Dynamics of diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae), in cabbage under intercropping, biological control and Bt-based sprays[1]

Ángel L. González-Rodríguez[2] *and Raúl Macchiavelli*[3]

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ABSTRACT

A field study (1998-99) was conducted at the Juana Díaz Substation (AES-UPR) to determine the population dynamics of *Plutella xylostella* (L.) in cabbage in a monoculture and in relay-type substitutive dicultures of cabbage/tomato or cabbage/wedelia. In 1998, subplots were created by spraying half of the main plots with *Bacillus thuringiensis* (Bt)-based products. All treatments, except for the control monoculture, were sprayed with Bt-based products in 1999. *Cotesia plutellae* Kurjumov, a larval parasitoid of *P. xylostella*, was released augmentatively for biological control. Tomato, as a companion crop, showed a tendency for reducing *P. xylostella* densities in cabbage, reduced the levels of *C. plutellae* parasitism and competed with cabbage, causing fewer and smaller heads. Bt-based sprays reduced *P. xylostella* densities, but these were at damaging levels at the critical stages of cupping and head formation, thus permitting cosmetic damage to cabbage heads. *Cotesia plutellae* did not regulate the *P. xylostella* population, thus resulting in parasitism levels of 65.3 and 11.6% in the unsprayed monoculture in 1998 and 1999, respectively. The legume *Crotalaria juncea* L. as a border did not improve parasitism by *C. plutellae*. The interpretation and application of the results are discussed.

Key words: diamondback moth, intercropping, biological control, Bt-based products, substitutive dicultures

RESUMEN

DINÁMICA POBLACIONAL DE LA ALEVILLA DEL DORSO DE DIAMANTE, *PLUTELLA XYLOSTELLA* (L.) (LEPIDOPTERA: PLUTELLIDAE), EN REPOLLO BAJO CONDICIONES DE INTERCALADO, CONTROL BIOLÓGICO Y ASPERSIONES CON PRODUCTOS A BASE DE BT

Se realizó un estudio (1998-99) en la Subestación Experimental Agrícola de Juana Díaz (EEA-UPR) para determinar la dinámica poblacional de *Plutella xylostella* (L.) en repollo de monocultivo y en dicultivos sustitutivos tipo relevo de repollo/tomate o repollo/wedelia. En 1998, se crearon subparcelas tratando la mitad de las parcelas principales con productos a base de Bt. Todos los tratamientos se asperjaron con Bt en 1999 excepto por las par-

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[2] Associate Professor, Department of Crop Protection, University of Puerto Rico-Mayagüez, P.O. Box 9030, Mayagüez, P.R. 00681-9030.

[3] Professor, Department of Agronomy and Soils.

celas del control en monocultivo. Se liberaron avispillas de *Cotesia plutellae* Kurdjumov, un parasitoide de larvas de *P. xylostella*, para el control biológico por inundación. El tomate como planta acompañante mostró una tendencia a reducir las poblaciones de *P. xylostella*, redujo el parasitismo por *C. plutellae* y compitió con el repollo causando la producción de cabezas más pequeñas y menos numerosas en el policultivo. Las aspersiones con Bt redujeron la densidad poblacional de *P. xylostella*, pero éstas permanecieron por encima de 0.5 larvas por planta durante las etapas críticas de acopamiento y desarrollo de las cabezas, permitiendo así daños cosméticos a la cabeza. El parasitismo por *C. plutellae* fue de 65.3 y 11.6% en el monocultivo sin Bt en 1998 y 1999, respectivamente. El parasitoide no pudo regular el crecimiento poblacional de su hospedero en este estudio. La leguminosa *Crotalaria juncea,* utilizada como borde, no mejoró el parasitismo por *C. plutellae*. Se discute la interpretación y aplicación de los resultados.

INTRODUCTION

Cabbage and other brassicaceous crops are attacked by several destructive insect pests in America and other parts of the world. Among these, the diamondback moth (DBM), *Plutella xylostella* (L.), has become the most damaging because of its widespread resistance to most classes of insecticides, including *Bacillus thuringiensis* (Bt)-based products (Armstrong, 1990; Pérez and Shelton, 1996; Shelton et al., 1993; Talekar, 1992; Talekar and Shelton, 1993). Talekar (1992) estimated at $1 billion the annual world cost of controlling the DBM on brassicaceous crops.

In Puerto Rico, about 47,727 kg of cabbage is consumed annually (Alamo, 1992). Of the total consumption, only 14% (6,818 kg) and 8.6% (4,091 kg) was produced on the Island during the years 1996-97 and 1997-98, respectively, a drastic reduction compared to the 1980s figures (Dept. Agric., 1998). The decline in cabbage production started in 1989-90, when a 40% reduction was reported as compared with the mean production of 22,727 kg (47% of the total consumption) for the previous five years (Alamo, 1992). Inefficacy of control methods for the DBM, traditionally based on chemical sprays on a calendar basis, is considered the major factor in the reduction of cabbage acreage and yield in the central mountainous region and on the south coast (Armstrong, 1990, 1992; Alamo, 1992).

