism rates and insecticide application with this relationship being stronger in Dipel treatments. Three species of parasitoids were recorded from the control treatment, followed by two species in the Dichlorvos treatments, and one species in the Dipel treatments. The complete absence of *A. halfordi* during this period is unusual, although it has shown to be sporadic (Nofemela and Kfir, 2005; Nofemela, 2013b). Assuming that all three parasitoid species (*C. vestalis*, *O. sokolowskii* and *D. collaris*) were active at the landscape level, a plausible explanation for the higher parasitoid species richness on the control treatment is that the pest incidence was higher. It is well established that direct and indirect competition between parasitoid species becomes intense when hosts are limited. Under these conditions, the parasitoid species that attack younger host life stages gains an advantage to an abundant host resource over those species attacking advanced host stage (Price, 1972; Chesson, 1991; Nofemela, 2013b), provided the latter cannot successfully utilize parasitized hosts (Briggs, 1993; Oishi and Sato, 2008). Since *C. vestalis* is very efficient in utilizing younger *P. xylostella* instars (Kawagushi and Tanaka, 1999; Nofemela, 2004), it has been shown that it limits host availability for *O. sokolowskii* and *D. collaris* at low host densities (Nofemela, 2013b). Thus, the dominance of *C. vestalis* across all treatments is due to its high efficiency and that it is a superior competitor to *O. sokolowskii*, which is also its intraguild predator (Nofemela, 2013b). Despite pupal hosts being recorded nearly throughout the season on the control treatment, the fact that *O. sokolowskii* (which mainly successfully attacks host larvae that were missed by *C. vestalis*) was more abundant during this season implies that only a fraction of host pupae were suitable for *D. collaris*. Hence, *D. collaris* occurred at much lower density relative to *O. sokolowskii*. The effects of strong interspecific interactions between the parasitoids at lower pest densities are even clearer in the other treatments. In Dichlorvos treatments that had similar pest incidences, which were significantly lower than the control, only *C. vestalis* and *O. sokolowskii* were recorded. Furthermore, only *C. vestalis* was recorded in the Dipel treatments, which had the least infestation levels.

Although Dichlorvos is toxic to adult *P. xylostella* parasitoids (Lin *et al.* 2007; Wu *et al.*, 2007), this insecticide dissipates fairly quickly (Anonymous, 2007) compared to Dipel (Haseeb *et al.*, 2004), which degrades in about 4 days due to solar radiation (Côté *et al.*, 2001). The difference in persistence of the two insecticides is confirmed by lower incidence of *P. xylostella* in Dipel compared to Dichlorvos treated plots. All the parasitoid species recorded in this study spend their pupal stages either in a silken cocoon (*C. vestalis* and *A. halfordi*) or inside the host pupa (*O. sokolowskii* and *D. collaris*) and thus do not come into direct contact with insecticides. As there is always a resident parasitoid population in each plot, the impact of either insecticide application on host density increases parasitoid to host ratio such that parasitism levels remain as relatively high as in the control plots.

5 General discussion and conclusion

Plutella xylostella is a serious threat to successful production of cabbage at the Department of Correctional Services Baviaanspoort's farm, and the quality of the produce was generally poor despite weekly/bi-weekly applications of broad-spectrum insecticides (Cypermethrin, Deltamethrin and Parathion). In 2010, the ARC–Plant Protection Research Institute was approached for advice on strategies that can be used to suppress the pest population density. Their entomologists have published widely on *P. xylostella* for about two decades. A preliminary study conducted during spring in 2010 showed that the insecticides named above were no longer effective in suppressing the pest populations, which meant that their continued use only increased input costs without providing the benefit of controlling the insect pest.

