Influence of Selected Insecticides on the Population Dynamics of Diamondback Moth (Lepidoptera: Plutellidae) and Its Parasitoid, *Diadegma insulare* (Hymenoptera: Ichneumonidae), in Cabbage[1]

Travis A. Hill and Rick E. Foster[2]

Department of Entomology, Purdue University, West Lafayette, IN 47907 USA

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Abstract The effects of insecticides on the diamondback moth, *Plutella xylostella* (L.), and its parasitoid, *Diadegma insulare* (Cresson), were evaluated in the field. Insecticides applied for control of the diamondback moth caused variations in parasitism by *D. insulare* ranging from 20 to 84%. Permethrin applications were effective at controlling diamondback moth. Applications of spinosad also resulted in low diamondback moth populations; however, percent parasitism was higher than in untreated plots and over 4X higher than in plots treated with permethrin. Selective materials that conserve *D. insulare* populations and maintain diamondback moth populations below economic thresholds may reduce the frequency of application, thus prolonging the efficacy of these materials.

Key Words *Plutella xylostella, Diadegma insulare,* insecticides

The diamondback moth, *Plutella xylostella* (L.), is a major cosmopolitan pest of cabbage and other crucifers (Talekar et al. 1986). Insecticides have dominated attempts to control diamondback moth for more than 40 yrs (Ho 1965, Syed 1992). Compounds from virtually all insecticide classes have been used, including organochlorines, organophosphates, carbamates, pyrethroids, avermectins, acylureas, and botanicals (Talekar and Griggs 1986, Talekar 1992). *Bacillus thuringiensis* Berliner and other microbial-based insecticides, such as baculoviruses, also have been used (Kadir 1992, Ooi 1992). Sustained use of products from all major insecticide classes has been associated with the subsequent development of insecticide resistance to one or more compounds in those classes (Furlong et al. 1994).

Historically, diamondback moth was held below economic thresholds in the United States by natural enemies (Marsh 1917). Predators have not generally been considered significant factors in the regulation of diamondback moth, as indicated by the almost total absence of published research on the subject. A wide range of parasitoids has been associated with diamondback moth. Major parasitoids of the diamondback moth in the Midwest are *Diadegma insulare* (Cresson), *Diadromus subtilicornis* (Gravenhorst), and *Microplitis plutellae* (Muesbeck) (Mahr et al. 1993). However, the capability of *D. insulare* to be highly synchronized with its host's developmental stage

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[2]To whom offprint requests are addressed (email: rick_foster@entm.purdue.edu).

along with its excellent searching capacity make it essential for consideration for integrated diamondback moth management (Harcourt 1969, 1986).

Diadegma insulare and other parasitoids of diamondback moth are capable of exerting significant levels of control over diamondback moth. Up to 88% parasitism has been achieved by field populations of *D. insulare,* indicating its potential as an alternative or complementary method for controlling diamondback moth in cabbage fields (Mahr et al. 1993, McHugh 1994). Although diamondback moth parasitoids have a demonstrated potential for control, chemical insecticides are extensively used to produce a highly marketable crop to meet consumer demands because of other caterpillar pests, including imported cabbageworm, *Pieris rapae* L., and cabbage looper, *Trichoplusia ni* (Hübner). Therefore, synthetic insecticides are likely to remain essential tools for diamondback moth management in the foreseeable future and thus cannot be ignored. However, their use should be minimized to prevent growers from becoming dependent on them as the exclusive means of control, thus causing the subsequent development of resistance. Lim (1992) argued that integrated pest management (IPM) of the diamondback moth was poorly developed due to disproportionate research emphasis on chemical control compared with IPM.

The objectives of this study were to evaluate the effect of insecticides in the field on the mortality of diamondback moth larvae and parasitism by *D. insulare,* and to demonstrate the role of *D. insulare* and its potential for inducing high mortalities of diamondback moth.