Worldwide, DBM control has been based primarily on sprays of synthetic insecticides in the groups of organophosphates, carbamates, pyrethroids and insect growth regulators (Armstrong, 1992; Talekar, 1992; Talekar and Shelton, 1993). Bt products were introduced in the 1970s, but their use was limited to areas where other insecticides had failed and in integrated pest management programs focused on conserving parasitoids and predators. Resistance to all major classes of insecticides was reported a few years after their introduction for DBM control (Armstrong, 1992; Liu et al., 1981; Shelton and Wyman, 1992; Sun et al., 1978; Talekar, 1992; Talekar and Griggs, 1986). Cross-resistant and multiple-resistant strains of DBM are now common in various parts of its geographical range (Talekar, 1992; Talekar and Shelton, 1993). In Southern areas of the continental Unites States and Hawaii, brassica production was not profitable for a while because of DBM resistance to insecticides (Cartwright et al., 1992; Tabashnik et al., 1990, 1992; Talekar and Shelton, 1993). Levels of resistance to Bt in some areas of Florida remained very high for several consecutive years, more than 1,000-fold higher than resistance levels of a susceptible strain (Pérez and Shelton, 1996; Shelton et al., 1993). Up to 20 insecticide applications per season in rotations of pyrethroids, carbamates, organophosphates and Bts, often at increasingly higher rates, were required in some areas of the southern USA (Cartwright et al., 1992).

Alternate control approaches are necessary to manage the DBM in cabbage to avoid the adverse effects of the pesticide treadmill. This study was conducted to determine the effects on the DBM populations of intercropping cabbage with tomato or wedelia [*Wedelia trilobata* (L.)] in substitutive arrangements, biological control with a DBM larval parasitoid, and sprays with Bt-based products.

MATERIALS AND METHODS

First experiment (1998)

This study was conducted at the Agricultural Experiment Station at Juana Díaz. A split-plot design (3 × 2) was arranged in a randomized complete block with six treatments and four replications. Main plots were 1) a cabbage monoculture (C); 2) a cabbage/tomato diculture (C/T) in a substitutive arrangement; 3) a cabbage/wedelia diculture (C/W) in a substitutive arrangement. The subplots consisted of 1) no Bt-based sprays (-Bt); 2) Bt-based sprays (+Bt). Experimental plots consisted of five hills 1.8 m wide by 15.2 m long. The cabbage monoculture was of two rows per hill, planted at a distance of 0.6 m between rows and 0.3 m apart within the row. In the dicultures, one of the cabbage rows in each hill of the monoculture was replaced by tomato or wedelia to produce substitutive arrangements. All plots were bordered by two rows of field corn (cv Mayorbela) on each side. A 6.1-m alley of field corn separated the blocks. Field corn as a bordering plant and tomato (cv Duke) and wedelia (planted as fresh cuttings) as companion plants were planted 27 and 28 January. Cabbage (cv Izalco) was transplanted 10 February (10 to 11 days later) to produce relay-type intercrops. A total of 79.5 kg/ha each of N, P_2O_4, and K_2O was preplant incorporated. In addition, three applications of 14.6 kg/ha of urea nitrogen were made through fertigation. All other recommended practices for intensive cabbage production on the south coast of Puerto Rico were followed, except that no plastic cover was used over the rows, and weeds were controlled chemically or by hand weeding (Agric. Exp. Sta., 1999).

Bt-based products [Xentari® WDG (ai *B. thuringiensis*, subsp. *aizawai*, 10.3% w/w), Dipel® 2x WP (ai *B. thuringiensis*, subsp. *kurstaki*, 6.4% w/w) and Mattch® AF (ai *B. thuringiensis*, subsp. *kurstaki*, Cry 1A and Cry 1C encapsulated delta endotoxins in dead cells of *Pseudomonas fluorescens*, 12% w/w)][4] were sprayed weekly; we alternated mixtures or individual products to control lepidopterous defoliators. To reduce an outbreak of the fall armyworm, *Spodoptera frugiperda* (Smith), Xentari was applied at the rate of 0.57 kg/ha 27 February and 24 March, and Mattch was sprayed at the rate of 4.8 L/ha 13 and 20 March and 3 April. A mixture of Dipel and Xentari (0.5 kg/ha each) was applied 6 March and 17 April. The bioinsecticides were applied with a Solo® sprayer, model 322, at a pressure of 4.23 kg/cm^2 and a volume of 360 L of water/ha. The surfactant Spray Aid® was added at a concentration of 0.1% (v/v) to all applications.

Larval and pupal stages of the DBM were counted weekly by sampling five cabbage plants of the three central rows of each subplot, except at 16 days after planting (DAP), when ten plants per plot were sampled. Counts were made on the standing plants during the first four sampling dates, but were made on plants clipped at soil level for the remaining samples. On the latter, leaves were cut and examined individually to obtain more accurate counts on larger plants. Samples were taken 16, 23, 31, 37, 44, 51, 63 and 70 DAP. Table 1 summarizes the dates of Bt product sprays and DBM samples on cabbage.

