Available online at http://ajol.info/index.php/ijbcs

Int. J. Biol. Chem. Sci. 4(4): 1062-1082, August 2010

International Journal of Biological and Chemical Sciences

ISSN 1991-8631

Original Paper

http://indexmedicus.afro.who.int

Population dynamics of the diamondback moth *Plutella xylostella* L. (Lepidoptera: Yponomeutidae) in the Sydney Region of Australia

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ABSTRACT

The population dynamics of the diamondback moth (DBM), *Plutella xylostella* L. (Lepidoptera: Yponomeutidae) was investigated at three farms on the Western side of the Sydney Basin, Australia, from November 2003 to October 2004. Adult populations were monitored fortnightly by counting the number that was trapped on yellow sticky traps, which peaked around November to December (summer) in all three farms, with virtually no trap catches in the winter months (June-August). The seasonal trend of adult DBM showed a higher number per trap in summer, ranging from 34.5-41.7 compared with the other seasons. Larval and pupal densities were highest in summer (2.0-4.0 and 3.3-5.1 per plant, respectively), while the lowest numbers were recorded in winter. Rainfall had a significant impact on the DBM populations. The activity (numbers and parasitism) of the DBM parasitoid *Diadegma semiclausum* Héllen (Hymenoptera: Ichneumonidae) was recorded in all three farms, with the population showing a synchrony with that of the DBM. The highest number of parasitoids per trap (36.8-53.8) was recorded in summer compared with the other seasons. Parasitism was highest in the non-sprayed farm (56.3%) in summer compared with 16.4% and 31.5% in the other farms which have been sprayed with insecnticides. Canonical correspondence analysis showed environmental variables accounting for 11.2% of the variability in the insect data, out of which 83.9% was explained along the first canonical axis.

Keywords: Diamondback moth, *Plutella xylostella, Diadegma semiclausum,* parasitism, brassica

INTRODUCTION

In Australia, cole crops are produced in all states. According to FAOSTAT (2010) figures, over 78,000 tonnes of broccoli and cauliflower, and over 80,000 tonnes of cabbage were produced in Australia in 2008 and either sold to the domestic market or exported. Large scale production is however constrained by infestation of insects, particularly the diamondback moth (DBM), *Plutella xylostella* L. (Lepidoptera: Yponomeutidae).

The DBM is a cosmopolitan pest of crucifers (Talekar and Shelton, 1993). Damage is caused by all the four instar-larval stages which feed on the foliage at every stage of plant growth. It also feeds on the heads and florets of broccoli and cauliflower, pupating in them making the produce unmarketable. Heavy infestation may result in complete crop failure.

The control of DBM has largely depended on the use of synthetic insecticides to which the insect has now developed resistance (Wright et al., 1995). Resistance to *Bacillus thuringiensis* (Bt) Berliner based biopesticides (Talekar et al., 1985; Tabashnik et al., 1990; Talekar et al., 1990; Shelton et al., 1993) and insect growth regulators (IGRs) (Perng et al., 1988) have been reported. In the Sydney region of Australia, resistance to indoxacarb, some organophates and synthetic pyrethroids has also been reported (Eziah et al., 2008)

Recent ecological concerns about the effect of insecticides have spurred renewed interest in the search for alternative pest management practices that are ecologically friendly and sustainable. Effective pest management strategies call for knowledge of all factors that are inimical to the survival of pests. The DBM is affected by factors such as natural enemies (Morallo et al., 1996; Sastrosiswojo and Grey, 1996; Furlong et al., 2004) temperature and rainfall (Harcourt 1963; Talekar and Lee, 1985) but in the Sydney region there is limited information on these factors and how they affect the DBM. Understanding the population dynamics is central to the development of an integrated management strategy for control of the pest (Verkek and Wright, 1996).

Diadegma semiclausum is a specialist endoparasitoid of DBM larvae (Gauld, 1984; Wang and Keller, 2002). Introduced in the 1940s into New Zealand and Australia, it is now the dominant parasitoid of DBM in these two countries (Waterhouse and Norris, 1987). Despite its importance, very little is known about its role in regulating DBM populations in the Sydney region. In September 2003, we made a preliminary survey of farms in parts of the Sydney region and observed that *D. semiclausum* was prevalent in the area.

Iga (1985) reported that seasonal fluctuation of DBM populations depended mainly on the action of natural enemies. Guilloux et al. (2003) have also reported that precipitation severely affected survival of early instar stages of the DBM. Extreme temperatures have also been shown to adversely affect both the DBM and *D. semiclausum* (Wakisaka et al., 1991). This study investigated the dynamics of DBM populations in the field as well as its association with temperature, rainfall, relative humidity and natural enemies (particularly *D. semiclausum*) from November 2003 to October 2004.

MATERIALS AND METHODS

Sampling sites and farming practices

Three sites were selected for this work. Two commercial farms established at Castlereagh Road (CrC) (33° 40′ 22″S, 150° 40′ 34″E) and Yaramundi Lane, Yaramundi (YaC) (33° 35′ 40″S, 150° 43′ 14″E) (approx. 5 km apart) at the western side of the Sydney Basin, and a succession of cabbage crops maintained at Darlington (DaC) campus of the University of Sydney (33° 53′ 29″S, 151° 11′ 28″E), at least 50 km in the south eastern direction from the first two sites (Figure 1).

At CrC, the farmer produced cabbages and cauliflowers all year round. The farmer at YaC has been in production for over 7 years growing cabbages and cauliflowers among other vegetables all year round. These farms are over 4 acres large but the area used for the study was limited to 1 acre. Insect pests were controlled in these farms using conventional insecticides such Fipronil®, Indoxacarb, Regent®, spinosad®. The DaC site was an unsprayed field of cabbages, cropped all year round.

Abundance of adult DBM

The population of adult DBM was monitored from November 2003 to October 2004 at the three farms described above, using yellow sticky traps (Bugs for Bugs®, Mundubbera, Queensland). Ten yellow sticky traps were installed at approximately 10 m apart and about a metre high from the ground, in the cabbage farms to trap the adult insects. The traps were removed every 14 days and replaced with new ones. They were taken to the entomology laboratory of The University of Sydney where all trapped DBM were counted. *Diadegma semiclausum* that had been trapped were also identified, counted, and their numbers recorded. In the commercial farms, the traps were removed to new sites whenever the crops were harvested.

