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# Seasonal abundance of the parasitoid complex associated with the diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae) in Hangzhou, China

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## Abstract

An investigation of insect parasitoids of the diamondback moth, *Plutella xylostella* (Linnaeus), in brassica vegetable crops in the suburbs of Hangzhou was conducted during five periods from 1989 to 1997. Eight species of primary parasitoids were recorded: *Trichogramma chilonis* Ishii, *Cotesia plutellae* Kurdjumov, *Microplitis* sp., *Oomyzus sokolowskii* Kurdjumov, *Diadromus collaris* (Gravenhorst), *Itoplectis naranyae* (Ashmead), *Exochus* sp. and *Brachymeria excarinata* Gahan. Seven species of hyperparasitoids were also collected. Rates of parasitism of eggs of *P. xylostella* were usually very low. However, rates of parasitism of larvae and pupae were substantial and showed two peaks each year, around June–July and September–November respectively. Rates of parasitism during peaks were usually 10–60% and reached over 80% on a few occasions. *Cotesia plutellae, O. sokolowskii* and *D. collaris* were the major larval, larval-pupal and pupal parasitoids respectively. In the field, *C. plutellae* was active throughout the year. *Oomyzus sokolowskii* was active from May to October, entered a quiescent pupal stage in October–November to overwinter and did not emerge until next April–May. *Diadromus collaris* was recorded from April to July and October. Rates of parasitism of *P. xylostella* in radish and mustard fields were usually higher than those in cabbage and Chinese cabbage fields in the same locality. Negative correlations of parasitism rates between *C. plutellae* and *O. sokolowskii* indicate a competitive relationship for host larvae between these two larval parasitoids.

## Introduction

The diamondback moth, *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae), was a minor pest of brassica vegetable crops in China before 1960. Its pest status has increased rapidly since the early 1960s when large scale application of chemical insecticides was started in vegetable crops. During the last 30 years, this insect has become a major pest of brassica vegetable crops, especially in the Changjiang River Valley and Southern China (Shi & Liu, 1995; Zhao *et al.*, 1996; Liu & Yan, 1998). Similar to the situations observed in Southeast Asia and North America (Shelton & Wyman, 1992; Sun, 1992; Talekar & Shelton, 1993; Tabasknik, 1994; Iqbal *et al.*, 1996), the populations of *P. xylostella* in China have developed resistance to all groups of insecticides, including insect growth regulators and *Bacillus thuringiensis* Berliner (Tang *et al.*, 1992; Sun *et al.*, 1995; Feng *et al.*, 1996; Zhao *et al.*, 1996). Development and implementation of integrated pest management (IPM) systems are now considered to be the only solution to combat this highly resistant insect pest (Liu *et al.*, 1995; Zhao *et al.*, 1996; Liu &Yan, 1998).

During the past 20 years, development and implementation of biological control-based IPM has made

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remarkable achievements in the management of *P. xylostella* in many parts of the world including Southeast Asia (Ooi, 1992; Talekar *et al*., 1992; Talekar & Shelton, 1993; Biever *et al*., 1994). In these IPM systems, introduction and augmentation of insect parasitoids have played a key role.

On the mainland of China, preliminary surveys of insect parasitoids of *P. xylostella* have been conducted in Hubei (Lu, 1983), Guangzhou (Chen *et al*., 1987), Beijing (Wu *et al*., 1987) and Hangzhou (Ke & Fang, 1982). However, most of the parasitoids recorded have not been identified to species, and little is known about the impact of insect parasitoids on the populations of *P. xylostella*. As part of an effort to help develop biological control-based IPM of *P. xylostella* in the Changjiang River Valley, we conducted an investigation of insect parasitoids of *P. xylostella* in the brassica vegetable fields in the suburbs of Hangzhou and observed the seasonal changes of rates of parasitism during five separate periods from 1989 to 1997. We also investigated the patterns of seasonal abundance of the major parasitoids.

## Materials and methods

Irregular sampling in commercial, sprayed plots of brassica vegetable crops and regular sampling in unsprayed plots, were carried out in the suburbs of Hangzhou, where a vegetable cropping system typical of those in the Changjiang River Valley has existed for many years. Sprayed plots were sampled one to two times each month. Samples were taken from one or more plots of different brassica crops. In the study area, brassica vegetable crops were sprayed frequently (usually once a week) with high dosages of mixtures of chemical insecticides including organophosphates, pyrethroids and insect growth regulators during May to November each year when insect pest infestations were usually high. Because of the frequent sprays of insecticides, the plots sampled were not chosen at random. They were selected on the basis of no spray of chemical insecticides in the previous 10 days and relatively high numbers of *P. xylostella*. The plot size varied from 0.03 to 0.07 ha. Sampling was conducted during August–December 1989, April–July 1990, April–December 1994, January 1995–June 1996, and September–November 1997. In contrast, sampling of unsprayed plots was made at intervals of 5–10 days from transplanting to harvest for each crop. Two crops of Chinese cabbage, *Brassica campestris* (Linnaeus) ssp. *chinensis* Hanalt (Brassicaceae), were sampled from September to October 1989 and from June to July 1990, and one crop of cabbage, *B. oleracea* var *capitata* (Linnaeus) (Brassicaceae), was sampled from May 1995 to January 1996, respectively. Each of the three crops was planted in a 0.04 ha plot.

The following sampling methods were used for both types of sampling. On each sampling date, depending on the density of *P. xylostella*, usually 30–50 plants (as many as 200 plants when the insect density was very low) were sampled at random in each plot. All larvae (except first instar), prepupae, pupae and parasitoid pupae were removed from each plant in the sample and taken to the laboratory. Thirty to 80 eggs of *P. xylostella* were also taken from the plants. In the laboratory, eggs of *P. xylostella* were kept in groups of 5–10 in glass vials. Larvae of *P. xylostella* were retained singly on fresh cabbage leaves in glass vials. Prepupae and pupae of *P. xylostella* and parasitoid pupae were kept singly in glass vials. All vials were kept at room temperatures except during July–August when they were kept at 25°C in a temperature-controlled room. Eggs of *P. xylostella* were kept until eclosion or parasitoid emergence. Larvae, prepupae and pupae of *P. xylostella* and parasitoid pupae were reared until emergence of parasitoid adults or emergence of *P. xylostella* moths. Dead individuals were dissected to see whether there were parasitoid larvae or eggs inside.

During the five periods of this study, samples were taken from five varieties of four species of brassica crops including cabbage, Chinese cabbage, cauliflower, *B. oleracea* var. *botrytis* Linnaeus, radish, *Raphanus sativus* Linnaeus var. *longipinnatus* Bailey, and mustard, *B. juncea* Linnaeus (Brassicaceae). All parasitoid adults were sorted into species and identified by one of us (J.H.H.). In all instances, parasitism was related to the date of sampling and not to the date of parasitoid adult emergence.