Cotesia plutellae Kurdjumov, a larval parasitoid of DBM, was released in the experimental area on 9 and 24 March (29 and 44 DAP, respectively) at a rate of 1,182 pairs per hectare. The parasitoid was obtained from Biofac, Inc. (P.O. Box 87, Mathis, Texas 78368). The parasitoid larva emerges from the mid fourth host larva to pupate outside its host. Early fourth instar DBM larvae were collected 14 days after the first release and at harvest to quantify parasitism. Ten cabbage plants from the central rows of each subplot were sampled and all DBM larvae in the proper stage of development removed. The DBM larvae were placed in 15-mm petri dishes and maintained in the laboratory on cabbage leaves until pupation occurred or a parasitoid

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[4] Trade names in this publication are used only to provide specific information. Mention of a trade name does not constitute a warranty of equipment or materials by the Agricultural Experiment Station of the University of Puerto Rico, nor is this mention a statement of preference over other equipment or materials.

TABLE 1.—*Dates of Bt products application and diamondback moth sampling on cabbage, 1998-1999, Juana Díaz.*

	Dates (DAP)[1]						
	February		March		April		Total
1998	Spray	Sample	Spray	Sample	Spray	Sample	sprays
Xentari WDG	27 (17)	26 (16)	24 (42)	26 (44)			2
Dipel 2X WP + Xentari WDG			6 (24)	5 (23)	17 (66)	14 (63) 21 (70)	2
Mattch AF			13 (31) 20 (38)	13 (31) 19 (37)	3 (52) 5 (47)	2 (51)	3
1999							
Mattch AF			18 (30) 25 (37)	11 (23) 18 (30) 31 (42)	12 (54) 23 (65)	8 (50) 15 (57) 22 (64) 29 (71)	5

[1] Days after planting.

emerged. Percentage parasitism was calculated as [number of parasitized DBM larvae/ (number of DBM larvae + pupae)] × 100.

Cabbage was harvested at 67 DAP. Head quality was rated according to a 1 to 6 scale modified from Greene et al. (1969) as follows: 1) no apparent damage (first quality); 2) minor damage to wrapping leaves (about 5% of leaves damaged, first quality); 3) minor damage to wrapper leaves (10%), one head leaf damaged (second quality); 4) minor damage to wrapper leaves, two head leaves damaged (second quality); 5) three to four leaves of head damaged, moderate damage to wrapper leaves (unmarketable); 6) four or more leaves of head damaged (unmarketable).

Data were analyzed by using a split-plot model and means were separated with Tukey-Kramer on least square means at $\alpha = 0.05$. Normality was tested with the Wilk-Shapiro test, and variances were tested for homogeneity with the Levene test. All analyses were performed on SAS version 6.12 for Windows. Counts were log $(x + 1)$-transformed when assumptions for the analysis of variance were not met.

Second Experiment (1999)

This study was conducted at the Agricultural Experiment Station in Juana Díaz. Four treatments were arranged in a randomized complete block design with four replications. Experimental treatments were 1) a cabbage monoculture, no Bt sprayed (-Bt/C); 2) a cabbage monoculture plus a border row of *C. juncea* (CJ) (as an insectary plant) and Bt-based sprays (+Bt/C/CJ); 3) a cabbage/tomato diculture in a substitutive arrangement and Bt-based sprays (+Bt/C/T); 4) a cabbage/tomato diculture in a substitutive arrangement plus a border row of *C. juncea* and Bt-based sprays (+Bt/C/T/CJ). Experimental plots consisted of five hills 1.8 m wide by 15.2 m long. In the -Bt/C and +Bt/C/CJ treatments, ten rows (two per hill) of cabbage per plot were planted at 0.91 m between rows and 0.30 m apart in the row. In the dicultures (+Bt/C/T and +Bt/C/T/CJ treatments), one cabbage row of the monoculture was replaced alternatively by a tomato row. Bare ground alleys of 9.1 m and 15.2 m separated the plots within the blocks and between blocks, respectively. A total of 114 kg/ha each of N, P_2O_4, and K_2O was incorporated before planting. Additionally, 163 kg/ha each of N, P_2O_4, and K_2O was side-dressed at the beginning of cupping stage, 42 DAP. All other practices were as specified for the 1998 experiment.

Crotalaria juncea was planted from seed on 2 December (77 days before cabbage); tomato (cv Duke) was transplanted 19 January and cabbage (cv Izalco) 18 February. DBM larvae were controlled with Mattch AF at the rate of 6.3 L/ha in a volume of water of 341 L/ha. A higher rate than the one used in the 1998 experiment was applied to achieve a better control of DBM larvae. The equipment and the spray pressure used for the application were as described for the first experiment, except that the boom of the sprayer (Solo® 322 sprayer) was modified to have one nozzle to direct the spray toward the top of the plants and two to direct the spray toward the underside of leaves. Spraying was done on 18 and 25 March, and 5, 12 and 23 April. A surfactant was added as before.