This study compared the efficacy of two insecticides (Dipel and Dichlorvos) that were not previously used in the farm to suppress *P. xylostella* population densities during two seasons (October–December 2011 and March–May 2012) in combination with biological control using parasitoids, a previously unrecognised pest control method in the farm. It was established that *P. xylostella* infestation levels were higher during October–December 2011 than during March–May 2012 season (Chapter 2) due to generally lower (<50 %) parasitism levels at the beginning of the season. This result is similar to previous studies that demonstrated that parasitism rates of *P. xylostella* are positively influenced by field temperatures such that when average temperature remains above 20 °C parasitism levels are high (Nofemela, 2010). Furthermore, this study showed Dipel was more effective in suppressing *P. xylostella* population density than Dichlorvos in both seasons (Chapter 2), while weekly applications of Dipel during October–December 2011 were more effective in suppressing the pest population densities below 1 *P. xylostella* per plant per week than the other treatments. Cabbage produced from Dipel treatments during October–December 2011 season were bigger compared to Dichlorvos and control treatments. However, the cabbage weights were similar among the treatments during the March–May season despite the very low *P.*

xylostella infestation levels on Dipel treatments. This was due the fact that infestations levels were generally below 1 *P. xylostella* per plant in all treatments. Thus, there is no economic benefit in applying the insecticides on a weekly basis when the pest population density is low, and this is especially true when parasitism levels are high. This study showed that when parasitism levels are very high during March–May 2012, the impact of parasitoids on the pest population is comparable to that of an efficient insecticide in terms of protecting the yield.

Four species of parasitoid Hymenoptera (*C. vestalis*, *A. halfordi*, *O. sokolowskii* and *D. collaris*) were recorded during this study. In both seasons, the parasitoid species richness was higher on control than on insecticide treated plots. Although Dichlorvos is toxic to adult parasitoids (Lin *et al.*, 2007; Wu *et al.*, 2007), it was interesting to observe that parasitoid species richness was not higher in treatments with a selective insecticide (Dipel). Since Dichlorvos dissipates in about 2 days on the crop surface (Anonymous, 2007), its impact on the parasitoids populations is short-lived. Although broad-spectrum insecticides have been shown to negatively impact parasitoid population densities and thus parasitism rates (Furlong *et al.*, 2008; Liu *et al.*, 2012), use of an insecticide with a short residual period may be the best option considering that broad-spectrum insecticides are usually cheaper than specific insecticides such as Dipel.

Cotesia vestalis was the most dominant parasitoid accounting for >80 % of total parasitism levels in all treatments. This result is similar to that of previous studies (Kfir, 1997, Nofemela and Kfir, 2005). Recently, Nofemela (2013a) showed that it is easier to estimate parasitism levels from ratios of parasitoid cocoons to infestations, and a 20 % ratio is equivalent to 50 % parasitism level. Thus, by scouting the crop for abundance of *P. xylostella* and its parasitoids at least once week, a grower can make an informed decision on whether or not to apply an insecticide. By applying insecticides only when necessary, growers can delay development of resistance and thus extend efficacy of insecticides against the pest (Sarfraz and Keddie, 2005). Thus, by harnessing the impact of parasitoids on *P. xylostella* and only use insecticides as a backup option (Kogan, 1998) as part of integrated pest management, management of populations of this problematic insect pest will become sustainable.

REFERENCES

Allen, W.A. and Rajotte, E.G. (1990). "The changing role of extension entomology in the IPM era." *Annual Review Entomology*, **35**: 379-397.

Anonymous (2007). *A Guide for the Control of Plant Pests*. 14th Edition. Department of Agriculture, South Africa.

Anonymous (2000). *Diamondback Moth*. Saskatchewan Agriculture, Food and Rural Revitalization. URL [http://www.agr.gov.sk.ca/docs/crops/integrated_pest_management/insects/diamond.asp] (accessed May, 2010).

Ayalew, G. (2011). Effect of insect growth regulator novaluron on diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae), and its indigenous parasitoids. *Crop Protection*, **30**: 1087-1090.

Ayalew, G. (2006). Comparison of yield loss on cabbage from diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae) using two insecticides. *Crop Protection*, **25**: 915-919.

Beck, N.G., Herman, T.J.B., and Cameron, P.J. (1992). Scouting for lepidopteran pests in commercial cabbage fields. pp. 31–34. Popay, A.J. (Ed.) *Proceedings of the 45th New Zealand Plant Protection Conference*, 11–13 August 1992, Wellington, New Zealand.

Bernardi, D., Botton, M., Da Cunha, U.S., Bernardi, O., Malausa, T., Garcia, M.S., and Nava, D.E. (2013). Effects of *azadirachtin* on *Tetranychus urticae* (Acari: Tetranychidae) and its compatibility with predatory mites (Acari: Phytoseiidae) on strawberry. *Pest Management Science*, **69**: 75-80.