Determination of population densities of DBM larvae and pupae

The population densities of DBM larvae and pupae were monitored for 1 year. Twenty plants were randomly examined at each visit, and with the exception of the first instar stages, all other immature stages (larvae, pupae and cocoons) found were collected and taken to the laboratory for the total number per plant to be assessed.

Determination of DBM larval/pupal parasitism

The immature DBM stages collected were individually isolated in 70 ml ventilated cylindrical plastic containers at 23 ± 2°C and 24 h light until DBM and/or parasitoid emergence. The larvae were fed with fresh insecticide-free cabbage (cv. coronet) leaves. Since the parasitoids emerged at the pupal stage, DBM larvae and pupae were pooled to calculate percentage parasitism on a fortnightly basis (ie each visit). The parasitoids that emerged were identified and the percentage parasitism calculated by conventional approach. Parasitism was calculated as total number of parasitoid(s) / total number of viable larvae and pupae x 100. The DBM larvae and pupae that died of unknown causes were not included in this calculation. The presence or absence of generalist predators in these farms was noted but their numbers were not recorded.

Climatic data

Weather data on rainfall, relative humidity and temperature during the survey period were obtained from the Richmond Royal Australian Air Force (RAAF) (for sites CrC and YaC), and the Sydney Observatory Hill (for site DaC) weather stations.

Presentation and analysis of data

Analyzable data were square root transformed, while percentage parasitism data were arcsine transformed and analyzed using two-way analysis of variance (ANOVA). The means were separated using least significant difference (LSD). For the purposes of analysis, seasons were defined as follows; summer (late November to February), autumn (March to May), winter (June to August) and spring [September to October (when the survey ended)]. To determine the association between environmental variables (total fortnightly rainfall, mean fortnightly maximum temperature, and mean maximum relative humidity) and the various stages of the pest (larvae, pupae and adults) and the parasitoid, *D. semiclausum*, direct canonical correspondence analysis (CCA) (CANOCO version 4.5, ter Braak & Smilauer, 2002) was conducted, using the farms and Julian date as covariables. Farms were presented as a dummy variable. The CCA was followed by Monte Carlo permutation tests on all canonical axes to determine the significance of variation in the species data that was explained by the environmental variables (ter Braak and Smilauer, 2002).

RESULTS

Abundance of adult DBM and *D. semiclausum*

The populations of adult DBM and *D. semiclausum* followed similar patterns in all the three farms (Figure 2). At YaC (Figure 2A) the adult DBM population increased from the first week of November 2003 to a peak in the first week of December 2003 (late spring to summer). After that, the population dropped in mid December 2003, and remained low till the end of April 2004 (mid-autumn). No adults were trapped between May and August 2004 (winter).

At CrC (Figure 2B), the population of adult DBM fluctuated between November and December 2003 with a peak in the first week of December, which fell in the latter part of the same month. The population remained very low until March 2004. In April 2004 however, a few adults were trapped. Between May and August 2004, no adult DBM were recorded in the traps.

The adult DBM population peaked in the third week of November 2003 at DaC and then fell sharply (Figure 2C). The DBM population remained low between January and the end of February 2004, and increased thereafter, with a minor peak in the second week of April before declining to zero after May through to August 2004.

There was a synchrony between adult DBM and *D. semiclausum* populations at the three farms, with *D. semiclausum* populations generally lagging two weeks behind those of the DBM (Figures 2A-C). The population of *D. semiclausum* from YaC (Figure 2A) increased from November 2003 and peaked in the third week of the same month. The population then fell and fluctuated between the first week of December 2003 and March 2004. No trap catches were made from the second week of May to the first week of September.

At CrC, the parasitoid population increased from the first week of November 2003 and peaked in the third week of the same month (Figure 2B). The population then declined in the first week of December 2003 and continued to fall gradually until after the third week of April 2004.

The trend at DaC was similar to the other two locations (Figure 2C), with the population increasing from November to a peak in mid December 2003. It then fell sharply to the end of January 2004 and remained very low till the third week of April 2004, when a minor peak occurred. Between May and September 2004, no trap catches were made.

Seasonal trends in abundance of adult DBM and *D. semiclausum*

Significantly ($P < 0.05$) more adult DBM were collected per trap in summer than the rest of the seasons at the three locations (Figure 3A). The DaC location recorded the highest number of adult DBM per trap (41.7) in summer although this was not significantly different from those recorded at CrC (36.2) or YaC (34.5) (Figure 3A). The lowest number of adult DBM per trap was recorded in the winter months with values ranging from 0.0 (CrC) to 1.5 (YaC) per trap. In spring, significantly ($P < 0.05$) higher numbers of adult DBM per trap were recorded at all the three locations than those in winter. Season and site had no significant interactive effect on the DBM populations (Figure 3A).

Similarly, site and season showed significant differences ($P < 0.05$) in numbers of *D. semiclausum* per trap, while the interactive effect of these two factors did not. Significantly ($P < 0.05$) higher numbers of *D. semiclausum* per trap were recorded in summer at the three locations (Figure 3B). At DaC, a mean of 53.1 *D. semiclausum* per trap was recorded and this dropped to 0.2 in winter. At CrC and YaC, mean values of 36.8 and 53.8 *D. semiclausum* per trap were recorded in summer, respectively. The trap catches at these two locations in autumn and spring were not significantly different from each other but were higher compared to winter where no *D. semiclausum* was caught (Figure 3B).

Abundance of DBM larvae and pupae

Generally the population of the immature stages was low (Figure 4). The larval abundance at DaC was higher than those of the other two locations at the commencement of the study (Figure 4A). However, from December 2003 to June 2004, generally more larvae were recorded at CrC and YaC compared to DaC. At DaC, five peaks were observed in November 2003, April, June, August and September. The larval population was low from January to February and May to July. The larval population at CrC was highest with four peaks occurring in December 2003, January, April, and May 2004. No larvae were recorded between July and September at this site. The pattern of larval population at YaC was similar to that at CrC. Four peaks were observed: in December 2003, April, June and August 2004.

Three major peaks in pupal population were observed at DaC (Figure 4B). These occurred in Dec 2003, April and October 2004. At CrC, the first major peak occurred in January 2004 and then fluctuated between April and June before declining to zero in July to August. The pupal population at YaC showed one major peak in April 2004.