Materials and Methods

This study was conducted three times over the 1996 to 1997 growing seasons at the O'Neall Memorial Research Farm south of Lafayette (Tippecanoe Co.), Indiana. The summer 1998 study had very low diamondback moth densities and these data are not discussed herein. For each year of this study, field plots were 5.5 by 7.6 m and were planted 3.1 m apart. Each plot consisted of six rows of cabbage per plot with 1.0 m between rows and plants 0.3 m apart within a row. Fertilizer (10-20-10) was broadcast and preplant incorporated at a rate of 2,000 kg/ha. Trifluralin (0.85 kg [AI]/ha) also was preplant incorporated for weed control. Head cabbage seedlings ('Market Prize') were transplanted in the field when the plants were at the 5-leaf stage (Andaloro et al. 1983). All transplants were sprinkle-irrigated immediately after planting. Treatments were arranged in a randomized complete block design with four replications per treatment.

All treatments were applied using a hand-held CO_2 sprayer with four VSX-10 nozzles (Spraying Systems Co., Wheaton, IL) at 7.1 kg/cm^2 pressure and 239 l/ha. All materials were applied on a 14-d schedule when natural diamondback moth populations exceeded one larva per plant.

Bacillus thuringiensis var. *aizawai* (Agree, Certis USA LLC, Columbia, MD) is a spore-forming bacterium that produces crystals of toxic δ-endotoxin proteins that are released outside the cell wall, which is effective only against lepidopterous larvae. *Bacillus thuringiensis* is recommended for caterpillar control when larvae are small and to maintain beneficial insects. *Bacillus thuringiensis* was evaluated in this study because it was thought that it would provide effective diamondback moth control and have a minimal impact on *D. insulare.*

Imidacloprid (Provado 1.6F, Bayer Corp., Kansas City, MO) is a chloronicotinyl insecticide used in cabbage for aphid control. It is recommended for IPM programs because it is relatively nontoxic to many natural enemies. Imidacloprid was chosen for this study to demonstrate that the combination of selective chemicals for caterpillar and aphid control can provide an effective integrated control strategy.

Carbaryl (Sevin XLR Plus, Aventis Crop Science, Research Triangle Park, NC) is an *N*-methyl carbamate insecticide and a cholinesterase inhibitor. Its primary use in cabbage is for the control of flea beetles, particularly early in the season when the beetles may destroy newly-set plants. This material also will provide fair control of caterpillar pests in cabbage. Because carbaryl is a broad-spectrum insecticide, it is often harmful to natural enemies. This product was chosen to evaluate what would happen to the caterpillar complex in the absence of natural enemies with an insecticide that is only moderately effective against diamondback moth.

Permethrin (Pounce 3.2 EC, FMC Corp., Philadelphia, PA) is a pyrethroid insecticide commonly used by growers to control the caterpillar complex in cruciferous crops. Due to its high efficacy and relatively low cost, permethrin has been widely used by growers and, as such, diamondback moth resistance has developed in some areas (Sun et al. 1986, Shelton et al. 1993). Permethrin is toxic to many natural enemies because of its broad-spectrum activity. Permethrin was chosen for this study because it was assumed that it would provide good caterpillar control while decimating natural enemy populations.

Spinosad (Spin-Tor, DowAgrosciences, Indianapolis, IN) is a mixture of spinosyn A and spinosyn D. The spinosyns are a naturally-derived group of insect control molecules from a species of actinomycetes bacteria, *Saccharopolyspora spinosa.* Spinosad acts both as a contact and a stomach poison. Although the material degrades rapidly in the environment, residual activity is comparable to pyrethroid standards in the laboratory. Spinosad selectively preserves many beneficial insects. As such, spinosad may be a useful IPM tool in crops where preservation of beneficial insects plays an important role in pest management practices.

Tebufenozide (Confirm 2F, DowAgrosciences, Indianapolis, IN) imitates the natural insect molting hormone, 20-hydroxyecdysone. It works by binding to the ecdysone receptor protein that initiates the molting process. Once this insecticide binds to the ecdysone receptor, the caterpillar ceases feeding and produces a new, but malformed cuticle beneath the old cuticle. The caterpillar, unable to shed its old cuticle, dies of dehydration and starvation. Tebufenozide was used in this study because we suspected that its selective properties would reduce diamondback moth larval numbers while maintaining *D. insulare* populations.