## Results

### *Species of parasitoids*

Eight primary hymenopterous parasitoids were recorded (table 1). *Oomyzus sokolowskii* Kurdjumov (Eulophidae) is the only gregarious parasitoid, all the others are solitary parasitoids. *Cotesia plutellae* Kurdjumov (Braconidae) and *O. sokolowskii* were most abundant, and *Diadromus collaris* (Gravenhorst) (Ichneumonidae) was also abundant at times (see below). These three species were the major parasitoids. *Oomyzus sokolowskii* was recorded also as a facultative hyperparasitoid.

Seven hymenopterous species of parasitoid of *Cotesia plutellae* (hyperparasitoids of *P. xylostella*) were recorded: *Eurytoma verticillata* (Fabricius) (Eurytomidae), *O. sokolowskii*, *Ceraphron manilae* Ashmead (Ceraphronidae),

Table 1. Hymenopterous parasitoids of *Plutella xylostella* recorded from Hangzhou, China.

| Stages attacked | Parasitoids | | Relative abundance |
|---|---|---|---|
| | Species | Family | |
| Egg | *Trichogramma chilonis* Ishii | Trichogrammatidae | + |
| Larva | *Cotesia plutellae* Kurdjumov | Braconidae | +++ |
| | *Microplitis* sp. | Braconidae | + |
| Larva-pupa | *Oomyzus sokolowskii* Kurdjumov | Eulophidae | +++ |
| Pupa | *Diadromus collaris* (Gravenhorst)[2] | Ichneumonidae | ++ |
| | *Itoplectis naranyae* (Ashmead)[2] | Ichneumonidae | + |
| | *Exochus* sp. | Ichneumonidae | + |
| | *Brachymeria excarinata* Gahan[2] | Chalcididae | + |

[1] +++ abundant; ++ frequently seen; + occasionally seen.

[2] New records from mainland of China.

*Trichomalopsis apanteloctenus* (Crawford), *T. shirakii* Crawford, *Trichomalopsis* sp.1 and *Trichomalopsis* sp. 2 (Pteromalidae). *Eurytoma verticillata* and the four species of *Trichomalopsis* are solitary parasitoids, while *O. sokolowskii* and *C. manilae* are gregarious parasitoids.

Voucher specimens of all species of parasitoids recorded were deposited in the Insect Collection, Institute of Applied Entomology, Zhejiang University, China.

### *Rates of parasitism of* Plutella xylostella *eggs*

Rates of parasitism of *P. xylostella* eggs were generally low throughout the study periods. In 1994, parasitized eggs were found in only five of the 34 samples and rates of parasitism ranged from 2 to 6%. Similarly, in 1995 parasitized eggs were found in only four of the 25 samples and the rates of parasitism ranged from 1 to 11%.

### *Rates of parasitism of* Plutella xylostella *larvae*

The parasitism rates of third and fourth instar larvae were used as an index of larval parasitism. In most of the samples taken from May to early December each year when *P. xylostella* was usually abundant in the field, each sample contained 30–200 third and fourth instar larvae. However, when larval density in the field was low, the numbers of third and fourth instar larvae in each of the samples ranged from 15 to 30. Rates of parasitism varied greatly with time, between plots of the same crop and between plots of different crops at the same time of the year (fig. 1). Variations were not unexpected, especially in view of the differences of chemical treatments in different plots. Nevertheless, the data in fig. 1 show that parasitism of larvae was substantial on many occasions despite the heavy input of chemical insecticides into the crop system. The rates of parasitism were generally highest during June to early July and September–November each year, when the *P. xylostella* population was also most abundant. During these two peak periods, rates of parasitism were usually 10–60% (fig. 1), mainly through the action of *C. plutellae* and *O. sokolowskii* (table 2). Field and laboratory observations on *C. plutellae* showed that this parasitoid was active throughout the year, although it exhibited very low numbers and developed slowly during winter months.

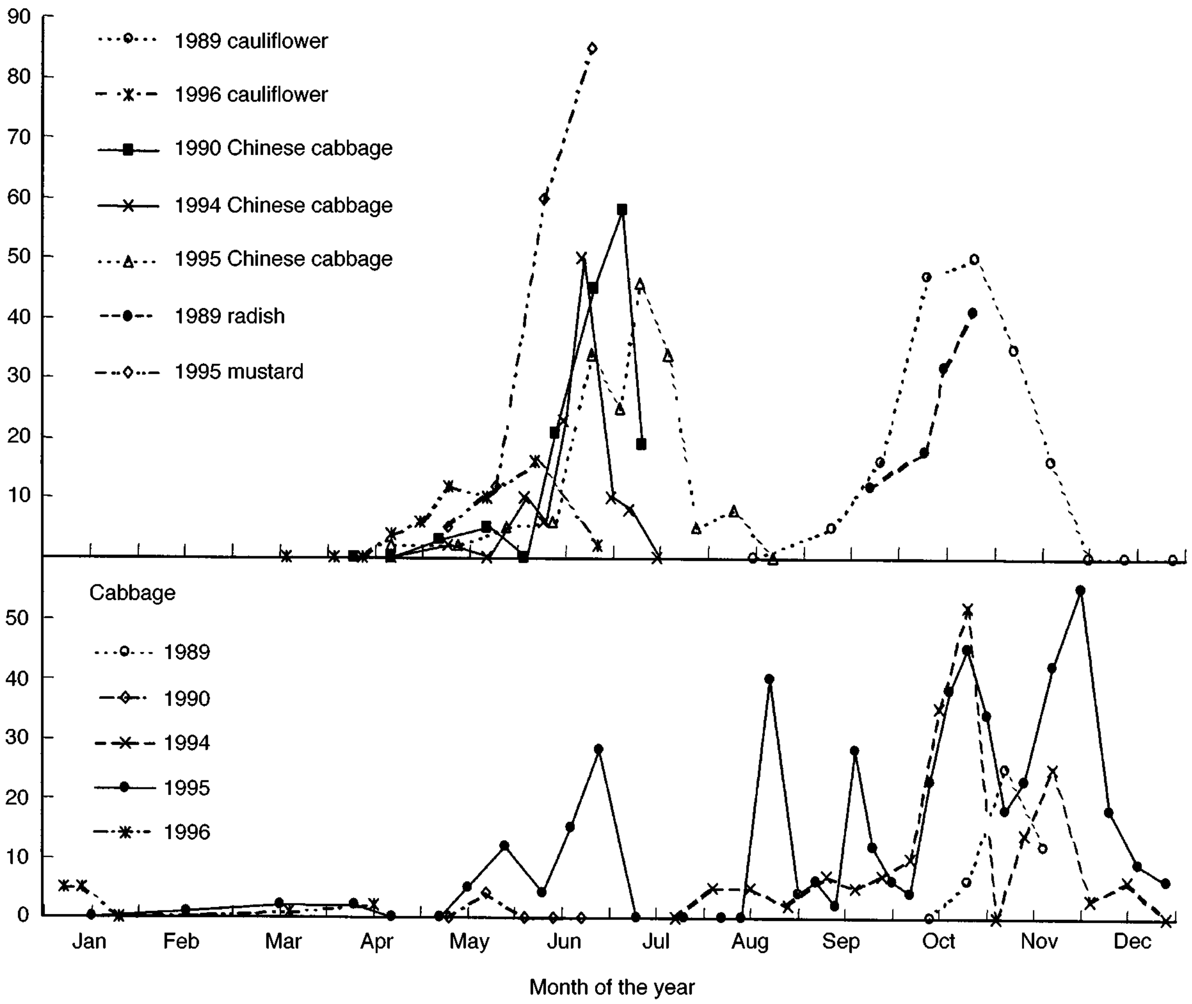

Fig. 1. Seasonal changes of parasitism rates of *Plutella xylostella* larvae in sprayed plots of brassica vegetable crops in Hangzhou, China.