Larval and pupal stages of the DBM were estimated in cabbage 23, 30, 37, 42, 50, 57, 64 and 71 DAP. Ten standing cabbage plants per plot were checked in the field during the first four sampling dates, but only five plants per plot were clipped at soil level during the remaining dates. All leaves were inspected on all the sampling dates and stages of DBM counted. Samples were taken from the three innermost rows. Table 1 summarizes the dates of Bt product sprays and DBM samples on cabbage.

The parasitoid *C. plutellae* was released 54 DAP at the rate of 1,681 pairs per hectare. The parasitoid was not delivered on time by the supplier for the scheduled releases. A higher rate was used in this experiment to compensate for a 25 to 30% mortality of the parasitoid adults that occurred before releases in the 1998 experiment. To estimate the percentage of parasitism, we collected fourth instar DBM larvae on ten cabbage plants per plot 14 days after the parasitoid was released. Collected larvae were handled as before. A sample was also collected after harvest to monitor parasitism on crop residues.

Cabbage was harvested at 72 DAP (30 April). Two inner rows per plot were harvested; plants at each end of the rows were left. Cabbage heads were rated for quality as in the 1998 experiment.

Data were analyzed by using the GLM procedure on SAS for Windows, and means were separated with Tukey's test at $\alpha = 0.05$. Normality and homogeneity of variances were tested as before. When necessary, counts were transformed as before.

RESULTS

First Experiment (1998)

DBM populations peaked 44 DAP with 46, 29.3 and 38.5 larvae + pupae (L+P in tables) per plant and then declined 70 DAP to 4.4, 10.8 and 10.5 larvae + pupae per plant in the -Bt/C, -Bt/C/T and -Bt/C/W subplots, respectively (Table 2). Peak populations of DBM were also reached 44 DAP in the +Bt subplots. There were no significant differences ($P > 0.05$) in the total number (L+P) of DBM among the -Bt subplots, although there was a tendency for the C/T diculture to have lower densities than the monoculture or the C/W diculture on some of the sampling dates (Table 2).

Bt sprays significantly reduced the number of DBM per plant compared with that of the untreated subplots (-Bt by +Bt comparisons, Table 2) on sampling dates 31 to 51 DAP, but this reduction was not sufficient to maintain DBM populations below economic injury levels. This result was also confirmed by comparisons in the number of DBM between subplots within main plots on some of the sampling dates (main plot-subplot combinations). Larval densities were 15.8 per plant in the Bt-treated subplots at the beginning of the critical stages of cupping and head formation (~44 DAP). DBM larval (L) densities continued above acceptable economic levels until harvest in the +Bt subplots. Seven sprays of Bt-based products were made alternatively or in mixtures, but larvae were able to cause feeding damage on the heads between sprays. Once the larvae bore into the head, it was impossible to reach them with Bt-based sprays. Intercropping (C/T, C/W) did not cause any reduction in DBM populations compared with those of the monoculture; moreover, the number of DBM larvae was significantly higher in the C/T intercropping than in the monoculture on the last sampling date (70 DAP). Furthermore, the number of DBM pupae on cabbage in both intercroppings was significantly higher than in the monoculture 70 DAP.

Tomato used as a companion plant for cabbage significantly reduced the total weight (kg) of cabbage heads compared to that in the monoculture (main plots, Table 3). Also, fewer heads were harvested in C/T

TABLE 2.—*Population of the diamondback moth (DBM) on cabbage under intercropping and Bt-based sprays, Juana Díaz, Puerto Rico, 1998.*