Data collection. A preliminary survey (10 plants per plot) was conducted after each planting to determine the density of diamondback moth larvae and *D. insulare* pupae. Diamondback moth larval density was always >1.0 per plant, so releases to supplement natural field populations were not necessary. Data collection began 1 to 2 wk after planting, depending upon diamondback moth infestation levels. After data collection began, weekly whole-plant counts of diamondback moth, imported cabbageworm, cabbage looper, and aphids were made from 10 randomly selected plants in rows 3 and 4 of each plot. Caterpillar larvae and pupae encountered during the sampling process were left on the plants. Cabbage plants from rows 3 and 4 also were rated weekly for injury by all leaf defoliators.

Parasitism rates also were monitored weekly. All caterpillar larvae and pupae were removed from randomly selected plants in rows 2 and 5 of each plot until a total of 10 diamondback moth larvae or pupae were collected. If 10 larvae or pupae could not be found after inspecting all 50 plants, percentage of parasitism was calculated from

Table 1. Cumulative caterpillar populations per plot (mean ± SEM) for diamondback moth, imported cabbageworm, and cabbage looper for the 20 May 1996 planting (df = 7, 21)

	Cumulative caterpillar populations		
	Diamondback moth	Imported cabbageworm	Cabbage looper
B. thuringiensis	54.00 ± 8.46ab	2.25 ± 0.25a	1.75 ± 1.11
B. thuringiensis + imidacloprid	78.00 ± 11.56bc	5.75 ± 1.11a	2.00 ± 0.82
Carbaryl	70.00 ± 11.74bc	5.00 ± 1.00a	4.75 ± 1.93
Imidacloprid	106.25 ± 15.85de	21.00 ± 5.28b	3.75 ± 1.18
Permethrin	38.00 ± 13.86a	1.75 ± 0.48a	1.50 ± 0.87
Spinosad	30.25 ± 0.75a	3.50 ± 1.44a	1.00 ± 0.71
Tebufenozide	96.25 ± 10.09cd	2.75 ± 0.63a	1.75 ± 1.03
Untreated	122.75 ± 3.64e	30.50 ± 6.13c	3.50 ± 1.32
F-value	13.51	12.89	1.20
P-value	0.0001	0.0001	0.3466

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

those collected. All larvae and pupae collected from each plot were placed into 170-ml plastic containers (Plastics Inc., St. Paul, MN) for transport to the laboratory. When in the laboratory, each larva or pupa was placed into a 28.4-ml plastic cup (Plastics Inc., St. Paul, MN) for determination of parasitism. Larvae and pupae were held until either an adult diamondback moth or an adult parasitoid emerged. If emergence failed from some of the collected pupae, then calculations of percentage of parasitism were made from those that did emerge. Numbers of diamondback moth and parasitoid pupae formed were recorded and percentage of *D. insulare* parasitism was calculated as the total number of *D. insulare* pupae X 100 divided by the total number of *D. insulare* plus diamondback moth pupae. Parasitoids that emerged were identified and voucher specimens were deposited in the Purdue University Entomological Research Collection.

Final damage ratings (1, very slight damage to wrapper leaves only; 2, moderate damage to wrapper leaves only; 3, damage to 2 layers of cabbage head; 4, damage to more than 2 layers of cabbage head) to leaves by all leaf defoliators were conducted on rows 3 and 4 in each plot just before harvest. The percentage of marketable cabbage heads (those with no insect feeding on layers of head going to market after wrapper leaves are removed) per plot also was determined. Finally, all of the cabbage heads in rows 3 and 4 of each plot were hand harvested and combined for weight determination. Yields from each plot were determined to the nearest 0.25 kg.

Statistical analysis. Data were analyzed by a two-way analysis of variance (ANOVA) to determine significant differences among treatments (Gagnon et al.