Bommarco, R., Miranda, F., Bylund, H., and Björkman, C. (2011). Insecticides suppress natural enemies and increase pest damage in cabbage. *Journal of Economic Entomology*, **104**: 782-791.

Briggs, C.J. (1993). *The Effect of Multiple Parasitoid Species on the Gall-forming Midge Rhopalomyia californica* . PhD thesis, University of California, Santa Barbara .

Brooks, D.M., Pando, V.L., Ocmin, P.A., and Tejada, R.J. (2001). Resource separation in a Napo-Amazonian gamebird community. pp. 213–225. In: Brooks, D.M., and Gonzalez, F. (Eds.) *Biology and Conservation of Cracids in the New Millenium.* Misc. Publ. No. 2, Houston Museum of Natural Sciences, Houston, Texas.

Carter, D.J. (1984). Pest Lepidoptera of Europe with special reference to the British Isles. *Series Entomology*, **31**: 81–83.

Castle, S., and Naranjo, S.E. (2009). Sampling plans, selective insecticides and sustainability: the case for IPM as 'informed pest management.' *Pest Management Science*, **65**: 1321-1328.

Carson, R. (1962). *Silent Spring*. Fawcett Crest, New York.

Casula, P., Wilby, A., and Thomas, M.B. (2006). Understanding biodiversity effects on prey in multi-parasite systems. *Ecology Letters*, **9**: 995–1004.

Chesson, P. (1991). A need for niches? *Trends in Ecology and Evolution*, **6**: 26-28.

Chilcutt, C.F., and Tabashnik, B.E. (1997). Host-mediated competition between the pathogen *Bacillus thuringiensis* and the parasitoid *Cotesia plutellae* of the diamondback moth (Lepidoptera: Plutellidae). *Environmental Entomology*, **26**: 38-45.

Constanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., and Van Den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, **387**: 253-260.

Côté, P., Mclaughlin, D.E., Hanes, D.A., Bridges, T.J., Geisler, D., Merritt, D., Hesser, E.J., Gretchen, L.H.H., and Lee, M.G. (2001). Dynamic of globular cluster System Associated with M87 (NGC 4486). II. Analysis. *The Astrophysical Journal*, **559**: 828-850.

Cross, P. (2012). Pesticide hazard trends in orchard fruit production in Great Britain from 1992 to 2008: a time-series analysis. *Pest Management Science*, **69**: 768-774.

Debach, P., and Huffaker, C.B. (1971). Experimental techniques for evaluation of the effectiveness of natural enemies. pp 113–140. In: Huffaker, C.B. (Ed.) *Biological Control*: Plenum Press, New York.

Debach, P., and Rosen, D. (1991). *Biological Control by Natural Enemies*: Cambridge University Press, Cambridge, UK.

Dent, D. (1991). *Insect Pest Management.* CAB International, Wallingford.

Devine, G.J., and Furlong, M.J. (2007). Insecticide use: contexts and ecological consequences. *Agriculture and Human Values*, **24**: 281-306.

Dennill, G.B., and Pretorius, W.L. (1995). The status of diamondback moth, *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae), and its parasitoids on cabbages in South Africa. *African Entomology*, **3**: 65–71.

FAOSTAT (2012). Production statistics. Rome: FAO. http://faostat.fao.org/sote/567/default.aspx#ancor

Furlong, M.J., Wright, D.J., and Dosdall, L.M. (2013). Diamondback moth ecology and management: problems, progress, and prospect. *Annual Review of Entomology*, **58**: 517-541.

Furlong, M.J., Ju, K.H., Su, P.W., Chol, J.K., Il, R.C., and Zalucki, M.P. (2008). Integration of endemic natural enemies and *Bacillus thuringiensis* to manage insect pests of *Brassica* crops in North Korea. *Agriculture, Ecosystems and Environment*, **125**: 223-238.

Furlong, M.J., Shi, Z.H., Liu, Y.Q., Guo, S.J., Lu, Y.B., Liu, S.S., and Zalucki, M.P. (2004). Experimental analysis of the influence of pest management practice on the efficacy of an endemic arthropod natural enemy complex of the diamondback moth. *Journal of Economic Entomology*, **97**: 1814–1827.