	Mean number of DBM/plant[1, 2]													
DAP	23		31		37		44		51		63		70	
	L	L+P	L	L+P	L	L+P	L	L+P	L	L+P	L	L+P	L	L+P
							Main plots							
C	3.8 a	4.0 a	5.6 a	7.5 a	4.8 a	5.8 a	27.0 a	31.1 a	10.2 a	15.2 a	0.8 a	1.2 a	2.8 a	3.8 a
C/T	5.1 a	5.1 a	7.9 a	10.5 ab	3.6 a	4.2 a	17.4 a	19.9 a	4.7 a	8.6 a	1.3 a	2.1 a	6.5 b	11.3 a[3]
C/W	4.9 a	5.0 a	11.1 a	14.9 b	7.7 a	9.4 a	28.4 a	31.9 a	11.1 a	18.4 a	1.5 a	2.1 a	5.3 ab	7.9 a[3]
							Subplots							
-Bt	4.0 a	4.1 a	9.2 a	12.8 a	8.7 a	10.7 a	32.7 a	38.0 a	11.2 a	18.6 a	1.3 a	2.2 a	5.5 a	8.6 a
+Bt	5.2 a	5.4 a	7.1 a	9.1 b	2.0 b	2.4 b	15.8 b	17.3 b	6.1 b	9.5 b	1.0 a	1.3 a	4.3 a	6.8 a
							Main plot-Subplot combinations							
-Bt/C	3.8 a	4.0 a	5.8 a	8.2 a	7.8 a	9.8 a	39.2 a	46.0 a	12.9 a	20.2 a	0.6 a	1.3 a	3.2 a	4.4 a
+Bt/C	3.8 a	4.0 a	5.4 a	6.8 a	1.6 a	1.8 a	14.8 b	16.2 b	7.4 a	10.0 b	0.8 a	1.1 a	2.4 a	3.2 a
-Bt/C/T	3.5 a	3.5 a	10.0 a	13.6 a	6.5 a	7.7 a	25.2 a	29.3 a	4.9 a	10.2 a	1.6 a	2.6 a	6.8 a	10.8 a
+Bt/C/T	6.7 a	6.8 a	5.8 a	7.4 b	0.8 b	1.0 b	9.6 b	10.4 b	4.5 a	7.6 a	1.0 a	1.2 a	6.2 a	11.8 a
-Bt/C/W	4.7 a	4.8 a	12.0 a	16.8 a	11.8 a	14.6 a	33.7 a	38.5 a	15.8 a	25.4 a	1.7 a	2.7 a	6.5 a	10.5 a
+Bt/C/W	5.1 a	5.4 a	10.1 a	13.0 a	3.6 a	4.2 b	23.2 a	25.3 a	6.5 a	11.3 b	1.2 a	1.6 a	4.3 a	5.3 a

[1] DAP = days after planting; C = cabbage monoculture; C/T = cabbage/tomato diculture in a substitutive arrangement; C/W = cabbage/*wedelia* diculture in a substitutive arrangement; -Bt = no *Bacillus thuringiensis* based sprays; +Bt = with *B. thuringiensis*-based sprays; L and P = larvae and pupae of DBM per cabbage plant.

[2] Means followed by the same letter within a column and effect are not significantly different ($\alpha = 0.05$, Tukey-Kramer test).

[3] Significantly higher number of pupae occurred in the C/T (4.8) and C/W (3.1) dicultures than in the C monoculture (1.0).

TABLE 3.—*Weight and quality of cabbage heads, and percentage of parasitism by* Cotesia plutellae *under intercropping and Bt-based sprays, Juana Díaz, Puerto Rico, 1998.*

Effect[1,2]	Total wt. (kg)	No. heads	Wt. (kg/head)	Rating	Parasitism (%) 3/23	Parasitism (%) 4/21
			Main plots			
C	63.8 a	103.2 a	0.61 a	6.00 a	7.6 a	65.3 a
C/T	16.1 b	31.4 b	0.49 b	5.94 a	10.1 a	37.3 b
C/W	30.6 ab	45.9 b	0.66 a	6.00 a	5.0 a	50.7 ab
			Subplots			
-Bt	30.9 b	55.9 a	0.54 a	5.99 a	8.4 a	51.8 a
+Bt	42.8 a	64.4 a	0.64 b	5.97 a	6.8 a	50.4 a
			Main plot-Subplot combinations			
-Bt/C	53.7 a	97.0 b	0.56 a	6.00 a	12.1 a	63.1 a
+Bt/C	73.9 b	109.5 b	0.67 a	6.00 a	3.1 a	67.4 a
-Bt/C/T	12.7 c	27.0 a	0.46 a	5.98 a	4.2 a	41.0 a
+Bt/C/T	19.4 c	35.8 a	0.52 a	5.90 a	16.2 a	33.6 a
-Bt/C/W	26.3 c	43.8 a	0.60 a	6.00 a	8.9 a	51.2 a
+Bt/C/W	35.0 c	48.0 a	0.73 a	6.00 a	1.0 a	50.2 a

[1] C = cabbage monoculture; C/T = cabbage/tomato diculture in a substitutive arrangement; C/W = cabbage/*wedelia* diculture in a substitutive arrangement; -Bt = no *Bacillus thuringiensis*-based sprays; +Bt = with *B. thuringiensis*-based sprays.

[2] Means followed by the same letter within a column and effect are not significantly different ($\alpha = 0.05$, Tukey-Kramer test).

and C/W main plots than in the monoculture (C). A significantly higher total yield was obtained in the +Bt and -Bt subplots (main plot-subplot combinations) of the monoculture (C) than in the +Bt and -Bt subplots of the C/T or C/W dicultures, but no difference was found between the +Bt and the -Bt subplots of the two latter subplots. In addition, the +Bt/C subplot had higher total yield than the -Bt/C subplot. Within main plots, size of heads was significantly reduced in the C/T diculture compared with that in the C or C/W main plots. In addition, significantly more heads were harvested in the monoculture (main plot) than in the two intercrops.