Table 2. Cumulative caterpillar populations per plot (mean ± SEM) for diamondback moth, imported cabbageworm, and cabbage looper for the 21 May 1997 planting (df = 7, 21)

	Cumulative caterpillar populations		
	Diamondback moth	Imported cabbageworm	Cabbage looper
B. thuringiensis	142.00 ± 34.25bc	5.50 ± 1.85a	4.25 ± 1.65abc
B. thuringiensis + imidacloprid	99.50 ± 5.55ab	6.50 ± 1.32a	3.50 ± 0.50ab
Carbaryl	144.50 ± 22.53bc	19.50 ± 2.99b	4.50 ± 1.50abc
Imidacloprid	298.25 ± 29.94de	72.50 ± 7.37c	6.00 ± 0.91bc
Permethrin	54.50 ± 7.10a	0.25 ± 0.25a	4.50 ± 1.26abc
Spinosad	47.75 ± 10.73a	7.50 ± 2.90a	1.00 ± 0.71a
Tebufenozide	222.25 ± 34.05cd	3.00 ± 2.04a	0.50 ± 0.29a
Untreated	318.75 ± 38.78e	94.00 ± 3.24d	8.25 ± 3.12c
F-value	14.37	105.00	2.75
P-value	0.0001	0.0001	0.0341

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

1989). Parasitism data were analyzed by an analysis of covariance to evaluate the parasitism per plot given a constant host population. All data were compared weekly and also summed for comparison. Separation of statistically different means was determined by Fisher's protected least significant difference test ($P = 0.05$).

Results and Discussion

Effects on pest insects. In the 20 May 1996 planting, permethrin and spinosad provided the highest level of control of diamondback moth populations; whereas, plots treated with imidacloprid and tebufenozide provided little control ($F = 13.51$; df = 7, 21; $P = 0.0001$) (Table 1). Imidacloprid also had little effect on imported cabbageworm populations, but tebufenozide was highly effective against this pest with similar cumulative imported cabbageworm levels as spinosad-treated plots.

Cumulative populations of all three caterpillar species were significantly different among treatments in the 21 May 1997 planting (Table 2). Permethrin and spinosad again provided the greatest level of control of diamondback moth larvae; whereas, plots treated with imidacloprid and tebufenozide provided little control ($F = 14.37$; df = 7, 21; $P = 0.0001$). As with diamondback moth, imidacloprid had little effect in reducing imported cabbageworm and cabbage looper populations; whereas, tebufenozide was highly effective against these pests with similar cumulative imported cabbageworm and cabbage looper levels as spinosad-treated plots (Table 2).

Table 3. Cumulative caterpillar populations per plot (mean ± SEM) for diamondback moth, imported cabbageworm, and cabbage looper for the 11 July 1997 planting (df = 7, 21)

	Cumulative caterpillar populations		
	Diamondback moth	Imported cabbageworm	Cabbage looper
B. thuringiensis	110.00 ± 2.68bc	71.25 ± 10.59c	10.25 ± 2.06ab
B. thuringiensis + imidacloprid	92.00 ± 9.10b	68.75 ± 15.26bc	11.00 ± 2.55abc
Carbaryl	137.25 ± 3.47c	102.00 ± 13.77d	26.75 ± 6.29d
Imidacloprid	181.50 ± 24.50d	178.25 ± 7.43e	19.50 ± 4.33cd
Permethrin	21.00 ± 5.58a	39.25 ± 3.28ab	3.00 ± 0.41a
Spinosad	36.75 ± 3.79a	38.25 ± 9.39a	9.00 ± 1.47a
Tebufenozide	216.75 ± 6.84de	37.00 ± 9.01a	4.25 ± 1.38a
Untreated	222.25 ± 25.33e	163.50 ± 13.94e	18.75 ± 4.05bcd
F-value	33.18	30.83	6.85
P-value	0.0001	0.0001	0.0003

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

In fact, tebufenozide plots had the lowest cumulative number of cabbage looper of any of the plots in this planting.

In the 11 July 1997 planting, diamondback moth populations per 10 plants in permethrin and spinosad treatments were significantly lower than all other treatments ($F = 33.18$; df = 7, 21; $P = 0.0001$) (Table 3). In fact, permethrin and spinosad treatments had consistently lower diamondback moth counts on all sampling dates after the first application. All materials tested except tebufenozide resulted in significantly lower cumulative diamondback moth populations than the untreated plots (Table 3). Tebufenozide again was highly effective against imported cabbageworm and cabbage looper (Table 3).

Effects on *Diadegma insulare*. There were highly significant differences in percentage of parasitism of diamondback moth larvae by *D. insulare* between treatments ($F = 67.37$; df = 7, 21; $P = 0.0001$) in the 20 May 1996 planting (Table 4). Cumulative percentage of parasitism of diamondback moth larvae by *D. insulare* was highest in plots treated with spinosad, and lowest in plots treated with permethrin. Although plots treated with imidacloprid and tebufenozide provided little control of diamondback moth larvae, they did allow for high levels of parasitism by *D. insulare* in the field (Table 4).