Giles, K.L., Jones, D.B., Royer, T.A., Elliot, N.C., and Kinler, S.D. (2003). Development of a sampling plan in winter wheat that estimates cereal aphid parasitism levels and predicts population suppression. *Journal of Economic Entomology*, **96**: 975-982.

Godfray, H.C.J. (1994). *Parasitoids: Behavioural and Evolutionary Ecology*. Princeton University Press, New Jersey, USA.

Grzywacz, D., Rossbach, A., Rauf, A., Russell, D.A., Srinivasan, R., and Shelton, A.M. (2010). Current control methods for diamondback moth and other *Brassica* insect pest and the prospect for improved management with lepidopteran-resistant Bt vegetable *brassicas* in Asia and Africa. *Crop protection*, **29**: 68-79.

Gunn, D. (1917). The small cabbage moth (*Plutella maculipennis* Curtis). *Bulletin of the Department of Agriculture*, *Union of South Africa*, **8**: 1–10.

Harcourt, D.G. (1986). Population dynamics of the diamondback moth in southern Ontario. pp. 3–16. In: Talekar, N.S., and Griggs, T.D. (Eds.) *Diamondback Moth Management*: proceedings of the first international workshop, 11–15 March 1985, Asian Vegetable Research and Development Center, Tainan, Taiwan.

Harcourt, D.G. (1957). Biology of the diamondback moth, *Plutella maculipennis* (Curt.) (Lepidoptera: Plutellidae), in eastern Ontario, II. life-history, behaviour, and host relationships. *Canadian Entomology*, **89**: 554-564.

Hardy, J.E. (1938). *Plutella maculipennis* Curt., its natural and biological control in England. *Bulletin of Entomological Research*, **29**: 343–373.

Haseeb, M., Liu, T.X., and Jones, W.A. (2004). Effects of selected insecticides on *Cotesia plutellae* (Hymenoptera: Braconidae), an endolarval parasitoid of *Plutella xylostella* (Lepidoptera: Plutellidae). *BioControl*, **49**: 33–46.

Hawkins, B.A., Mills, N.J., Jervis, M.A., and Price, P.W. (1999). Is the biological control of insects a natural phenomenon? *Oikos*, **86**: 493–506.

Hawkins, B.A., and Sheehan, W. (1994). *Parasitoid Community Ecology*. Oxford University Press, Oxford.

Heisswolf, S., Houlding, B.J., and Deuter, P.L. (1997). A Decade of Integrated Pest Management (IPM) in *Brassica* Vegetable Crops - The Role of Farmer Participation in its Development in Southern Queensland, Australia. pp. 228-232. In*:* Sivapragasam, A., Loke, W.H., Hussan, A.K., and Lim, G.S. (Eds.) *The Management of Diamondback*

Moth and other Crucifer Pests: proceedings of the third international workshop. Malaysian Agricultural Research and Development Institute, Kuala Lumpur, Malaysia.

Higley, L.G., and Peterson, R.K.D. (2009). Economic decision rules for IPM. pp. 25-32. In: Radcliffe, EB, Hutchison, W.D., and Cancelado, R.E. (Eds.) *Integrated Pest Management: concepts, tactics, strategies, and case studies.* Cambridge University Press, Cambridge,

Hoffmann, M.P., and Frodsham, A.C. (1993). *Natural Enemies of Vegetable Insect Pests*. Cornel University Press, New York. 63pp.

Idris, A.B., and Grafius, E. (1993). Pesticides affect immature stages of *Diadegma insulare* (Hymenoptera: Ichneumonidae) and its host the diamondback moth (Lepidoptera: Plutellidae). *Journal of Economic Entomology*, **86**: 1203-1212.

Iqbal, M., and Wright, D.J. **(**1996). Host resistance to insecticides can confer protection to endo-larval parasitoids. *Bulletin of Entomological Research*, **86**: 721–723.

Joia, B.S., Udeaan, A.S., and Chawla, R.P. (1996). Toxicity of cartap hydrochloride and other insecticides to multi-resistant strains of the diamondback moth, *Plutella xylostella* (L.), in the Punjab. *International Journal of Pest Control*, **38**:158–59.