In this trial, the quality of cabbage heads was not acceptable for commercial purposes. Quality ratings were at the maximum of the scale or close to it (Table 3). DBM larval borings to the head was the primary reason for the high damage ratings.

The percentage of *C. plutellae* parasitism was not affected by Bt-based sprays (Table 3). No differences occurred in parasitism rates between -Bt and +Bt subplots on either of the two sampling dates.

Parasitism by this parasitoid was enhanced in the monoculture (main plot), significantly higher than in the C/T diculture. An intermediate parasitism rate was observed in the C/W main plot. Parasitism in the monoculture was high (65.3%) at harvest, but it occurred too late to significantly delay DBM population growth.

Second Experiment (1999)

DBM larval densities peaked to 40.6 per cabbage plant in the monoculture (-Bt/C) at 64 DAP (Table 4). Although peak densities were reached at a later stage in this study than in the 1998 experiment (44 DAP, Table 1), peak larval densities were about the same in both years. Bt-based sprays were much more effective in controlling the insect in 1999 than in the 1998 experiment, probably because of the higher rate of Bt used and the modification in the spraying equipment. At the highest larval densities, numbers were 2.4, 1.2 and 1.8 larvae per plant in the +Bt/C/CJ, +Bt/C/T, and +Bt/C/T/CJ treatments, respectively. Significant differences between the Bt-sprayed treatments and the control occurred from 42 DAP until harvest (71 DAP). The number of DBM larvae + pupae peaked to 54.2 per cabbage plant in the monoculture at 64 DAP (Table 5). Significant differences in the number of larvae + pupae between the Bt-sprayed treatments and the -Bt/C monoculture occurred from 37 DAP and continued until harvest. Generally, no differences in

TABLE 4.—*Population of diamondback moth larvae on cabbage under intercropping, Bt-based sprays and biological control, Juana Díaz, Puerto Rico, 1999.*

	Number of larva/plant/treatment[2]				
DAP[1]	-Bt/C	+Bt/C/CJ	+Bt/C/T	+Bt/C/T/CJ	*P*-value (F Test)
23	0.02 ± 0.02 a	0.05 ± 0.03 a	0.00 ± 0.00 a	0.00 ± 0.00 a	0.3272
30	0.07 ± 0.02 a	0.05 ± 0.05 a	0.28 ± 0.19 a	0.05 ± 0.05 a	0.4162
37	0.30 ± 0.06 a	0.20 ± 0.09 a	0.08 ± 0.05 a	0.08 ± 0.05 a	0.0543
42	1.12 ± 0.25 a	0.48 ± 0.12 b	0.30 ± 0.11 b	0.15 ± 0.12 b	0.0028
50	5.40 ± 2.59 a	1.05 ± 0.22 b	1.00 ± 0.22 b	0.75 ± 0.41 b	0.0130
57	12.30 ± 2.56 a	1.00 ± 0.55 b	0.45 ± 0.22 b	0.55 ± 0.15 b	0.0003
64	40.56 ± 11.06 a	2.45 ± 0.70 b	1.15 ± 0.29 b	1.80 ± 0.74 b	0.0001
71	16.10 ± 3.96 a	2.00 ± 0.32 b	1.60 ± 0.22 b	1.00 ± 0.26 b	0.0001
Total	9.60 ± 2.06 a	1.00 ± 0.14 b	0.68 ± 0.14 b	0.60 ± 0.20 b	0.0001

[1] Days after planting.

[2] Means (± SEM) followed by different letters within a row are significantly different at $\alpha = 0.05$ according to Tukey's test. Analysis based on log (x+1), observed data is shown. -Bt/C = cabbage alone; +Bt/C/CJ = cabbage with a border row of *Crotalaria juncea* plus Bt sprays; +Bt/C/T = cabbage with alternate rows of tomato plus Bt sprays; +Bt/C/T/CJ = cabbage with alternate rows of tomato and a border of *Crotalaria juncea* plus Bt sprays.

TABLE 5.—*Population of diamondback moth larvae (L) + pupae (P) on cabbage under intercropping, Bt-based sprays and biological control, Juana Díaz, Puerto Rico, 1999.*

	Number of L + P/plant/treatment[2]				
DAP[1]	-Bt/C	+Bt/C/CJ	+Bt/C/T	+Bt/C/T/CJ	*P*-value
23	0.10 ± 0.07 a	0.05 ± 0.03 a	0.02 ± 0.02 a	0.00 ± 0.00 a	0.2427
30	0.20 ± 0.07 a	0.30 ± 0.14 a	0.68 ± 0.42 a	0.30 ± 0.11 a	0.4222
37	0.98 ± 0.18 a	0.22 ± 0.08 b	0.22 ± 0.10 b	0.10 ± 0.04 b	0.0005
42	1.40 ± 0.03 a	0.48 ± 0.12 b	0.35 ± 0.12 b	0.20 ± 0.17 b	0.0029
50	10.15 ± 4.31 a	1.40 ± 0.37 b	1.15 ± 0.36 b	0.80 ± 0.39 b	0.0019
57	16.50 ± 3.37 a	1.70 ± 0.92 b	1.00 ± 0.48 b	0.80 ± 0.29 b	0.0005
64	54.20 ± 11.53 a	3.05 ± 0.90 b	1.40 ± 0.38 c	1.90 ± 0.72 bc	0.0001
71	41.00 ± 10.87 a	2.55 ± 0.19 b	2.25 ± 0.36 bc	1.20 ± 0.36 c	0.0001
Total	15.65 ± 2.82 a	1.35 ± 0.22 b	1.04 ± 0.26 bc	0.74 ± 0.23 c	0.0001

[1] Days after planting.