Although percentage of parasitism of diamondback moth in the 11 July planting was lower than in the 20 May 1996 planting, differences between treatments remained highly significant ($F = 24.90$; df = 7, 21; $P = 0.0001$) in the 21 May 1997 planting (Table 4). Cumulative percentage of parasitism of diamondback moth by *D.*

Table 4. Cumulative percentage of parasitism of diamondback moth by *Diadegma insulare* per plot (mean ± SEM) for all plantings (df = 7, 21)

	Cumulative percent parasitism by *D. insulare*		
	20 May 1996	21 May 1997	11 July 1997
B. thuringiensis	63.5 ± 4.1cd	56.7 ± 2.6b	38.4 ± 2.1c
B. thuringiensis + imidacloprid	61.6 ± 3.4c	60.4 ± 1.8bcd	36.2 ± 2.5c
Carbaryl	33.0 ± 3.7b	34.2 ± 2.0a	25.0 ± 1.3b
Imidacloprid	63.8 ± 2.6cd	56.3 ± 2.3b	50.5 ± 2.6d
Permethrin	19.6 ± 2.2a	30.4 ± 5.2a	10.5 ± 2.7a
Spinosad	83.8 ± 1.8e	68.3 ± 2.5d	42.5 ± 2.7c
Tebufenozide	66.5 ± 1.5cd	65.0 ± 2.5cd	42.5 ± 4.0c
Untreated	71.0 ± 1.9d	60.0 ± 1.2bc	53.0 ± 0.6d
F-value	67.37	24.90	28.39
P-value	0.0001	0.0001	0.0001

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

insulare was highest in plots treated with spinosad; whereas, plots treated with the conventional synthetic insecticides, carbaryl and permethrin, had low rates of parasitism.

Cumulative percentage of parasitism of diamondback moth by *D. insulare* was significantly higher in untreated plots and plots treated with imidacloprid compared with the other treated plots (Table 2). Plots treated with the conventional synthetic insecticides carbaryl and permethrin again had low levels of parasitism due to their acute toxicity to the *D. insulare* parasitoid. Although plots treated with imidacloprid and tebufenozide provide little to no control of diamondback moth, they do allow for high levels of parasitism by *D. insulare* in the field.

Effects on cabbage crop. Table 5 shows the harvest data for the 20 May 1996 planting. Weight per head was not significantly different between treatments. Damage ratings were significantly different ($F = 35.21$; df = 7, 21; $P = 0.0001$), with permethrin and spinosad plots sustaining the least amount of feeding damage. As a result, a high percentage of cabbage heads in the permethrin- and spinosad-treated plots were marketable, as were plots treated with *B. thuringiensis.* Plots treated with *B. thuringiensis* had a high level of marketable heads in this planting likely due to low populations of imported cabbageworm and cabbage looper, which can contribute significantly to overall damage (Tables 1, 5).

Table 6 shows the harvest data for the 21 May 1997 plantings. Weight per head was not significantly different between treatments. However, differences in insect defoliation among treatments were highly significant with permethrin and spinosad plots sustaining the least amount of feeding damage. As a result, a high percentage of cabbage heads in the permethrin- and spinosad-treated plots were marketable. In

Table 5. Cabbage yield and damage per plot (1, very slight damage; 4, serious damage) for the 20 May 1997 planting (df = 7, 21)

	Head yield and damage		
	Kilograms per head	Damage rating	Percent marketable
B. thuringiensis	1.73 ± 0.09	1.48 ± 0.06bc	90.00 ± 4.16cde
B. thuringiensis + imidacloprid	1.65 ± 0.10	1.68 ± 0.06cd	82.00 ± 2.58bcd
Carbaryl	1.68 ± 0.05	1.86 ± 0.13de	77.00 ± 2.52bc
Imidacloprid	1.61 ± 0.04	2.95 ± 0.21f	40.00 ± 12.33a
Permethrin	1.58 ± 0.02	1.03 ± 0.03a	100.00 ± 0.00e
Spinosad	1.63 ± 0.05	1.20 ± 0.07ab	96.00 ± 0.00de
Tebufenozide	1.82 ± 0.09	2.13 ± 0.13e	66.00 ± 2.00b
Untreated	1.58 ± 0.10	3.00 ± 0.20f	37.00 ± 9.00a
F-value	1.28	35.21	18.90
P-value	0.3070	0.0001	0.0001