Seasonal trends in abundance of DBM larvae and pupae

The number of DBM larvae per plant at the three locations was significantly ($P < 0.05$) higher in summer compared to the other seasons (Figure 5A). In summer, the number of larvae per plant ranged from a mean of 2.0 (YaC) to 4.0 (CrC). The lowest numbers were collected in winter (from 0.7-1.6 larvae/plant). In general, the number of larvae per plant declined from summer to winter at all three locations. At DaC the number of larvae/plant in autumn and spring were not significantly different from one another but at the other two locations significantly ($P < 0.05$) higher numbers/plant were collected in autumn compared to spring, which explains the significant site and season interaction (Figure 5A). The pupal density followed a pattern similar to that of the larvae. Significantly ($P < 0.05$) higher numbers of pupae/plant were collected in summer (Figure 5B) at all three locations. In summer, mean numbers of 3.3, 3.2 and 5.1 pupae/plant were collected at DaC, YaC and CrC, respectively. Again, the lowest numbers per plant were collected in winter at all three locations and were significantly lower than those collected in autumn and spring at the respective locations (Figure 5B). There was also a significant interactive effect between season and site.

Climatic conditions at the sites during the survey

Total fortnightly rainfall at CrC and YaC were highest in summer with a maximum of 135.2 mm recorded in early December 2003 (Figures 2 A and B). In autumn, fairly high rainfall was recorded with a maximum of 39 mm in mid to late April 2004. Rainfall was very low (< 25 mm in June) in winter, but was quite high in spring (150-175 mm in September and October). The mean minimum and maximum temperatures increased from between 10.2 and 25.9 °C in November 2003 to a maximum of between 18.9 and 32.8 °C in February. The temperatures then dropped to 2.3 and 17.4 °C in mid-winter 2004 before rising to 11.9 and 25.3 °C in mid-spring (Table 1).

There was considerable rainfall at DaC during the period of the survey (Figure 2C). The heaviest rainfall was recorded in the first week of December 2003 with a total fortnightly value of 102.8 mm followed by 44.8 mm in the third week of the same month. From the last week of January to the first week of April 2004, total fortnightly figures ranged from 23.5-95.8 mm. There was little rain from late April to late August, with the exception of 36.6 mm recording in mid June 2004. Rainfall in spring 2004 was also quite high. Mean fortnightly minimum and maximum temperatures rose from between 12.5 and 23.3 °C in early November 2003 to between 17.6 and 29.0 °C in mid-February 2004, and dropped to 8.3 and 17.1 °C in late July before rising to 15.4 °C and 24.3 °C in late October (Table 2).

The mean maximum and minimum relative humidity at the three sites followed a similar pattern and did not vary much. The maximum values at the sites varied between 51% and 85%, while minimum values ranged from 21%-65% (Tables 1 and 2).

The Monte Carlo test of all canonical axes showed a significant trend (P = 0.002, F = 4.125, 499 permutations under reduced model) between the adult DBM, its immature stages, *D. semiclausum*, and environmental variables. The covariables (farms and Julian date) explained 31.7% of the total variability in the insect data. After fitting the covariables, the environmental variables (rainfall, maximum temperature, and maximum relative humidity) explained 11.2% of the variability in the data. Out of this variability, 83.9% was explained along the first canonical axis. The first two canonical axes (1^{st} and 2^{nd}) usually explain the largest proportion of the variance in the data and numbers are representational only. The presence of adult DBM was negatively associated with rainfall and maximum temperature (Figure 6), while those of the larvae and pupae were positively associated with relative humidity. Surprisingly, the presence of *D. semiclausum* was positively associated with rainfall.

Determination of larval/pupal parasitism

The percentage parasitism of DBM larvae/pupae was estimated from the number of parasitoid(s) bred from the immature stages. Two parasitoid species were encountered during the survey. They were *Cotesia plutellae* Kurdjumov (Hymenoptera: Braconidae) and *D. semiclausum*. *Cotesia plutellae* was rarely present in the three fields. *Diadegma semiclausum* was the dominant species present and the levels of parasitism are presented (Table 3).

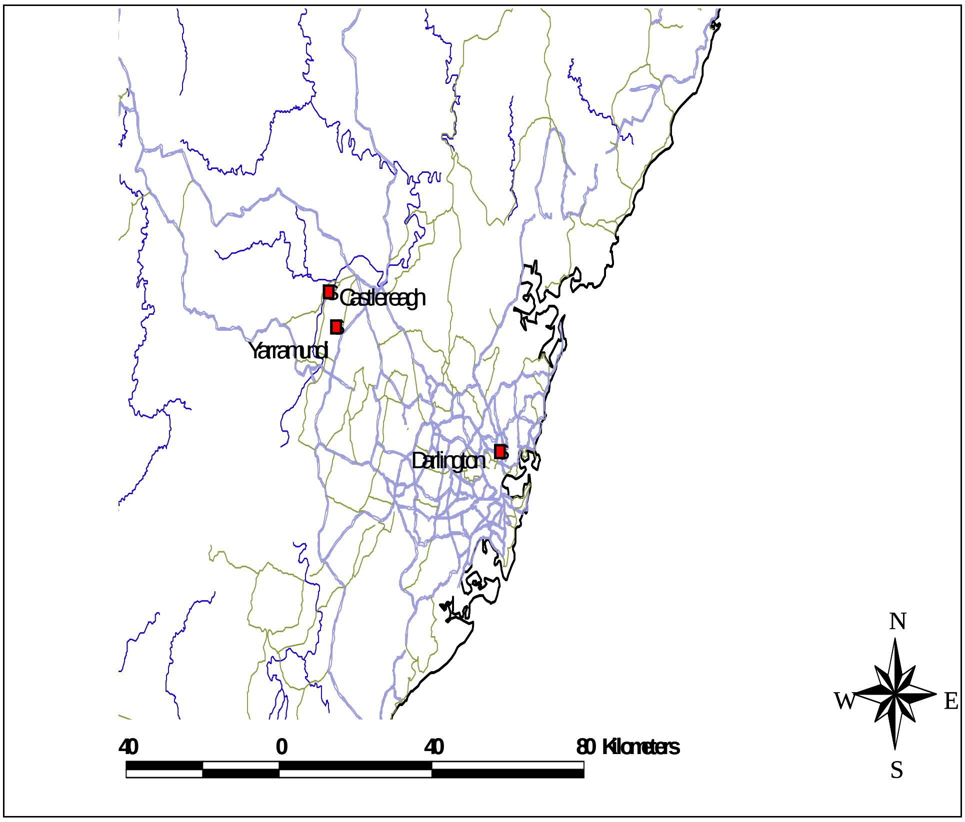

Figure 1: Location of cooperating brassica growers in the Sydney region of NSW.