Table 2. Relative proportions of *Plutella xylostella* larvae parasitized by *Cotesia plutellae* and *Oomyzus sokolowskii.*

| Crop | Date | No. of samples | Total no. of larvae sampled | Mean % parasitized* | Mean relative proportions (%) by† | |
|---|---|---|---|---|---|---|
| | | | | | *C. plutellae* | *O. sokolowskii* |
| Cabbage | Oct–Nov '89 | 4 | 168 | 11.5 | 12 | 88 |
| | May–Jun '90 | 5 | 145 | 1.1 | 21 | 78 |
| | Jul–Sept '94 | 7 | 133 | 3.3 | 32 | 68 |
| | Oct–Dec '94 | 9 | 461 | 19.1 | 8 | 90 |
| | Jan–Mar '95 | 3 | 43 | 0.7 | 64 | 36 |
| | Apr–Jun '95 | 10 | 1245 | 6.0 | 98 | 0 |
| | Jul–Sept '95 | 12 | 634 | 9.8 | 94 | 6 |
| | Oct–Dec '95 | 13 | 738 | 25.8 | 86 | 12 |
| | Jan–Apr '96 | 6 | 417 | 1.9 | 97 | 3 |
| Cauliflower | Aug–Sept '89 | 3 | 147 | 7.6 | 0 | 100 |
| | Oct–Dec '89 | 7 | 392 | 36.7 | 27 | 72 |
| | Mar–Jun '96 | 9 | 409 | 4.5 | 66 | 31 |
| Chinese cabbage | Apr–Jul '90 | 10 | 576 | 16.5 | 31 | 65 |
| | Apr–Jul '94 | 10 | 472 | 12.1 | 87 | 13 |
| | Apr–Jun '95 | 7 | 326 | 9.2 | 99 | 0 |
| | Jul–Aug '95 | 6 | 391 | 19.5 | 100 | 0 |
| Mustard | May–Jun '95 | 4 | 284 | 43.6 | 99 | 0 |
| | Aug '95 | 1 | 149 | 22.7 | 100 | 0 |
| Radish | Sept–Oct '89 | 4 | 178 | 25.3 | 7 | 93 |

*Mean value across samples.
†Mean relative proportions by each of the two parasitoids across samples.

*Cotesia plutellae* was parasitized by several secondary parasitoids, and the rates of parasitism exceeded 20% on a few occasions (table 3). *Oomyzus sokolowskii* was one of the major secondary parasitoids. In a laboratory observation at 28°C, we exposed 150 *P. xylostella* larvae already parasitized by *C. plutellae* (*C. plutellae* in late larval stage) to 50 female wasps of *O. sokolowskii* for 24 h. Twenty-seven (18%) of the *C. plutellae* individuals were parasitized by *O. sokolowskii*.

Plots of different crops were often sampled on the same day. Rates of parasitism in radish were usually higher than those in cabbage and Chinese cabbage, and rates of parasitism in mustard were higher than those in cabbage (see fig. 1). Because the duration of crop growth period in the field would affect the establishment of insect populations, only data from different crops of similar growth periods with similar levels of *P. xylostella* density could be compared. The comparison seemed to reveal some consistent differences between mustard and cabbage (fig. 2). It was noted that 99% of the parasitism presented in fig. 2 was due to *C. plutellae*.

The results from the unsprayed plot of cabbage in autumn to winter 1995 are shown in fig. 3. Larvae of *P. xylostella* increased rapidly initially to 25 per plant, then decreased to 10–15 per plant and continued at that level until crop harvest. Parasitoids of larvae were active throughout the crop growth period. Following the peak of *P. xylostella* larvae, rates of parasitism increased to a peak of over 50%. Decrease of parasitism from November onwards was accompanied by low temperatures apparently unfavourable to the parasitoids (fig. 3; Talekar & Yang, 1991; Shi & Liu, 1999b).

The two unsprayed plots of Chinese cabbage were mainly infested with *Pieris rapae* Linnaeus (Lepidoptera: Pieridae), and *Spodoptera* spp. (Lepidoptera: Noctuidae), and had a very low number of *Plutella xylostella*. The total numbers of *P. xylostella* in each sample were mostly below

Table 3. Rates of parasitism of *Cotesia plutellae* by *Oomyzus sokolowskii* in Hangzhou, China.

| Date | Crop | No. of samples | % parasitism |
|---|---|---|---|
| Oct '89 | Cauliflower | 1 | 15.6 |
| Oct '89 | Radish | 1 | 23.5 |
| Nov '89 | Cauliflower | 1 | 9.1 |
| Oct '94 | Cabbage | 1 | 5.6 |
| Nov '94 | Cabbage | 1 | 7.8 |
| Jun '95 | Mustard | 2 | 22.6, 25.0 |
| Jul '95 | Radish | 2 | 5.3, 20.5 |
| Jul '95 | Chinese cabbage | 2 | 12.6, 20.0 |
| Aug '95 | Chinese cabbage | 1 | 20.0 |

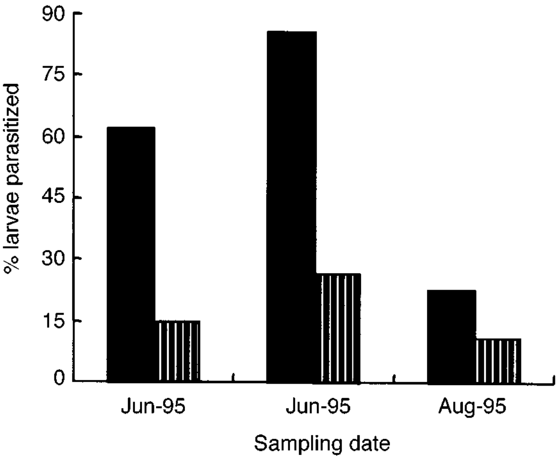

Fig. 2. Rates of parasitism of *Plutella xylostella* larvae on mustard (■) and cabbage (◧) collected on the same day.