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

this planting, plots treated with *B. thuringiensis* did not have acceptable levels of marketable heads due to higher populations of imported cabbageworm and cabbage looper present as compared to the 20 May 1996 planting (Tables 2, 6).

In the 11 July 1997 planting, imidacloprid and untreated plots had significantly lower head weights than all other treatments ($F = 6.62$; df = 7, 21; $P = 0.0003$). Permethrin and spinosad plots sustained the least amount of feeding damage ($F = 371.0$; df = 7, 21; $P = 0.0001$) (Table 7). As a result, permethrin and spinosad plots were the only treatments with acceptable levels of marketability. It is important to note that without the use of effective insecticides, the crop will not be marketable even though parasitism levels may be high, as was the case in plots treated with imidacloprid and untreated plots.

Effects on population dynamics. Figure 1 shows the population dynamics of *D. insulare* and diamondback moth for the 20 May 1996 planting. The population dynamics for the other two plantings was similar, and the 20 May 1996 planting is presented as a representative example. Figure 1c shows that the first application of carbaryl caused a disruption in the population dynamics of the parasitoid and its host compared with untreated plots (Fig. 1h). The diamondback moth population increased after the first carbaryl application; whereas, the rate of parasitism was reduced as a result of the application (Fig. 1c). This application was highly disruptive to the *D. insulare* population, resulting in a loss of natural control. Plots treated with *B. thuringiensis* or *B. thuringiensis* and imidacloprid did not adversely affect *D. insulare* populations, thus allowing *D. insulare* to remain synchronized with the population dynamics of its host (Figs. 1a, b). Imidacloprid and tebufenozide also were not dis-

Table 6. Cabbage yield and damage per plot (1 = very slight damage, 4 = serious damage) for the 21 May 1997 planting (df = 7, 21)

	Head yield and damage		
	Kilograms per head	Damage rating	Percent marketable
B. thuringiensis	1.23 ± 0.08	2.22 ± 0.10b	67.00 ± 4.73d
B. thuringiensis + imidacloprid	1.05 ± 0.07	2.43 ± 0.03bc	57.00 ± 2.52d
Carbaryl	1.16 ± 0.11	2.65 ± 0.06c	38.00 ± 4.76c
Imidacloprid	1.02 ± 0.08	3.96 ± 0.03e	0.00 ± 0.00a
Permethrin	1.10 ± 0.12	1.31 ± 0.07a	99.00 ± 1.00e
Spinosad	1.30 ± 0.09	1.39 ± 0.07a	97.00 ± 1.92e
Tebufenozide	1.28 ± 0.07	3.07 ± 0.17d	19.00 ± 6.81b
Untreated	1.02 ± 0.12	3.93 ± 0.03e	0.00 ± 0.00a
F-value	1.43	157.00	129.00
P-value	0.2477	0.0001	0.0001

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

ruptive to the natural population dynamics of *D. insulare* and diamondback moth (Figs. 1d, g). The first application of permethrin dramatically reduced both diamondback moth and *D. insulare* populations and the level of parasitism remained at near-zero levels throughout the remainder of the season (Fig. 1e). Because the population was susceptible to permethrin, diamondback moth levels were kept below the economic threshold even without help from natural enemies. Plots treated with spinosad provided good diamondback moth control and allowed for the survival of *D. insulare,* maximizing the effects obtained from the parasitoid population (Fig. 1f).

Summary. Because diamondback moth larvae feed on cruciferous vegetables, which usually have high cosmetic standards, a high level of control is necessary. Historically, the primary means of control has been the use of synthetic insecticides. The use of insecticides in this study significantly reduced the number of diamondback moth larvae in head cabbage. All insecticide treatments, except imidacloprid, were effective in lowering larval numbers compared with the untreated control (Tables 1, 2, 3). Permethrin and spinosad were consistently the two most efficacious compounds in this study, reducing diamondback moth populations by as much as 90 and 85%, respectively. As a result, these two compounds produced the only acceptable levels of marketability (Tables 5, 6, 7). *Bacillus thuringiensis* provided efficacy ranging from good to poor; whereas, carbaryl, imidacloprid, and tebufenozide applications resulted in poor control of diamondback moth populations.