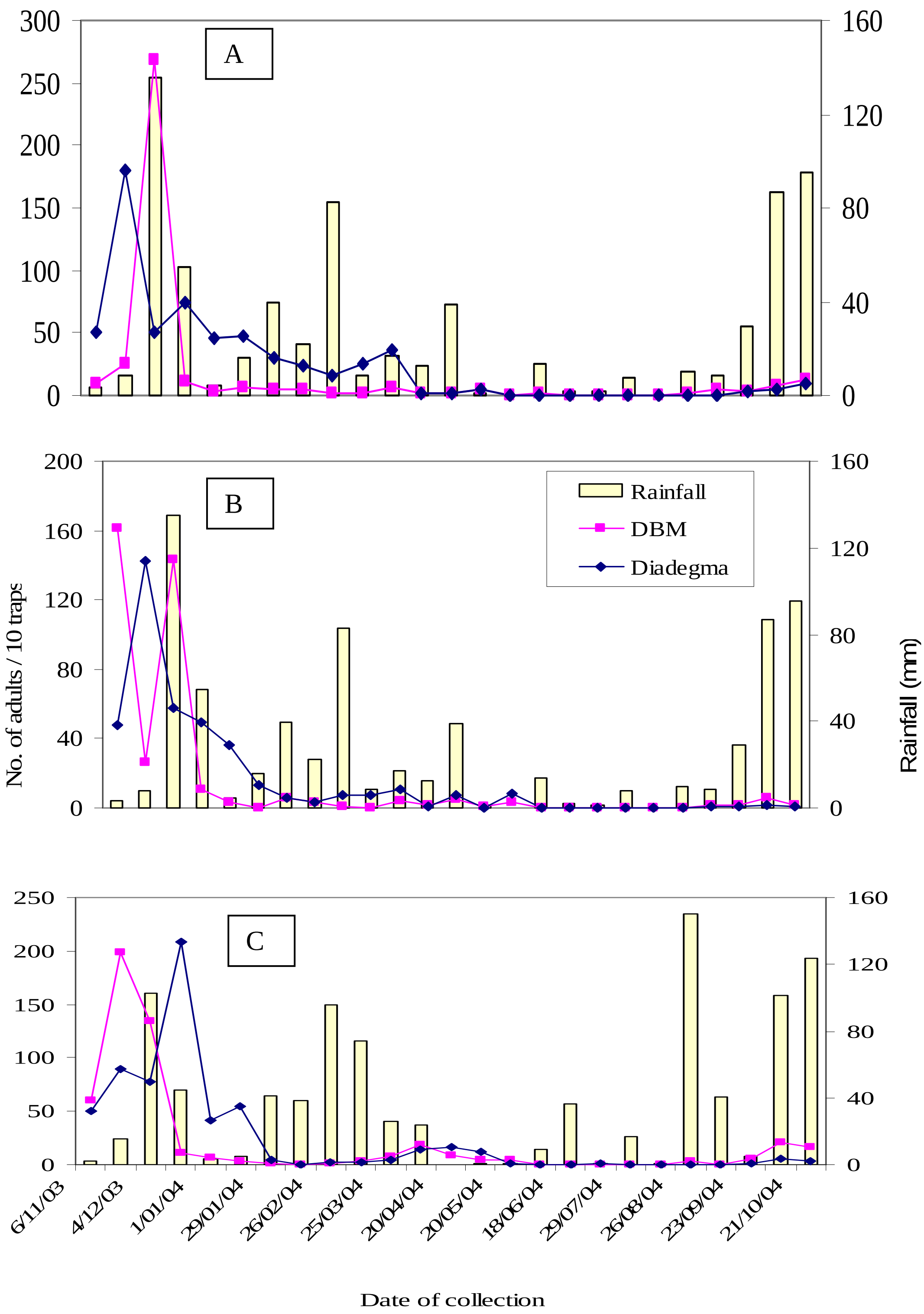

Figure 2: Abundance of adult DBM and *D. semiclausum*, ,and fortnightly rainfall from the three sampling sites. A = YaC (Yaramundi) B = CrC (Castlereigh) and C = DaC. (Darlington).