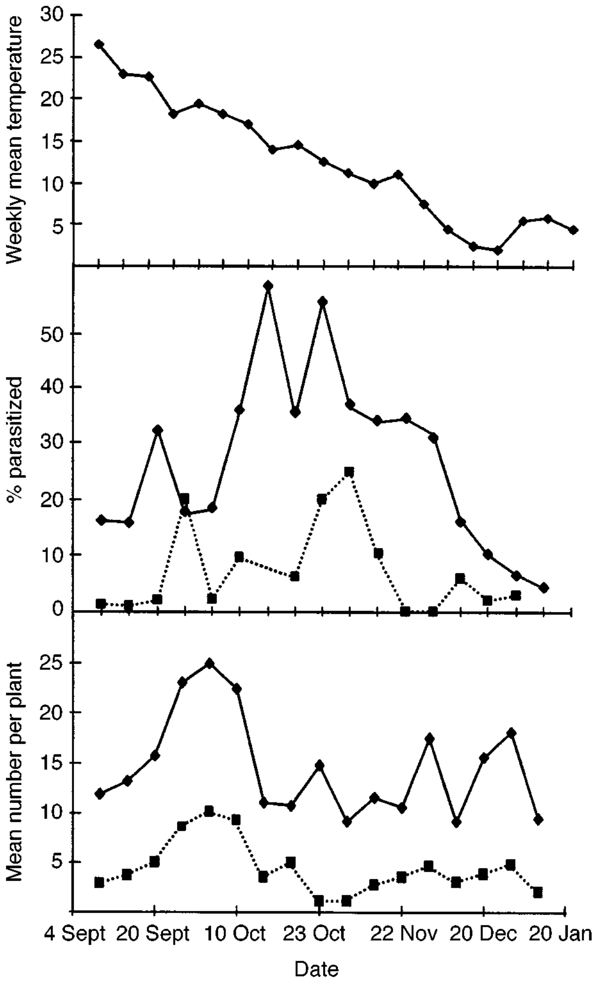

Fig. 3. Changes of mean numbers of *Plutella xylostella* larvae (—◆—) and pupae (····■····), and percentages of *Plutella xylostella* larvae and pupae parasitized by insect parasitoids in an unsprayed plot of cabbage in autumn to winter 1995 in Hangzhou, China; also shown are weekly mean air temperatures in the locality during the same period.

ten and parasitized individuals of *P. xylostella* were rarely encountered. It should be noted that the cultivar of Chinese cabbage in this study was a short season crop and usually grew for only four to six weeks from seeding to harvest.

Examination of the rates of parasitism by each of the larval parasitoids indicated a negative correlation of rates of parasitism between the two major larval parasitoids, *C. plutellae* and *O. sokolowskii*. Higher rates of parasitism of one species were usually accompanied by lower rates of the other species (fig. 4).

### *Rates of parasitism of* P. xylostella *pupae*

The patterns of parasitism of pupae, including seasonal variations and variations between plots and crops, were similar to those of larvae described above (fig. 5). Highest rates of parasitism occurred during June–July and October–November each year when *P. xylostella* was also most abundant. The rates during these peak periods were usually 10–60%, but reached 80–90% on several occasions. The dominant parasitoids were *O. sokolowskii* and *D. collaris* (table 4).

We observed the number and sex ratio of *O. sokolowskii* wasps that emerged from 556 parasitized pupae of *P. xylostella*. The mean number of parasitoids per pupa of *P. xylostella* was 7.8 ± 3.3 (range 1–23). Females constituted 85% of total number of parasitoid adults. Of the 556 parasitized pupae, 18% produced only females, with an average of 6.3 individuals per pupa. These figures compare favourably with those reported by Ooi (1988).

Observations were made on the overwintering of *O. sokolowskii*. Immature individuals collected before early October developed normally to adult emergence. From mid-October onwards, an increasing proportion of individuals remained at the prepupal stage and did not develop through to adult emergence until April–May of the following year (table 5). Table 5 also shows that in October the proportions of immature parasitoids which entered a state of overwintering were higher in host larvae than those in host pupae collected on the same day. Because *O. sokolowskii* is a larval-pupal parasitoid, individuals collected from host pupae started their development earlier than those collected from host larvae. A higher proportion of parasitoids in host pupae developed to the pupal stage at the time of collection. These parasitoid pupae would continue their development to adult emergence.

## Discussion

In the suburbs of Hangzhou, *P. xylostella* is attacked by at least eight primary parasitoids, of which *C. plutellae*, *O. sokolowskii* and *D. collaris* are the three major species. In this study, investigations of parasitism of *P. xylostella* were conducted in sprayed and unsprayed plots of brassicas. However, strictly speaking, the terms 'sprayed' and 'unsprayed' are imprecise for what they describe. For the feasibility of sampling, the sprayed plots included in the study generally received less chemical insecticides than average in the locality and also had higher densities of *P. xylostella*. Meanwhile, the occurrence and development of insect populations in the unsprayed plots were undoubtedly affected by the heavy sprays in surrounding plots because of the small sizes of unsprayed plots. Nevertheless, our data suggest that insect parasitoids are active in the fields despite heavy spraying of chemical insecticides in the crop systems over the years, and they can kill a substantial proportion of *P. xylostella* populations during periods of the year when the pest is relatively abundant.

Problems with estimates of parasitism rates of *P. xylostella* were discussed by Waage & Cherry (1992). In the current study, we used the conventional density sampling method whereby rates of parasitism were derived from estimates of host and parasitoid density on each of a series of sampling occasions. This method is simple, but has been known to produce biases in the estimates (Van Driesche, 1983). With our data, one can speculate that our sampling method tended to produce underestimates of parasitism rates for eggs and pupae of *P. xylostella*, because eggs and pupae of young age included in our samples could be

Table 4. Relative proportions of *Plutella xylostella* pupae parasitized by *Oomyzus sokolowskii* and *Diadromus collaris*.

| Crop | Date | No. of samples | Total no. of pupae sampled | Mean % parasitized* | Mean relative proportions (%) by† | |
|---|---|---|---|---|---|---|
| | | | | | *O. sokolowskii* | *D. collaris* |
| Cabbage | Sept–Nov '89 | 5 | 266 | 4.2 | 100 | 0 |
| | May–Jun '90 | 6 | 142 | 8.0 | 0 | 100 |
| | Jul–Sept '94 | 3 | 143 | 2.3 | 100 | 0 |
| | Oct–Dec '94 | 6 | 316 | 31.3 | 99 | 0 |
| | Jan–Mar '95 | 3 | 41 | 0.7 | 100 | 0 |
| | Apr–Jun '95 | 10 | 1085 | 4.8 | 0 | 98 |
| | Jul–Sept '95 | 11 | 782 | 1.8 | 84 | 16 |
| | Oct–Dec '95 | 11 | 534 | 8.5 | 98 | 0 |
| | Jan–Apr '96 | 6 | 357 | 1.9 | 61 | 39 |
| | Sep–Nov '97 | 7 | 277 | 19.3 | 84 | 14 |
| Cauliflower | Sept–Nov '89 | 9 | 398 | 41.2 | 100 | 0 |
| Chinese cabbage | Sept–Dec '89 | 6 | 302 | 14.7 | 100 | 0 |
| | Jun–Jul '90 | 7 | 425 | 6.6 | 83 | 17 |
| | Apr–Jul '94 | 7 | 239 | 38.8 | 30 | 69 |
| | Apr–Jun '95 | 8 | 1003 | 12.5 | 0 | 99 |
| | Jul–Aug '95 | 6 | 940 | 0.9 | 3 | 97 |
| Mustard | May–Jun '95 | 3 | 102 | 19.0 | 0 | 99 |
| | Jul–Aug '95 | 3 | 119 | 1.8 | 13 | 87 |
| Radish | Oct '89 | 3 | 148 | 84.3 | 98 | 0 |
| | Jun–Jul '95 | 2 | 91 | 31.1 | 0 | 99 |

*Mean value across samples.
†Mean relative proportions by each of the two parasitoids across samples.