All stages of diamondback moth are attacked by numerous parasitoids and predators, with parasitoids being the most widely studied. More than 90 parasitoid species attack diamondback moth worldwide (Goodwin 1979). Among these, six species

Table 7. Cabbage yield and damage per plot (1 = very slight damage, 4 = serious damage) for the 11 July 1997 planting (df = 7, 21)

	Head yield and damage		
	Kilograms per head	Damage rating	Percent marketable
B. thuringiensis	0.66 ± 0.07b	2.13 ± 0.07b	74.00 ± 3.46c
B. thuringiensis + imidacloprid	0.71 ± 0.08b	2.12 ± 0.08b	77.00 ± 3.42c
Carbaryl	0.73 ± 0.07bc	2.76 ± 0.08c	33.00 ± 6.40b
Imidacloprid	0.44 ± 0.09a	3.87 ± 0.07d	0.00 ± 0.00a
Permethrin	0.89 ± 0.03c	1.06 ± 0.03a	100.00 ± 0.00d
Spinosad	0.71 ± 0.10b	1.14 ± 0.03a	100.00 ± 0.00d
Tebufenozide	0.71 ± 0.04b	2.69 ± 0.07c	33.00 ± 3.00b
Untreated	0.45 ± 0.03a	3.96 ± 0.02d	0.00 ± 0.00a
F-value	6.62	371.00	199.00
P-value	0.0003	0.0001	0.0001

Means within a column followed by the same letter are not significantly different by Fisher's protected least significant difference test ($P = 0.05$).

attack diamondback moth eggs, 38 attack larvae, and 13 attack pupae (Lim 1986). Of the parasitoids that attack diamondback moth, larval parasitoids are the most predominant and effective. Many of the effective larval parasitoids belong to two major genera, *Diadegma* and *Cotesia*. In diamondback moth life table studies conducted in Canada, Harcourt (1986) determined that *D. insulare* is a major mortality factor affecting larvae from the second stadium through the middle of the fourth stadium. Diamondback moth parasitism in his studies ranged from 0 to 89%, with an average of 38%. Our experiment also revealed that *D. insulare* was the most prominent of the diamondback moth parasitoids with percentage of parasitism as high as 84%.

The broad-spectrum insecticides carbaryl and permethrin adversely affected parasitism by *D. insulare* throughout this study. Of all the compounds tested, permethrin caused the most disruption to parasitism by *D. insulare;* however, high levels of caterpillar control were obtained in permethrin-treated plots. Currently, permethrin is a viable option that will provide Indiana cabbage growers with a highly marketable crop. However, overuse of permethrin through a unilateral chemical control approach likely will cause the development of resistance in the diamondback moth population, ultimately resulting in control failures.

Conversely, the selective insecticides *B. thuringiensis,* spinosad, and tebufenozide all allowed high levels of parasitism by *D. insulare.* However, spinosad was the only selective compound that consistently provided for a high cosmetic-quality cabbage crop. Percentage of parasitism was not affected by the spinosad applications thereby allowing *D. insulare* populations to effectively suppress diamondback moth populations. Thus, because spinosad reduces caterpillar populations, yet allows for *D. in-*