Kawagushi, M., and Tanaka, T. (1999). Biological characteristics of a larval endoparasitoid, *Cotesia plutellae* (Hymenoptera: Plutellidae): host stage preference, subsequent sex ratio of progeny and mate location of males. *Applied Entomology and Zoology*, **34**: 213-221.

Kfir, R. (2004). Effect of parasitoid elimination on populations of diamondback moth on cabbage. pp. 197–205. In: Endersby, N.M., and Ridland, P.M. (Eds.) *Management of Diamondback Moth and other Crucifer Pests*: proceedings of the fourth international workshop. Department of Natural Resources and Environment, Melbourne, Australia.

Kfir, R. (2002). Increase in cereal stem borer populations through partial elimination of natural enemies. *Entomologia Experimentalis et Applicata*, **104**: 299-306.

Kfir, R., and Thomas, J. (2001). Biological control of Diamondback moth on St Helena Island with Parasitoids supplied by ARC-PPRI. *Biocontrol News and Information*, **22**: 4N.

Kfir, R. (1998). Origin of the diamondback moth (Lepidoptera: Plutellidae). *Annals of the Entomological Society of America*, **91**: 164–167.

Kfir, R. (1997a). Parasitoids of *Plutella xylostella* (Lepidoptera: Plutellidae) in South Africa: an annotated list. *Entomophaga*, **42**: 517–523.

Kfir, R. (1997b). The diamondback moth with special reference to its parasitoids in South Africa. pp. 54-60. In: Sivapragasam, A., Loke, W.H., Hussan, A.K., and Lim, G.S. (Eds.) *The Management of Diamondback Moth and other Crucifer Pests*: proceedings of the third international workshop. Malaysian Agricultural Research Institute, Kuala Lumpur Malaysia.

Kogan, M. (1998). Integrated pest management: historical perspectives and contemporary developments. *Annual Review of Entomology*, **43**: 243-270.

Lim, G.S. (1986). Biological control of diamondback moth. pp. 159–171. In: Talekar, N.S., and Griggs, T.D. (Eds.) *Diamondback Moth Management*: proceedings of the first international workshop, 11–15 March 1985, Asian Vegetable Research and Development Center, Tainan, Taiwan.

Lin, Y.W., Wu, G., and Miyata, T. (2007). Insecticide susceptibility of surviving *Cotesia plutellae* (Hym: Braconidae) and *Diaeretiella rapae* (M'Intosh) (Hym: Aphidiidae) as affected by sublethal insecticide dosages of host insects. *Pest Management Science*, **63**: 841-850.

Liu, X., Chen, M., Collins, H.L., Onstad, D., Roush, R., Zhang, Q., and Shelton, A.M. (2012) Effect of insecticides and *Plutella xylostella* (Lepidoptera: Plutellidae) genotype on a predator and parasitoid and implications for the evolution of insecticide resistance. *Journal of Economic Entomology*, **105**: 354-362.

Löhr, B., Gathu, R., Obiero, J., and Gichini, G. (2007). Impact of an exotic parasitoid on *Plutella xylostella* (Lepidoptera: Plutellidae) population dynamics, damage and indigenous natural enemies in Kenya. *Bulletin of Entomological Research*, **97**: 337-350.

Luck, R.F., Shepard, B.M., and Kenmore, P.E. (1999). Evaluation of biological control with experimental methods. pp. 225–242. In: Bellows, T.S., and Fisher, T.W. (Eds.) *Handbook of Biological Control.* Academic Press, San Diego

Maalouly, M., Franck, P., Bouvier, J.C., Toubon, J.F., and Lavigne, C. (2013). Codling moth parasitism is affected by semi-natural habitats and agricultural practices at orchard and landscape levels. *Agriculture, Ecosystems and Environment*, **169**: 33-42.

Macfadyen, S., and Zalucki, M.P. (2012). Assessing the short-term impact of an insecticide (Deltamethrin) on predator and herbivore abundance in soybean Glycine max using a replicated small-plot field experiment. *Insect Science*, **19**:112-120.

Meyrick, E. (1928). *A Revised Handbook of British Lepidoptera*. Watkins and Doncaster Press, London. 803 pp.