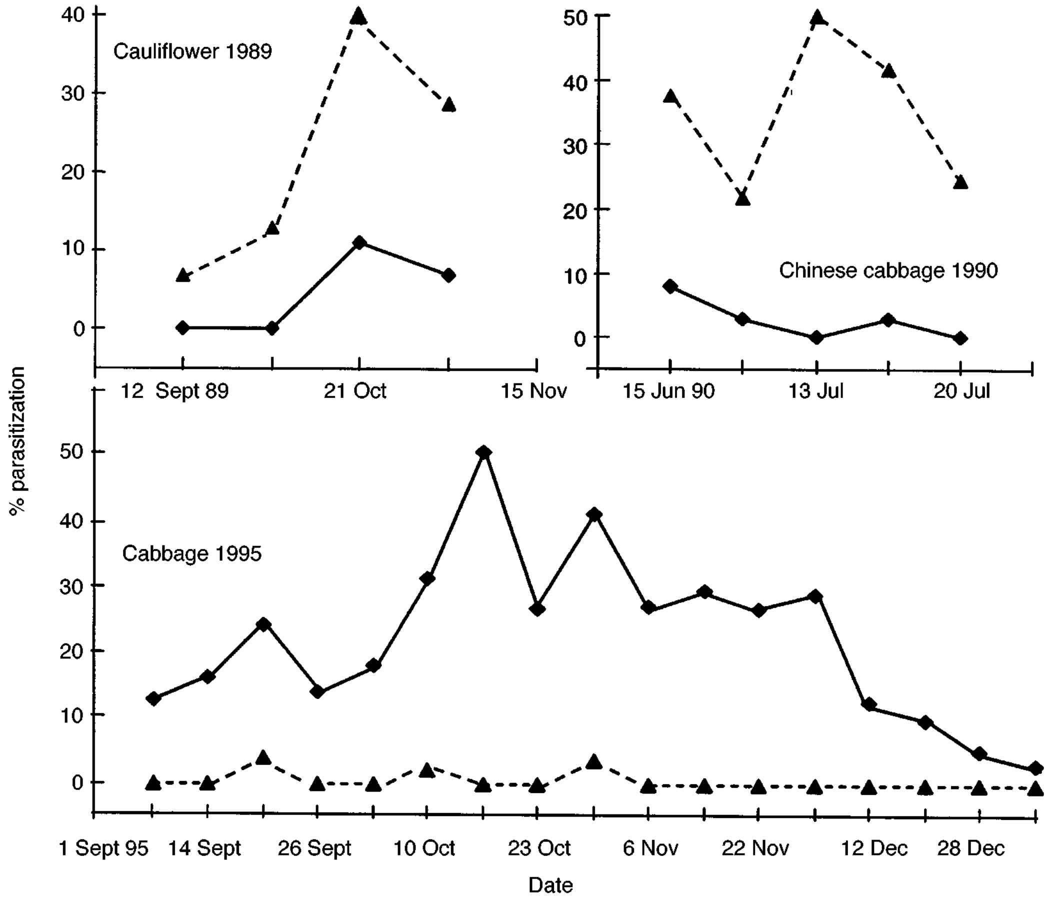

Fig. 4. Changes of percentages of *Plutella xylostella* larvae parasitized by *Cotesia plutellae* (—◆—) and *Oomyzus sokolowskii* (- - -▲- - -) in three plots of brassica vegetable crops in Hangzhou, China.

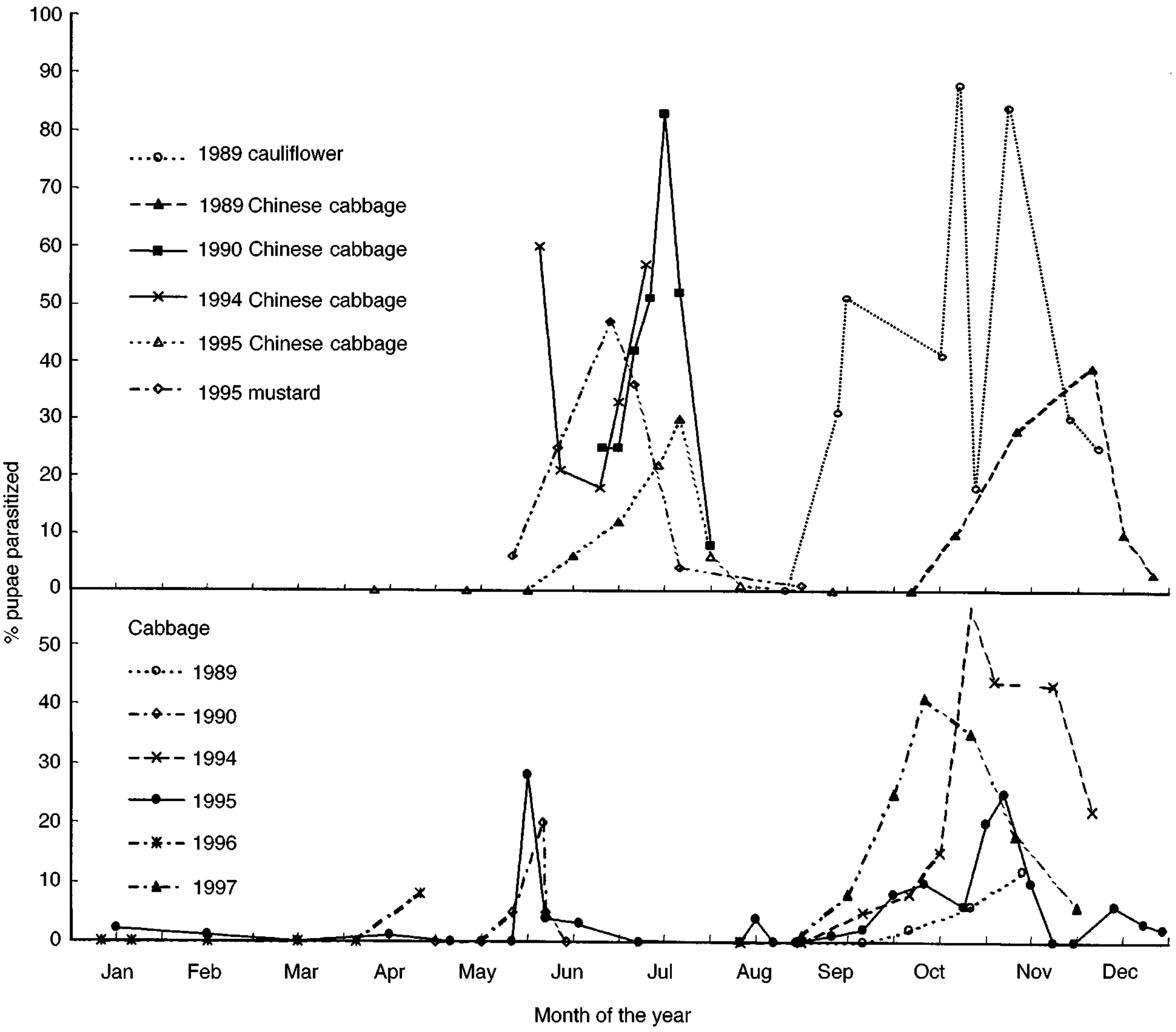

Fig. 5. Seasonal changes of parasitism rates of *Plutella xylostella* pupae in sprayed plots of brassica vegetable crops in Hangzhou, China.