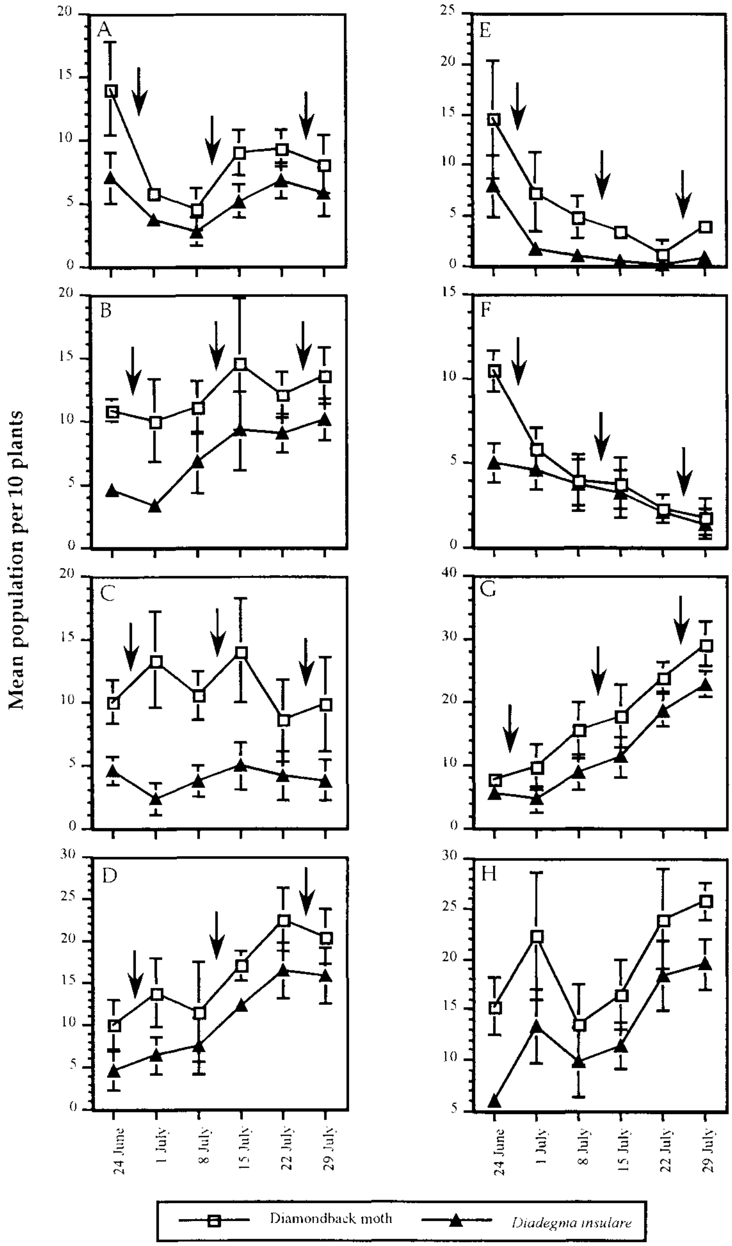

Fig. 1. Population dynamics of *D. insulare* and diamondback moth for the 20 May 1996 planting in plots treated with (A) *B. thuringiensis,* (B) *B. thuringiensis* and imidacloprid, (C) carbaryl, (D) imidacloprid, (E) permethrin, (F) spinosad, (G) tebufenozide, and (H) untreated plots. (Arrows indicate insecticide application.)

sulare survival, it provides the additive effect of chemical caterpillar control with biological control of diamondback moth throughout the growing season. Maintaining the resident *D. insulare* population is essential for a resistance management program because the presence of *D. insulare* can reduce the diamondback moth population, subsequently reducing the frequency of insecticide sprays necessary for caterpillar control. By reducing the number of insecticide sprays, we can delay the development of resistance by diamondback moth, thus prolonging the efficacy of insecticides in the field. In addition, reducing the frequency of insecticide sprays will reduce the cost of production for the grower.

As this study demonstrates, it is difficult to produce cabbage for the fresh market with high cosmetic quality and a low cull rate without the use of insecticides. However, several actions can reduce the impact of insecticides on resident natural enemy populations. It is important to use insecticides only when necessary as determined by pest monitoring. When it becomes necessary to use insecticides, only those that are known to have minimal impact on natural enemies should be used. Selective materials should be used early in the season to allow *D. insulare* populations to build up to keep diamondback moth at low levels throughout the remainder of the growing season. Compounds that provide good control of caterpillar pests and allow the survival of *D. insulare,* will likely require fewer applications throughout the season. Conversely, materials such as permethrin that are highly toxic to *D. insulare* will disrupt the natural control of diamondback moth and necessitate the application of insecticides throughout the season. This will make cabbage growers dependent on insecticide use, thereby promoting the development of resistance and dramatically increasing the cost of production.

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