Monnerat, R.G., Kirk, A.A., and Bordat, D. (2002). Biology of *Diadegma* sp. (Hymenoptera: Ichneumonidae), a parasitoid of *Plutella xylostella* (L.) (Lepidoptera: Yponomeutidae), from Reunion Island. *Neotropical Entomology*, **31**: 271–274.

Munthali, D.C. (2009). Evaluation of cabbage varieties for resistance to the cabbage aphid. *African Entomology*, **17**: 1-7.

Musser, F.R., and Shelton, A.M. (2003). Bt sweet corn and selective insecticides: impacts on pests and predators. *Journal Economic Entomology*, **96**: 71-80

Nicholas, A.H., Spooner-Hart, R.N., and Vickers, R.A. (2005). Abundance and natural control of the woolly aphid *Eriosoma lanigerum* in an Australian apple orchard IPM program. *BioControl*, **50**: 271-291.

Nofemela, R.S. (2013a). A simple method of estimating instantaneous levels of endoparasitism of *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae) by Hymenoptera in the field. *African Entomology*, **21**: 280-286.

Nofemela, R.S. (2013b). The effect of obligate hyperparasitoids on biological control: differential vulnerability of primary parasitoids to hyperparasitism can mitigate trophic cascades. *Biological Control*, **65**: 218-224.

Nofemela, R.S. (2013c). *Development of a biological control-based integrated management of Plutella xylostella (Linnaeus) (Lepidoptera: Plutellidae) in South Africa*. PhD thesis, University of Pretoria, Pretoria

Nofemela, R.S., and Mosiane, S.M. (2011). The secretive cabbage pest. *Plant Protection News*, **90**: 6

Nofemela, R.S. (2010). The ability of synthetic sex pheromone traps to forecast *Plutella xylostella* infestations depends on survival of immature stages. *Entomologia Experimentalis et Applicata*, **136**: 281-289.

Nofemela, R.S., and Kfir, R. (2008). Pest status of Diamondback moth and the role of *Cotesia plutellae* in suppressing the pest population in South Africa. pp. 239-249. In: Shelton, A.M., Collins, H.L., Youjun, Z., and Qingjun, W. (Eds.) *The Management of Diamondback Moth and Other Crucifier Pests*: proceeding of the fifth international workshop, 24-27 October 2006, China agricultural science and technology press, Beijing, China,

Nofemela, R.S., and Kfir, R. (2005). The role of parasitoids in suppressing diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), populations on unsprayed cabbage in the North West Province of South Africa. *African Entomology*, **13**: 71–83.

Nofemela, R.S. (2004). *Studies on Parasitoids of the Diamondback Moth, Plutella xylostella (L.) (Lepidoptera: Plutellidae), in South Africa*. MSc thesis, Rhodes University, Grahamstown.

Oishi, M., and Sato, H. (2008). Guild structure and coexistence mechanisms in the parasitoid assemblage associated with a leafminer, *Coptotriche japoniella* (Lepidoptera: Tischeriidae), on an evergreen tree, *Eurya japonica* (Theaceae). *Environmental Entomology*, **37**: 1231-1240.

Ooi, P.A.C. (1992). Role of parasitoids in managing diamondback moth in the Cameron Highlands, Malaysia, pp. 225-262. In: Talekar, N.S. (Ed.) *Diamondback moth and other crucifer pests*: proceedings of the second international workshop. AVRDC–The World Vegetable Centre, Tainan, Taiwan, publication no. 92-368.

Poelking, A. (1986). Diamondback moth in the Philippines and its control with *Diadegma semiclausum*. pp. 271-278. In: Talekar, N.S., and Griggs, T.D. (Eds.) *Diamondback Moth Management*: proceedings of the first international workshop, 11–15 March 1985, Asian Vegetable Research and Development Center, Tainan, Taiwan.

Price, P.W. (1972). Parasitoids utilizing the same host: adaptive nature of differences in size and form. *Ecology*, **53**: 190-195.

Rabindra, R.J., Justin, C.G.L., and Jayaraj, S. (1995). Relative susceptibility of two larval populations of diamondback moth *(Plutella xylostella*) to insecticides and *Bacillus thuringiensis*. *Indian Journal of Agricultural Science*, **65**: 152–153.

Renuka, S., and Regupathy, A. (1996). Monitoring of insecticide resistance in diamondback moth *Plutella xylostella* (Linnaeus) in Tamil Nadu. *Journal of Pesticide Research*, **8**: 168–171.