Table 5. Dates of adult emergence of *Oomyzus sokolowskii* collected from parasitized larvae or pupae of *Plutella xylostella* in late autumn and early winter from the field in Hangzhou, China.

| Dates of collection | Parasitoids in host larvae when collected | | Parasitoids in host pupae when collected | |
|---|---|---|---|---|
| | % emergence during Oct–Nov of the same year | % emergence during April–May of the coming year | % emergence during Oct–Nov of the same year | % emergence during April–May of the coming year |
| 20 Sep–1 Oct '89 | 100 | 0 | 100 | 0 |
| 16 Oct | 42 | 58 | 89 | 11 |
| 21 Oct | 0 | 100 | 72 | 28 |
| 25 Oct | 0 | 100 | 60 | 40 |
| 27 Oct | 0 | 100 | 20 | 80 |
| 7 Nov–25 Dec | 0 | 100 | 0 | 100 |
| 5 Oct '95 | | | 100 | 0 |
| 20 Dec | | | 0 | 100 |
| 28 Dec | | | 0 | 100 |

exposed to further parasitism in the field. For example, the major pupal parasitoid in Hangzhou, *D. collaris*, has been shown in the laboratory to parasitize *P. xylostella* pupae of all ages with a strong preference for young age groups (Wang & Liu, 1997).

Accurate assessment of parasitism requires accurate estimates of recruitment to both the host stage susceptible to attack and to the pool of parasitized hosts. Such accurate estimates can be obtained, in some cases, by the so-called recruitment method (Van Driesche *et al.*, 1991). Typically, estimates of recruitment are obtained via a 'double sampling' scheme in which sets of plants are stripped of hosts of susceptible stage on a sampling occasion and reexamined after a short interval, counting all hosts present. The number of hosts encountered on the subsequent sampling occasion is taken as the total recruitment during the interval between the two sampling occasions. Thus, this method assumes that losses due to predation and other mortality factors (such as washing off by rain) during the time interval between the first and subsequent sampling occasions are negligible. This assumption can be hardly met in many circumstances. For example, predation of eggs and early instar larvae of *Pieris rapae* in brassica crops have been shown to be substantial in many cases (Schmaedick & Shelton, 1999; Jones, 1987). When such losses due to predation and other mortality factors during the interval between the two sampling occasions are not quantified, the reliability of the recruitment estimates become questionable. Based on these arguments, one can comfortably challenge the validity of the estimates of host and parasitoid recruitment of *P. rapae* and *Cotesia glomerata* Linnaeus (Hymenoptera: Braconidae) presented by Van Driesche & Bellows (1988), from which the recruitment method was first put forward. There is no reason to assume that losses of early instar larvae of *Plutella xylostella* due to predation and other mortality factors in Hangzhou were negligible. In fact, we frequently observed in the field that larvae of *P. xylostella* were preyed upon by a variety of predators including spiders and ladybird beetles. Thus, for assessment of parasitism of *P. xylostella* larvae, the recruitment method not only would have required much more work, but also would have produced parasitism estimates with biases of unknown magnitude, just as would have with the conventional sampling method used in the current study.

Because the two major larval parasitoids, *C. plutellae* and *O. sokolowskii*, oviposit into *P. xylostella* larvae of all four instars ((Talekar & Yang, 1991; Talekar & Hu, 1996; Shi & Liu, 1999a), total parasitism would accumulate over the four instars. One may assume that the rates of parasitism of the fourth instar larvae would give good approximations of total parasitism of larvae. However, estimates of parasitism of the fourth instar larvae obtained by the conventional sampling method are affected by many factors. For example, parasitized larvae have significantly longer durations of the fourth instar than unparasitized ones, which would contribute to an overestimate of parasitism (Waage & Cherry, 1992; Shi & Liu, 1999a). On the other hand, collection of all fourth instar larvae from the field would prevent the early fourth instar larvae in the samples from further exposure to parasitization in the field, and thus would tend to contribute to an underestimate of parasitism. Further biases would arise when parasitized and unparasitized larvae have differential rates of mortality during development. All these complexities would mean that the ultimate biases are very difficult to quantify accurately. During our data analysis, we found that the rates of parasitism of the third instar larvae were similar to those of the fourth instar larvae in most cases. To increase the sizes of the samples, we thus used the total parasitism of both third and fourth instar larvae as an index of larval parasitism.

Despite all the biases that were difficult to avoid in the sampling, we believe that the changes of rates of parasitism obtained by frequently sampling over several years offer a good indicator of the general pattern of seasonal abundance of parasitoid activity on *P. xylostella* in the study area.

Metabolic mechanisms of resistance to insecticides in *P. xylostella* can confer protection to endo-larval parasitoids (Furlong & Wright, 1993; Iqbal & Wright, 1996). However, whether the high levels of resistance to insecticides in the Hangzhou population of *P. xylostella* (Tang *et al.*, 1992; Zhao *et al.*, 1996) has offered protection to its endo-parasitoids is not known. We do not know whether any of the endo-parasitoids has developed resistance to insecticides. Information on this aspect would be most valuable to the understanding of the *P. xylostella*–parasitoid interactions in the field.

Plant species can exert significant influence on the efficacy of insect parasitoids of *P. xylostella* (Verkerk & Wright, 1997; Verkerk *et al.*, 1998). In this study, apparent variations of rates of parasitism of *P. xylostella* larvae were observed between plant species (fig. 2). However, as rates of parasitism in the field were affected by many factors, the indications of effects of plant species on parasitoids should not be accepted without well-controlled, quantitative comparative experiments, in both laboratory and field. The negative correlation in rates of parasitism of *P. xylostella* larvae between *C. plutellae* and *O. sokolowskii* observed in this study suggests competition between the two parasitoids, which also warrants further investigation.

During the periods of this study, rates of parasitism of *P. xylostella* eggs were very low, compared with field records from other parts of the world. For example, rates of parasitism of *P. xylostella* eggs were 5–21% in western Japan (Wakisaka *et al.*, 1992), 16–45% in the lowland areas of Thailand (Keinmeesuke *et al.*, 1992) and 5–50% in southern Queensland, Australia (Cooper & Hargreaves, 1999). *Trichogramma chilonis* Ishii (Hymenoptera: Trichogrammatidae) was the only egg parasitoid recorded from Hangzhou. Other strains of this parasitoid have been shown in the laboratory to have a high capacity for parasitism of *P. xylostella* eggs (Klemm *et al.*, 1992; Wuhrer & Hassan, 1993). Introduction of other strains of *T. chilonis* and other egg parasitoids should be attempted to increase egg parasitism of *P. xylostella* in Hangzhou.