[2] Means (± SEM) followed by different letters within a row are significantly different at $\alpha = 0.05$ according to Tukey's test. Analysis based on log (x+1), observed data is shown. -Bt/C = cabbage alone; +Bt/C/CJ = cabbage with a border row of *Crotalaria juncea* plus Bt sprays; +Bt/C/T = cabbage with alternate rows of tomato plus Bt sprays; +Bt/C/T/CJ = cabbage with alternate rows of tomato and a border of *Crotalaria juncea* plus Bt sprays.

the number of DBM were declared among the three treatments receiving Bt sprays, although there was a tendency for the cabbage/tomato dicultures to have lower densities.

No difference occurred in the mean weight of cabbage heads, but heads in the cabbage/tomato dicultures were 28% to 32% smaller than those in the +Bt/C/CJ plots and 16.7% to 21.7% smaller than in the -Bt/C plots (Table 6). Significantly lower ratings of the head quality were found in Bt-sprayed treatments than in the control (-Bt/C). Also, quality ratings were lower (~4.0) in the Bt-sprayed treatments than in the 1998 experiment (~6.0). Marketable yield (50 to 61% of the total heads harvested) was significantly higher in the treatments sprayed with Bt-based products than in the unsprayed monoculture (-Bt/C). *Cotesia plutellae* did not cause any significant mortality (3 to 11.6%) of DBM larvae, and no differences were detected among treatments (Table 6).

DISCUSSION

For the 1998 experiment, DBM populations peaked at 44 DAP, but for 1999 peak densities occurred at 64 DAP. A tendency similar to that observed in our 1998 test has been reported by other researchers in various areas of North America (Harcourt, 1986; Lasota and Kok, 1986;

TABLE 6.—*Yield and quality of cabbage heads and parasitism by* Cotesia plutellae, *Juana Díaz, Puerto Rico, 1999.*

Treatment[1,2]	Weight/head (kg)	Rating (1-6)	First (%)	Commercial (%)	Parasitism (%)
-Bt/C	1.20 ± 0.12 a	5.81 ± 0.06 a	0.65 ± 0.65 a	3.80 ± 2.20 b	11.62 ± 6.79 a
+Bt/C/CJ	1.39 ± 0.14 a	3.94 ± 0.32 b	18.58 ± 9.45 a	60.90 ± 9.26 a	10.00 ± 5.77 a
+Bt/C/T	1.00 ± 0.07 a	4.29 ± 0.21 b	10.52 ± 2.62 a	50.50 ± 9.85 a	4.18 ± 4.18 a
+Bt/C/T/CJ	0.94 ± 0.16 a	3.98 ± 0.32 b	15.98 ± 4.83 a	58.25 ± 10.76 a	3.12 ± 3.12 a
P-value (F test)	0.0515	0.0004	0.1110	0.0010	0.6734

[1] -Bt/C = cabbage alone; +Bt/C/CJ = cabbage with a border row of *Crotalaria juncea* plus Bt sprays; +Bt/C/T = cabbage with alternate rows of tomato plus Bt sprays; +Bt/C/T/CJ = cabbage with alternate rows of tomato and a border of *C. juncea* plus Bt sprays.

[2] Means (± SEM) followed by the same letters within a column are not significantly different ($\alpha = 0.05$, Tukey's test).

Pimentel, 1961). According to Harcourt (1986), DBM populations increase until female fecundity declines in response to a reduction in the crude protein content of cabbage leaves and to the deterioration of climatic conditions as the season progresses. During this study, environmental conditions for DBM reproduction were favorable (dry, temperature above 25°C) and plants were supplemented with nitrogen fertilizer. Thus, the difference in results between the two years may have been caused by differences in damage to cabbage plants by the guild of crucifer defoliators in the area. In 1998, cabbage plants suffered high levels of defoliation, at the seedling and pre-cupping stages, by *S. frugiperda* larvae dispersing from corn plants and later by *P. xylostella* and *P. includens* larvae. This high defoliation rendered cabbage plants less attractive for colonization at an earlier stage of development in 1998 than in the 1999 experiment. *Plutella xylostella* host-finding cues and oviposition stimuli are reduced in heavily damaged host plants (Pivnick et al., 1994).