Sarfraz, M., Keddie, B.A., and Dosdall, L.M. (2005). Biological control of the diamondback moth, *Plutella xylostella*: a review. *Biocontrol Science and Technology*, **15**: 763-789.

Sarfraz, M., and Keddie, B.A. (2005). Conserving the efficacy of insecticides against *Plutella xylostella* (L.) (Lepidoptera: Plutellidae). *Journal of Applied Entomology*, **129**: 149-157.

Sarfraz, M., Dosdall, L.M., and Keddie, B.A. (2007). Resistance of some cultivated *Brassicaceae* to infestations by *Plutella xylostella* (Lepidoptera: Plutellidae). *Journal of Economic Entomology*, **100**: 215–224.

Sastrosiswojo, S., and Sastrodihardjo, S. (1986). Status of biological control of diamondback moth by introduction of parasitoid *Diadegma eucerophaga* in Indonesia. pp. 185–194. In: Talekar, N.S., and Griggs, T.D. (Eds.) *Diamondback Moth Management*: proceedings of the first international workshop, 11–15 March 1985, Asian Vegetable Research and Development Center, Tainan, Taiwan.

Saxena, J.C., Rai, S.T., Srivastava, K.N., and Sinha, S.R. (1989). Resistance in the field population of the diamondback moth to some commonly used synthetic pyrethroids. *Indian Journal Entomology*, **51**: 265–268.

Sereda, B., Basson, N.C.J., and Marais, P. (1997). Bioassay of insecticide resistance in *Plutella xylostella* (L.) in South Africa. *African Plant Protection*, **3**: 67–72.

Shi, Z.H., Guo, S.J., Lin, W.C., and Liu, S.S. (2013). Evaluation of selective toxicity of five pesticides against *Plutella xylostella* (Lep: Plutellidae) and their side-effects against *Cotesia plutellae* (Hym.: Braconidae) and *Oomyzus sokolowskii* (Hym: Eulophidae). *Pest Management Science*, **60**: 1213-1219.

Singh, J., Upadhyay, A.K., Bahadur, A., Singh, B., Singh, K.P., and Rai, M. (2006). Antioxidant phytochemicals in cabbage (*Brassica oleracea L. var. capitata*). *Scientia Horticulturae,* **108**: 233-237.

Smith, T.J. (2004). *The Diamondback Moth Plutella xylostella (L.) (Lepidoptera: Plutellidae) and its Biological Control in the Eastern Cape Province, South Africa*. PhD Dissertation, Rhodes University, Grahamstown, South Africa.

Snyder, W.E., Finke, D.L., and Straub, C.S. (2006). Predator diversity strengthens herbivore suppression. *Ecology Letters*, **9**: 789–796.

Statistica (2013). Statistica 11 for windows. Statistica Enterprise System Technology, Tulsa, OK, USA.

Straub, C.S., Finke, D.L., and Snyder, W.E. (2008). Are the conservation of natural enemy biodiversity and biological control compatible goals? *Biological Control*, **45**: 225–237.

Talekar, N.S., and Shelton, A.M. (1993). Biology, ecology, and management of the diamondback moth. *Annual Review of Entomology*, **38**: 275–301.

Talekar, N.S., Yang, J.C., and Lee, S.T. (1986). Introduction of *Diadegma semiclausum* to control diamondback moth. pp. 263-270. In: Talekar, N.S., and Griggs, T.D. (Eds.) *Diamondback Moth Management*: proceedings of the first international workshop, 11–15 March 1985, Asian Vegetable Research and Development Center, Tainan, Taiwan.

Torres, J.B., and Ruberson, J.R. (2007). Abundance and diversity of ground-dwelling arthropods of pest management importance in commercial Bt and non-Bt cotton fields. *Annals of Applied Biology*, **150**: 27-39.

Trumble, J.T. (1998). IPM: overcoming conflicts in adoption. *Integrated Pest Management Review*, **3**: 195-207.

Ullyett, G.C., (1947). Mortality factors in populations of *Plutella maculipennis* Curtis (Tinedae: Lepidoptera), and their relation to the problem of control. Department of Agriculture and Forestry, Union of South Africa, *Entomology Memoirs*, **2**: 77–202.