Recently, Kfir (1998) speculated that *P. xylostella* may have originated in southern Africa on the basis of the rich and diverse native fauna of its parasitoids, the large number of indigenous brassicas, and the arrhenotokous form of the pupal parasitoid *D. collaris* in that region. The author also speculated that *D. collaris* may have also evolved in southern Africa and dispersed to Europe, because *D. collaris* is arrhenotokous in South Africa whereas it is thelytokous in Europe. Our data seem to add confusion to these speculations, because most of the arguments used by Kfir (1998) seem to apply to China. First, the native parasitoid fauna of *P. xylostella* in China is rich and diverse. During our sampling in Hangzhou, we recorded eight species of primary parasitoids from four families (table 1) and seven species of secondary parasitoids from four families of Hymenoptera. He (1998) recently classified his collection of hymenopterous parasitoids of *P. xylostella* from China, and found 23 species of primary parasitoids from six families (including the species listed in table 1) and 14 species of secondary parasitoids from six families. So far as the records show, no introduction of parasitoids of *P. xylostella* to the mainland of China had been made until the early 1990s, when *D. collaris* and *Diadegma semiclausum* Hellén (Hymenoptera: Ichneumonidae) were introduced from Malaysia to southern China (Zhang *et al.*, 1998; Li Li-ying, personal communication). The records of He (1998) show that these two species of parasitoids were widespread in central and north China before these introductions. Second, a large number of brassicas indigenous to China are host plants of *P. xylostella*. *Plutella xylostella* can feed and reproduce on plants of at least 28 genera of the family Brassicaceae (Talekar & Shelton, 1993). According to the records in Cheo *et al*. (1987), 13 of the 28 genera listed by Talekar & Shelton (1983) occur in China, and within these 13 genera that occur in China, 71 species are largely restricted to this country. It has also been argued, based on the findings of native *Brassica* species as well as the discovery of rapeseeds in graves from 4000–5000 B.C., that China is one of the original centres of *B. campestris* and *B. juncea* (Liu, 1984; Ye, 1989). Third, *Diadromus collaris* from Hangzhou is arrhenotokous and the female ratios are usually 50–70% (Wang & Liu, 1998).

*Oomyzus sokolowskii* has been recorded as a primary parasitoid as well as a facultative hyperparasitoid of *P. xylostella* (Waterhouse & Norris, 1987; Fitton & Walker, 1992). This has been shown to be true for the Hangzhou population of this parasitoid, because adult wasps of *O. sokolowskii* were reared from *P. xylostella* pupae and cocoons of *C. plutellae* in both field collections and laboratory studies. Talekar & Hu (1996) recently concluded from their laboratory observations that *O. sokolowskii* does not parasitize *C. plutellae* and thus is not a facultative hyperparasitoid. However, Talekar & Hu (1996) did not expose late-instar larvae of *C. plutellae* to *O. sokolowskii* for parasitism. We verified by direct observations that female wasps of *O. sokolowskii* penetrate the cuticle of parasitized *P. xylostella* larva to attack the late-stage larva of *C. plutellae* inside. In fact, this oviposition behaviour of *Oomyzus* species and related genera were recorded in detail many years ago (Clausen, 1940). Moreover, because mature larvae of *C. plutellae* emerge from host larvae for pupation, they can also be parasitized as mature larvae before they complete cocoon formation.

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## References

**Biever, K.D., Hostetter, D.L. & Kern, J.R.** (1994) Evolution and implementation of a biological control-IPM system for crucifers: 24-year case history. *American Entomologist* **40**, 103–108.

**Chen, L.L., Kuang, M.Z., Zhen, Z.D., Cao, Y. & Xu, W.W.** (1987) A survey of natural enemies of insect pests of vegetable crops in the suburbs of Guangzhou. pp. 393–399 *in* Fan, H.Z. (*Ed.*) *Integrated control of insect pests and diseases in vegetable crops*. Guangzhou, Guangzhou Science-Technology Press (in Chinese).

**Cheo, T.Y., Gue, R.L., Lan, Y.Z., Lou, L.L., Kuan, K.C. & An, Z.X.** (1987) *Flora reipublicae popularis sinicae, Tomus 33: Angiospermae: Dicotyledoneae: Cruciferae*. Beijing, Science Press.

**Clausen, C.P.** (1940) *Entomophagous insects*. 688 pp. New York, McGraw-Hill Book Company, Inc.

**Cooper, L. & Hargreaves, J.** (1999) Pests and beneficials population monitoring in unsprayed brassica plantings. *Termination report of ACIAR Project 9213, Vol.2., Appendix 9.1(5),* Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia.

**Feng, X., Chen, H.Y., Shaui, Y.Y., Xie, Q.H. & Lu, Y.C.** (1996) A study on the resistance of diamondback moth to *Bacillus thuringiensis* in Guangdong. *Acta Entomologica Sinica* **39**, 238–245.

**Fitton, M. & Walker, N.** (1992) Hymenopterous parasitoids associated with diamondback moth: the taxonomic dilemma. pp. 225–232 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Furlong, M.J. & Wright, D.J.** (1993) Effect of acylurea insect growth regulator teflubenzuron on the endo-larval stages of hymenopteran parasitoids *Cotesia plutellae* and *Diadegma semiclausum* in a susceptible and an acylurea-resistant strain of *Plutella xylostella*. *Pesticide Science* **39**, 305–312.

**He, J.H.** (1998) A preliminary list of hymenopterous parasitoids of *Plutella xylostella* (L.) from China. pp. 26–31 in *A collection of articles from ACIAR project 9213*, Zhejiang University, Hangzhou, China,

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

**Iqbal, M., Verkerk, R.H.J., Furlong, M.J., Ong, P.C., Syed, A.R. & Wright, D.J.** (1996) Evidence for resistance to *Bacillus thuringiensis* (*Bt*) subsp. *kurstaki* HD-1, *Bt* subsp. *aizawai* and abamectin in field populations of the diamondback moth from Malaysia. *Pesticide Science* **48**, 89–97.

**Jones, R.E.** (1987) Ants, parasitoids, and the cabbage butterfly *Pieris rapae*. *Journal of Animal Ecology*, **56**, 739–749.

**Ke, L.D. & Fang, J.L.** (1982) Studies on the biology of the braconid wasp, *Apanteles plutellae* Kudjumor. *Acta Phytophylacica Sinica* **9**, 27–33.

**Keinmeesuke, P., Vattanatangum, A., Sarnthoy, O., Sayampol, B., Miyata, T., Saito, T., Nakasuji, F. & Sinchaisri, H.** (1992) Life table of diamondback moth and its egg parasite, *Trichogrammatoidea bactrae* in Thailand. pp. 309–315 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

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

**Klemm, U., Guo, M.F., Lai, L.F. & Schmutterer, H.** (1992) Selection of effective species or strains of *Trichogramma* egg parasitoids of diamondback moth. pp. 317–323 in Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Liu, H.L.** (1984) Origin and evolution of rapeseeds. *Acta Agronomica Sinica* **10**, 9–18.