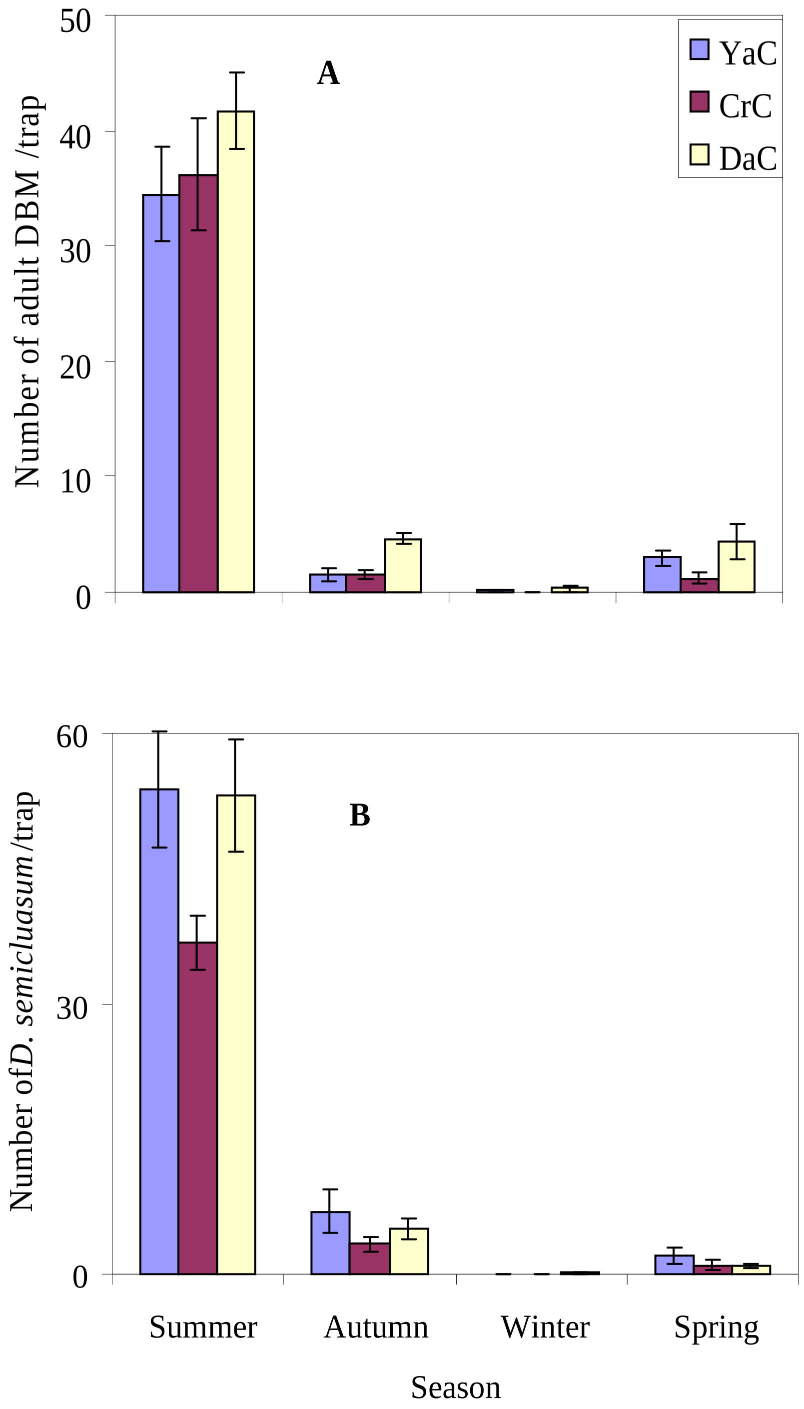

Figure 3: Mean (±SE) population abundance of insects collected from the three locations across the seasons. A = adult DBM, and B = *D. semiclausum*. The bars represent the standard errors of the means.

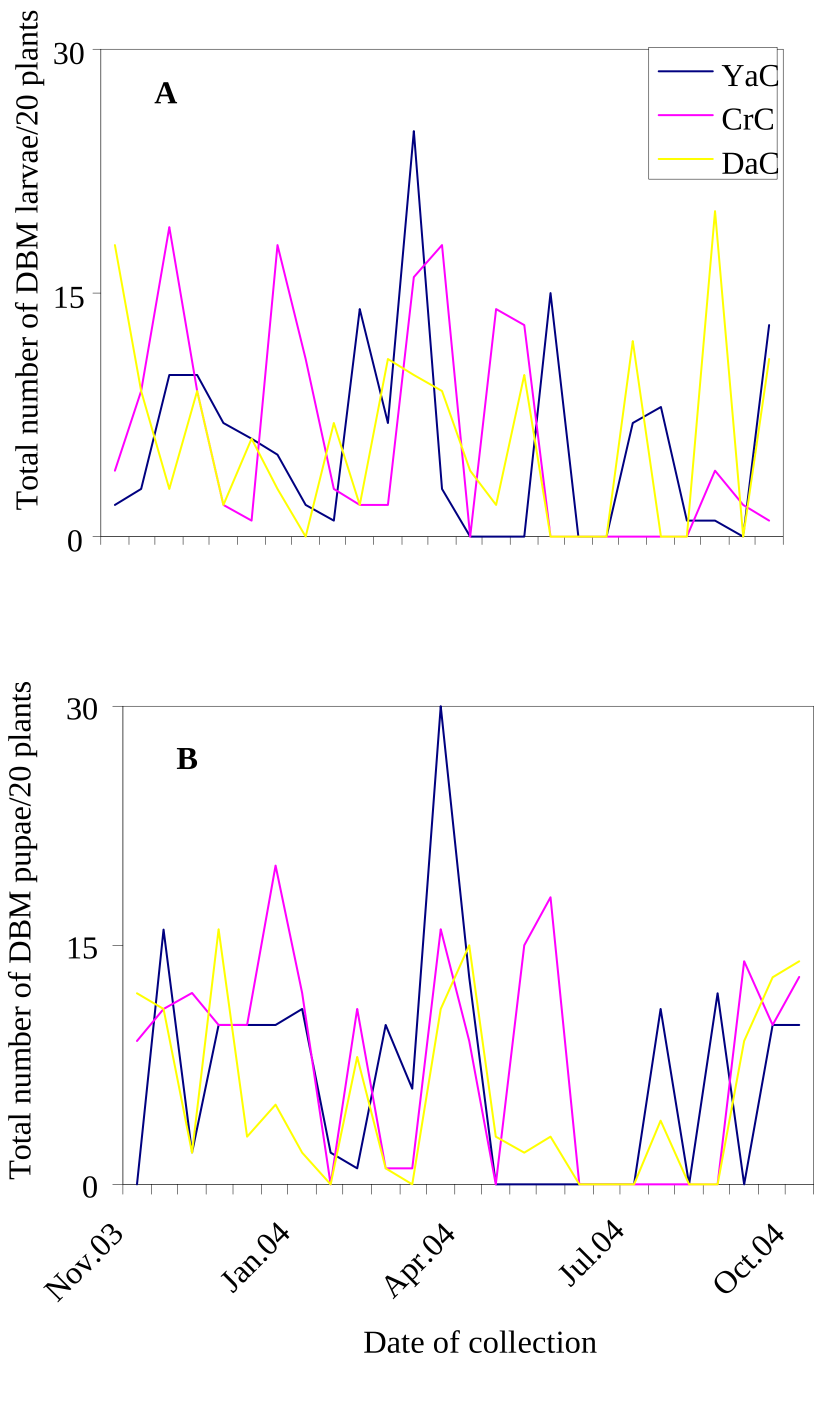

Figure 4: Abundance of DBM larvae (A) and pupae (B) at the three locations.
Nov–Feb, summer; Mar-May, autumn; June-Aug, winter; Sept-Oct, spring.