Upanisakorn, A., Jeerapong, L., Ketelaar, J.W., and Lim, G.S. (2011). Diversity and abundance of diamondback moth in north Thailand. pp. 97-102. In: Srinivasan, R., Shelton, A.M., and Collins, H.L. (Eds.) *Management of Diamondback Moth and Other Crucifer Insect Pests*: proceedings of the sixth international workshop. AVRDC–The World Vegetable Centre, Tainan, Taiwan, publication no. 11-755.

Van Alphen, J.J.M., and Jervis, M.A. (1996). Foraging behaviour. In: Jervis, M.A. and Kidd, N. (Eds.) *Insect Natural Enemies- practical approaches to their study and evaluation*. Chapman and Hall, London pp. 1-62.

Van Driesche, R.G. (1983). The meaning of percent parasitism in studies of insect parasitoids. *Environmental Entomology*, **12**: 1611–1622.

Van Driesche, R.G., Bellows, T.S., Elkinton, J.S., Gould, J.R., and Ferro, D.N. (1991). The meaning of percentage parasitism revisited: solutions to the problem of accurately estimating total losses from parasitism. *Environmental Entomology*, **20**: 1–7.

Vickers, R.A., Pell, J.K., White, A., and Furlong, M.J. (2004). Proof of concept trials for control of DBM by Auto dissemination. pp. 289–294. In: Endersby, N., and Ridland, P.M. (Eds.) *The Management of Diamondback Moth and Other Crucifer Pests*: proceedings of the fourth international workshop, 26–29 November 2001, Melbourne, Australia.

Vinson, S.B. (1984). Parasitoid-host relationships. pp. 205–233. In: Bell, W.J., and Cardé, R.T. *Chemical Ecology of Insects*, Chapman, & Hall, New York.

Waage, J.K., Hassell, M.P., and Godfray, H.C.J. (1985). The dynamics of pest-parasitoid-insecticide interactions. *Journal of Applied Ecology*, **22**: 825-838.

Waladde, S.M., Leutle, M.F., and Villet, M.H. (2001). Parasitism of *Plutella xylostella* (Lepidoptera: Plutellidae): Field and Laboratory Observations. *South African Journal of Plant and Soil*, **18**: 32-37.

Walker, M.P., Liston, C., Hobson, A.J., and Stickgold, R. (2002). Cognitive flexibility across the sleep-wake cycle: REM-sleep enhancement of anagram problem solving. *Cognitive Brain Research*, **14**: 317-324.

Weinzierl, R.A. 2009. Integrating pesticides with biotic and biological control for arthropod pest management. pp. 179-191. In: Radcliffe, E.B., Hutchison, W.D., and Cancelado, R.E. (Eds.) *Integrated Pest Management*: concepts, tactics, strategies and case studies. Cambridge University Press, Cambridge, U.K.

Wilby, A., Villareal, S.C., Lan, L.P., Heong, K.L., and Thomas, M.B. (2005). Functional benefits of predator species diversity depend on prey identity. *Ecological Entomology*, **30**: 497–501.

Wu, G., Miyata, T., Kang, C.Y., and Xie, L.H. (2007). Insecticide toxicity and synergism by enzyme inhibitors in 18 species of pest insect and natural enemies in crucifer vegetable crops. *Pest Management Science*, **63**: 500-510.

Zalucki, M.P., Shabir, A., Silva, R., Adamson, D., Liu, S.S., and Furlong, M.J. (2012). Estimating the economic cost of one of the world's major insect pests, *Plutella xylostella:* just how long is the piece of the string. *Journal of Economic Entomology*, **105**: 1115-1129.

Zalucki, M.P., Adamson, D., and Furlong, M.J. (2009). The future of IPM: whither or wither? *Australian Journal of Entomology*, **48**: 85-96.

Zhao, J.Z., Collins, H.L., Li, Y.X., Mau, R.F.L., Thompson, G.D., Boykin, R., Hertlein, M., Andaloro, J.T., and Shelton, A.M. (2006). Monitoring of diamondback moth (Lepidoptera: Plutellidae) resistance to spinosad, indoxacarb and emamectin benzoate. *Journal of Economic Entomology*, **99**: 176- 181.