**Liu, S.S. & Yan, S.** (1998) Brassica IPM in Asia: successes, challenges, and opportunities. pp. 85–97 *in* Zalucki, M.P., Drew, R.A.I. & White G.G. (*Eds*) *Pest management – future challenges. Proceedings of the Sixth Australasian Applied Entomological Research Conference, Brisbane, Australia, 29 September–2nd October 1998*, Volume 1. Brisbane, The University of Queensland Printery.

**Liu, S.S., Brough, E.J. & Norton, G.A.** (1995) *ACIAR workshop report: integrated pest management in brassica vegetable crops*. Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia.

**Lu, Y.X.** (1983) A preliminary survey of natural enemies of larvae of *Plutella xylostella*. *Natural Enemies of Insects* **5**, 188–189.

**Ooi, P.A.C.** (1988) Laboratory studies of *Tetrastichus sokolowskii*. *Entomophaga* **33**, 145–152.

**Ooi, P.A.C.** (1992) Role of parasitoids in managing diamondback moth in the Cameron Highlands, Malaysia. pp. 255–262 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Schmaedick, M.A. & Shelton, A.M.** (1999) Experimental evaluation of arthropod predation on *Pieris rapae* (Lepidoptera: Pieridae) eggs and larvae in cabbage. *Environmental Entomology* **28**, 439–444.

**Shelton, A.M. & Wyman, J.A.** (1992) Insecticide resistance of diamondback moth in North America. pp. 447–454 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Shi, Z.H. & Liu, S.S.** (1995) A review of research and management of diamondback moth in China. pp. 36–39 *in* Liu, S.S., Brough, E.J. & Norton, G.A. (*Eds*) *ACIAR workshop report: integrated pest management in brassica vegetable crops*. Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia.

**Shi, Z.H. & Liu, S.S.** (1999a) Parasitism preference of *Cotesia plutellae* to host age and the effect of parasitism on the development and food consumption of the host, *Plutella xylostella*. *Acta Phytophylacica Sinica* **26**, 25–29.

**Shi, Z.H. & Liu, S.S.** (1999b) Influence of temperature on the development, survival and reproduction of *Cotesia plutellae*, a larval parasite of *Plutella xylostella*. *Acta Phytophylacica Sinica* **26**, 142–146.

**Sun, C.N.** (1992) Insecticide resistance in diamondback moth. pp. 419–426 *in* Talekar, N.S. (Ed.) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Sun, Y.Q., Chen, Y.Q. & Ying, Y.** (1995) Insecticide resistance in diamondback moth in South China. *Pesticide Science* **43**, 355–357.

**Tabashnik, B.E.** (1994) Evolution of resistance to *Bacillus thuringiensis*. *Annual Review of Entomology* **39**, 47–80.

**Talekar, N.S. & Hu, W.J.** (1996) Characteristics of parasitism of *Plutella xylostella* (Lep., Plutellidae) by *Oomyzus sokolowskii* (Hym., Eulophidae). *Entomophaga* **41**, 45–52.

**Talekar, N.S. & 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.** (1991) Characteristic of parasitism of diamondback moth by two larval parasites. *Entomophaga* **36**, 95–104.

**Talekar, N.S., Yang, J.C. & Lee, S.T.** (1992) Introduction of *Diadegma semiclausum* to control diamondback moth in Taiwan. pp. 263–270 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Tang, Z.H., Zhou, C.L., Wu, S.C., Zheng, H.Z., Sheng, H.L. & Gu, Y.Z.** (1992) Insecticide resistance and the effects of synergists in the diamondback moth from Shanghai. *Acta Phytophylacica Sinica* **19**, 179–185.

**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.** (1988) Host and parasitoid recruitment for quantifying losses from parasitism, with reference to *Pieris rapae* and *Cotesia glomerata*. *Ecological Entomology*, 13, 215–222.

**Van Driesche, R.G., Bellows, T.S., Elkinton, J.S., Gould, J.R. & 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.

**Verkerk, R.H.J. & Wright, D.J.** (1997) Field-based studies with the diamondback moth tritrophic system in Cameron Highlands of Malaysia: implications for pest management. *International Journal of Pest Management*, **43**, 27–33.

**Verkerk, R.H.J., Leather S.R. & Wright, D.J.** (1998) The potential for manipulating crop-pest–natural enemy interactions for improved insect management. *Bulletin of Entomological Research*, **88**, 493–501.

**Waage, J. & Cherry, A.** (1992) Quantifying the impact of parasitoids on the diamondback moth. pp. 245–253 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Wakisaka, S., Tsukuda, R. & Nakasuji, F.** (1992) Effects of natural enemies, rainfall, temperature and host plants on survival and reproduction of the diamondback moth. pp. 15–26 *in* Talekar, N.S. (*Ed.*) *Diamondback moth and other crucifer pests: proceedings of the second international workshop*. AVRDC, Taiwan.

**Wang, X.G. & Liu, S.S.** (1997) Host age preference and suitability of *Diadromus collaris*, a major pupal parasite of *Plutella xylostella*. *Chinese Journal of Biological Control* **13**, 101–105.

**Wang, X.G. & Liu, S.S.** (1998) Bionomics of *Diadromus collaris* (Hymenoptera: Ichneumonidae), a major pupal parasitoid of *Plutella xylostella*. *Acta Entomologica Sinica* **41**, 389–395.

**Waterhouse, D.F. & Norris, K.R.** (1987) *Biological control: Pacific prospects*. Melbourne, Inkata Press.

**Wu, J.W., Wang, J.R., Wang J., Shi, B.D., Wang, W., Wang, B.Z., Dong, Z.H., Wei, D.Z. & Huang, Q.F.** (1987) A list of natural enemies of insect pests of vegetable crops in Beijing. *Acta Agricultura Boriali-Sinica* **2**, 75–96.

**Wuhrer, B.G. & Hassan, S.A.** (1993) Selection of effective species/strains of *Trichogramma* (Hym., Trichogrammatidae) to control the diamondback moth *Plutella xylostella* L. (Lep., Plutellidae). *Journal of Applied Entomology* **116**, 80–89.

**Ye, J.Y.** (1989) The review of names and cultivation origin of rapeseeds in China. *Studies in the History of Natural Sciences* **8**, 158–165.

**Zhang, M.L., Han, S.C., Li, L.Y., Zeng, B.K., Lu, L.M. & Guo, M.F.** (1998) The characteristics of biology and ecology of *Diadromus collaris*, a pupal parasitoid of diamondback moth. *Natural Enemies of Insects* **20**, 2–8.

**Zhao, J.Z., Wu, S.C., Gu, Y.Z., Zhu, G.R. & Ju, Z.L.** (1996) Strategy of insecticide resistance management in the diamondback moth. *Scientia Agricultura Sinica* **29**, 8–14.

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