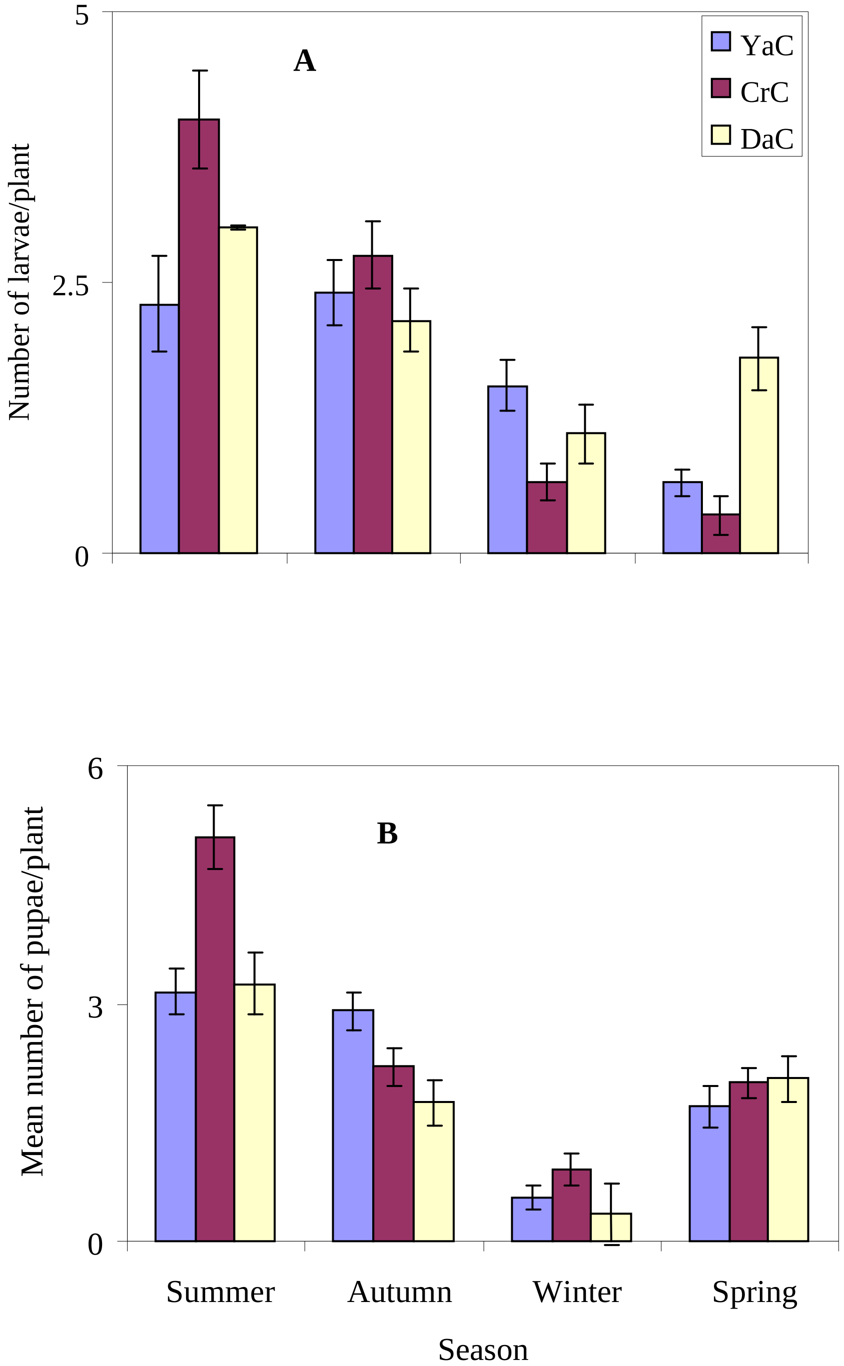

Figure 5: Mean (±SE) population abundance of insects collected from the three locations across the seasons. A= DBM larvae, and B = pupae. The bars represent the standard errors of the means.

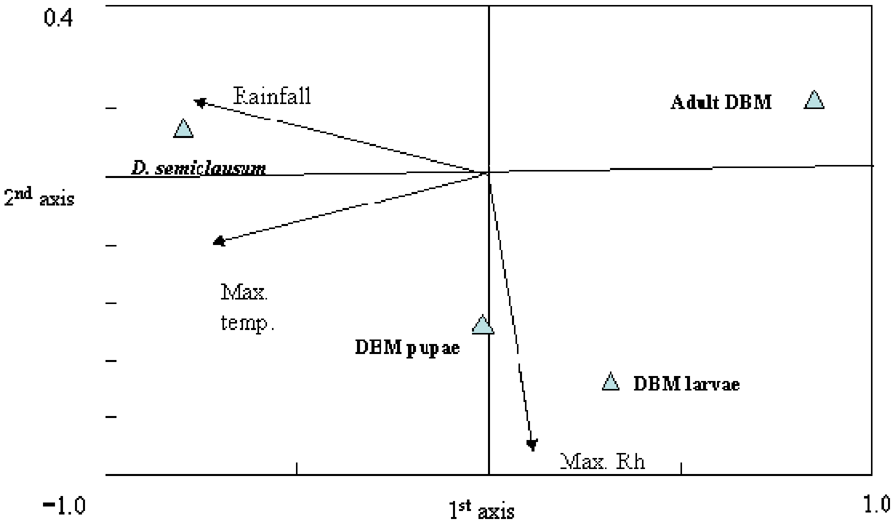

Figure 6: Ordination diagram of the first two axes of canonical correspondence analysis (CCA) for DBM and its immature stages, *D. semiclausum*, and three environmental variables: rainfall, maximum temperature and relative humidity. Julian date and farms comprised the covariables.

Table 1: Mean fortnightly maximum and minimum temperature, and relative humidity recorded at Richmond RAAF weather station for sites CrC (Castlereigh) and YaC (Yaramundi).

Date	Temperature		Relative humidity	
	Maximum	**Minimum**	**Maximum**	**minimum**
06-Nov 03	25.9	10.2	53.5	30.5
20-Nov. 03	27.6	12.8	61.2	37.9
04-Dec. 03	24.8	14.3	75.6	57.6
18-Dec. 03	26.3	16.3	71	41
01-Jan. 04	30.2	18.2	67.9	45.1
15-Jan. 04	32.4	18.9	64.1	39.8
29-Jan. 04	30.3	17.6	77.6	48.6
12-Feb. 04	32.8	17.6	69.6	44.9
26-Feb. 04	30.4	18.9	71.9	53.9
11-Mar. 04	27.7	15.6	78.4	50.8
25-Mar. 04	26.2	15.9	82.7	54.3
08-Apr. 04	26.5	14.1	74.9	49.7
20-Apr. 04	26.4	11.4	79.1	42.6
06-May 04	23.4	7.7	61.6	37.1
20-May 04	22	5.2	69.5	35.6
04-Jun. 04	20.5	3.8	83.8	42.9
18-Jun. 04	20.1	3.3	77.1	39.8
01-Jul. 04	19.9	2.8	60.8	32.6
15-Jul. 04	17.4	3.2	76.8	43.3
29-Jul. 04	19	2.3	67.1	34.2
12-Aug. 04	20.9	5.5	67.3	37.3

26-Aug. 04	21.7	7.8	68.6	42
09-Sept. 04	24.1	6.1	53.2	27.9
23-Sept. 04	24.9	11.8	67.7	44.7
07-Oct. 04	25.3	11.9	54.3	42.4

Table 2: Mean fortnightly maximum and minimum temperature, and relative humidity recorded at Sydney Observatory Hill for the DaC (Darlington) site.

Date	Temperature		Relative humidity	
	Maximum	Minimum	Maximum	Minimum
06-Nov 03	23.3	12.5	51.5	49.5
20-Nov. 03	23.7	16.4	69.8	59.3
04-Dec. 03	23.1	16.1	79.7	68.5
18-Dec. 03	24.8	18.2	68.4	59.9
01-Jan. 04	27.2	19.7	72.5	55.5
15-Jan. 04	27.9	20.5	68.9	56
29-Jan. 04	27.4	19.9	71.8	60.7
12-Feb. 04	29	20.3	75	62.6
26-Feb. 04	26.9	20.7	74.9	65.5
11-Mar. 04	26.4	18.5	77.6	58.4
25-Mar. 04	25.8	18.6	77.4	59.2
08-Apr. 04	25.5	18.1	69.4	59.6
20-Apr. 04	24.9	16.2	76.6	60.2
06-May 04	22.9	13.4	64.4	44.6
20-May 04	21.5	11.4	63.9	46.2
04-Jun. 04	20.7	11	70.7	50.4
18-Jun. 04	19.9	11	67.7	47.3
01-Jul. 04	19.1	10	58.3	39.9
15-Jul. 04	17.1	8.3	72.6	54.9
29-Jul. 04	18.9	8.8	63.3	38.6
12-Aug. 04	19.5	10	71.8	52.2
26-Aug. 04	20.8	11.2	70.6	57.1
9-Sept. 04	22	11.5	56.1	47.7
23-Sept. 04	19.1	11.1	72.3	61.6
07-Oct. 04	24.3	15.4	57.1	52.9

Table 3: Mean fortnightly parasitism of DBM larvae/pupae by *D. semiclausum* from Nov. 2003 to Oct. 2004.

Location	Season			
	Summer	Autumn	Winter	Spring
CrC	31.50c	15.70b	10.30ab	0.00a
DaC	56.30c	25.50b	7.70a	19.30ab
YaC	16.40a	18.80a	11.10a	5.40a
Mean	34.70b	20.00ab	9.70a	8.30a

YaC (Yaramundi), CrC (Castlereigh), DaC (Darlington)

Parasitism by *D. semiclausum* was observed throughout the seasons, except in spring at CrC where parasitism was absent. Significantly ($P < 0.05$) higher parasitism was observed in summer at DaC and CrC compared to the other seasons (Table 3). The DaC site (non-sprayed) had the highest fortnightly parasitism of 56.3%. This fell to 25.5% in autumn and further declined to 7.7% in winter. Parasitism level at this site (DaC) was higher in spring compared to winter, but there was no significant difference between them (Table 3). At YaC, parasitism ranged from 5.4% (spring) to 16.4% (summer) but there was no significant difference between the seasons (Table 3).

In addition to these parasitoid species, some predators such as spiders, ladybird beetles and assassin bugs were observed in all farms, but their activities/numbers were not assessed. The spiders and ladybird beetles were most common at the DaC site.

DISCUSSION

The population trends of the DBM at all three sites followed a similar pattern. The peak activities of the moth observed in November to December 2003 were not unexpected as conditions at the time were favourable for the development of the insect. Maximum and minimum temperatures during the period ranged from 23-27 °C and 10-18 °C, respectively, while maximum and minimum relative humidity ranged from 51-75% and 37-59%, respectively. Very low adult, larval, and pupal populations were also recorded from June to August 2004. Although trap catches of adults may not necessarily provide direct information about the level of damage, they serve as a warning of field infestation and can be used to predict subsequent larval populations (Mosiane et al., 2003).

The Monte Carlo test also showed a significant trend between environmental variables and the DBM populations but the environmental variables explained only a small percentage (11.2%) of the observed variation. Temperature, food availability (Wang, 1984) and rainfall (Talekar and Lee, 1985) have been reported to influence the development of DBM. Fairly high temperatures (25-30 °C) and low wind speeds provide favourable conditions for oviposition (Harcourt, 1957). Development time from egg to adult decreases with increasing temperature (Sarnthoy et al., 1989; Abro et al., 1992). Extreme temperatures are inimical to the development of the DBM (Yamada and Kawasaki, 1983; Sarnthoy et al., 1989). Wakisaka et al. (1991) have reported significantly lower fecundity, delayed developmental period, and reduced adult DBM emergence at 33 °C, compared to temperatures between 25-30 °C where the biotic performance of the adult was high and showed no significant differences. In the current study, although maximum and minimum temperatures increased from about 23-30 °C and 10 °C-18 °C, respectively, from November 2003 to January 2004, this did not result in adult population increases. In fact, adult DBM population and those of the immature stages fell after peaks in December 2004.

Several factors might have accounted for this observation. The high rainfall in late November (102.8 mm) and early December 2003 (135.2 mm) may have affected the immature stages and hence affected trap catches in subsequent sampling periods. Larval densities in summer ranged from 2.3-4.0 per plant. It is therefore not surprising that the CCA showed a negative association between the DBM, temperature and rainfall.

Talekar et al. (1986) and Guilloux et al. (2003) report of heavy rainfall as one of the key mortality factors among all stages of the pest, especially the neonate larvae which are highly susceptible to drowning during rainfall. The larvae are easily disturbed by droplets of rain and wriggle into leaf axles or the ground where they get submerged in pools of water. Harcourt (1986) related larval mortality to the amount of rainfall. Wakisaka et al. (1991) reported that the washing off of eggs and young larvae from plants as a result of the direct impact of rainfall is the major mortality factor for the DBM eggs and larvae. Heavy rainfall also hinders flight and oviposition activity by the adult (Talekar and Lee, 1985). Overhead sprinkler irrigation has been used to reduce infestation by DBM (Talekar et al., 1986). Chen and Su (1986) observed that although high temperatures in summer limit food availability in time and space and DBM populations in Taiwan, they supported Talekar and Lee (1985) that rainfall was the major mortality factor accounting for the minimum DBM population level observed during that period. Thus it is likely that the high rainfall in early summer at the sites of the present study contributed significantly to the sharp drop in DBM population.

Also, food availability contributed to the presence of DBM during many periods of the year. Farmers at the two commercial farms cultivated cabbages and cauliflowers throughout the year and this provided a continuous source of food supply for the insects. Unfortunately, after the heads were harvested, the plants were left standing in the fields leading to the production of young shoots which served as breeding grounds for DBM. According to Wang (1984), the DBM is more serious on crops like cabbage, which requires up to 3 months per crop season as the pest is able to complete two to three generations. Food quality also affects both development and fecundity. Larvae reared on younger plants develop faster and their adults laid more eggs than those reared on matured leaves (Atwal, 1955).

One other major factor that has contributed to the incidence of DBM in the region is the high dependence on synthetic insecticides for its management. Most brassica farmers in NSW have depended on insecticides (organophosphates, synthetic pyrethroids, avatar®, Firponil®) at high frequencies (weekly applications) for the control of the insect pest complex that attacks their crops, and this has led to the resistance development of the DBM to these products (Eziah et al., 2008). Evidence of significant *D. semiclausum* activity was recorded at all sites. This activity was synchronous with that of the DBM. The CCA however suggested that *D. semiclausum* and the adult DBM responded differently to the environmental variables. While *D. semiclausum* was positively associated with rainfall and temperature, the adult DBM was negatively associated with these factors. This observation may be merely coincidental as the *D. semiclausum* population lagged behind that of the adult DBM and coincided with periods of high rainfall. Also, parasitism was high during summer 2004, and the DBM population never recovered.

The low temperatures recorded in winter (17-20 °C maximum and 2-11 °C minimum) probably contributed to the low pest numbers recorded during the period. Sarnthoy et al. (1989) have reported that the developmental thresholds of strains of Japanese and Thai DBM adults and their immature stages were at 8 °C and 9 °C, respectively. The optimal temperatures for parasitism by *D. semiclausum* ranged from 15-25 °C. Temperatures outside this range led to a sharp drop in parasitism (Talekar, 1991). Considering that minimal rainfall was recorded during the winter period, it appears that the low winter temperatures and natural enemies played an important role in keeping the pest populations low. The minimum winter temperatures seem to be detrimental to the development of both the DBM and the parasitoid, which resulted in a prolonged life cycle in overwintering individuals and thereby exposing them to other mortality factors leading to the low DBM numbers recorded during the period. Also, the decline in parasitism at the sites from summer through to winter in the present study was therefore not unexpected.

In the current study, parasitism was generally most prominent at the DaC site compared to the other two farms probably due to the absence of insecticide pressure. The use of synthetic insecticides in DBM control has been reported to result in adverse effects on its natural enemies (Mushtaque and Mohyuddin, 1987; Dennil and Pretorius, 1995; Haseeb and Amano, 2002).

Considering the abundance and high rates of parasitism by *D. semiclausum* in these farms, its role as a biocontrol agent against the DBM larvae cannot be overemphasized. Brotodjojo (1998) recorded *D. semiclausum* and *Apanteles ippeus* (Nixon) (Hymenoptera: Braconidae) as parasitoids of the DBM in brassica commercial farms at Windsor and Richmond, NSW, within 10 km of the CrC and YaC sites of the present study. In that study, *D. semiclausum* was dominant, causing an overall parasitism of about 14%. Although the author recorded five other parasitoid species, most of them contributed < 0.8% of the total parasitism suggesting that these species were rarely present in that area.

Furlong et al. (2004) have reported that *D. semiclausum* was the dominant parasitoid of the DBM in southeastern Queensland and that it had the potential of being a key mortality factor of DBM in the region. *D. semiclausum* has also been reported to be effective against DBM in other countries including Indonesia (Sastrosiswojo and Grey, 1996), Japan (Iga, 1997), Malaysia (Ooi, 1991), Taiwan (Talekar and Yang, 1991) and the Philippines (Poelking, 1991).

During the current survey, other mortality factors such as assassin bugs, spiders and ladybird beetles were observed in the farms. Although their role was not assessed, they could have fed on immature stages of the DBM. Furlong et al. (2004) recorded a number of predatory arthropods including Araneae, Coccinellidae and Chrysopidae in pitfall traps and crop foliage in brassica farms in southeastern Queensland, and stated that these species together with the endemic natural enemy complex caused significant mortality in the immature stages of the DBM. Grundy and Maelzer (2002) showed that the assassin bug, *Pristhesancus plagipennis* (Walker) (Heteroptera: Reduviidae) is a potential biological control agent against *Helicoverpa armigera* larvae. Dead larvae, probably due to pathogen infection, were also observed during the survey; hence it is possible that these species also contributed to keeping the DBM populations in check.

In summary, the DBM is present throughout the year in brassica-growing areas in the Sydney region with a higher population from late spring to early summer. Populations are low during the winter. *Diadegma semiclausum* is also prevalent in the region and causes high parasitism of DBM larvae and pupae especially in summer. High rainfall during the period of survey also had a significant impact on the populations of the DBM.

The current findings showed that farmers need to avoid cropping in the peak period as has been successfully done in India (Shashdhar et al., 1994). Also farmers ought to maintain farm sanitation in order to deprive the pest of alternative hosts particularly brassica species since the insects feed only on these plants (Ooi, 1991). In addition, reducing acreages of brassica vegetables by introducing cereals such as corn during the peak season of the pest (a practice the farmers in the studied areas have adopted) will undoubtedly reduce the incidence of the pest during this period. Furthermore, the fact that the pest population was low for most parts of the year particularly in winter, calls for a reasonable reduction in the frequency at which synthetic insecticides are used. This will enhance the survival of natural enemies.

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