In this study, tomato plants were staked, and plants were high above cabbage plants forming a continuous barrier against DBM movement, thus producing a tendency for lower numbers in the C/T dicultures. This barrier may have reduced movement of DBM migrants from adjacent unsprayed plots, especially during the 1999 experiment, where plots were separated by greater distances. Previous studies have stated that tomato plants in close contact or in relay-type intercrops with cabbage and other brassicas reduce the densities of DBM on the brassicaceous crop (Chelliah and Srinivasan, 1986; Burundy and Raros, 1973; Bach and Tabashnik, 1990; González, 1998; Lim, 1992), whereas others have reported no reduction or even higher densities with the intercrops (Luther et al., 1996; Maguire, 1984; Talekar et al., 1986). In a two-choice test conducted in large cages, cabbage in a cabbage/tomato patch was less attractive as an oviposition substrate for DBM than cabbage alone, cabbage/sweet alyssum or cabbage/mustard patches (González, 1998). Reduction of DBM numbers in cabbage-tomato intercrops has been attributed to repellent compounds produced by tomato plants (Bach and Tabashnik, 1990). These compounds may interfere with host finding and ovipositing stimuli (Gupta and Thorsteinson, 1960; Tabashnik, 1985). Given the choice, DBM adults will disperse to less hostile monospecific cabbage patches after landing on tomato plants or on cabbage close to tomato in the cabbage/tomato dicultures, thus reducing tenure time and oviposition by DBM females in these patches.

Although Bt products were effective in reducing DBM and other crucifer defoliators, the reduction was not sufficient to harvest first quality produce which the market demands. The densities of DBM were above economic levels in the Bt-treated plots thus causing head damage and marketable yield reduction of 39 to 50%. Various reasons can be proposed to explain the damaging population levels in Bt-sprayed plots:

(1) In 1998, the design of the experiment in a split-plot design contributed to the difficulty of maintaining the DBM below damaging levels. The untreated subplots served as a refuge and a continuous source of DBM migrants. Diamondback moth adults were observed flying from the -Bt subplots onto the +Bt subplots. The dispersal of DBM adults from the Bt-free areas of the experiment into the Bt-sprayed subplots may be the consequence of reduced attraction of the unsprayed cabbage plants. Unsprayed plants in this study suffered heavy defoliation as the population densities of DBM and other lepidopteran defoliators increased. It is possible that the glucosinolates acting as stimulants of DBM host-finding (Palaniswamy et al., 1986; Pivnick et al., 1994) and oviposition behaviors (Gupta and Thorsteinson, 1960; Reed et al., 1989) change quantitatively and qualitatively as cabbage plants are damaged by the herbivores. It is known that allyl isothiocyanates, metabolites from glucosinolates, are produced in large quantities by damaged crucifer plants (Reed et al., 1989) and that these compounds are repellent to DBM females at very high concentrations as those in heavily defoliated plants (Pivnick et al., 1994). Moving from heavily defoliated host plants may be an adaptive behavior for the DBM since survival to adulthood will increase on healthier plants.

(2) Adult DBM may also have dispersed passively from unsprayed plants into adjacent Bt-sprayed cabbage. Luther et al. (1996) suggested that Bt-sprayed cabbage was infested with DBM that dispersed passively from adjacent rows of a mustard trap crop. Untreated refuge within Bt-sprayed plots is a questioned alternative for *P. xylostella* resistance management because the insect causes higher damage and thus cabbage heads of lower quality than those in uniformly Bt-sprayed plots (Pérez et al., 1997). A similar approach is being considered for managing resistance to Bt transgenic crops (Gould, 1998), a strategy that may have the same pitfall if the refuge areas (4% of the planted area) of Bt-free cultivars suffer heavy damage from the target insect pest and other defoliators.

(3) Larvae dislodging from the cabbage plants may have also dispersed through the ground to adjacent Bt-treated plants. DBM larvae dislodge from cabbage plants as a result of intraspecific encounters, which increase as larval density increases, and as a result of interspecific encounters, often as an evasion response to a parasitoid attack (González, 1998). The senior author observed in a previous greenhouse study (unpublished data) that dislodging and interplant movement of DBM larvae increase at densities of 16 or more larvae per plant on medium-sized cabbage plants. In the present study, DBM larvae numbered well above 16 per cabbage plant; thus it was highly possible that intraspecific encounters caused interplant and interplot dispersal of DBM larvae. Whatever the mechanism involved in DBM dispersal, this spillover effect may be avoided under commercial plantings where the total area is sprayed with Bt or another insecticide.

(4) Diamondback moth larvae may be showing resistance to the Bt delta endotoxin. Resistance to Bt products is of common occurrence in tropical and subtropical areas of the United States (Cartwright et al., 1992; Pérez and Shelton, 1996; Shelton et al., 1993). At the beginning of the 1990s in Puerto Rico, Bt products were the only insecticides causing high levels of larval mortality and good quality cabbage heads (Armstrong, 1990), but this apparently has changed at least in the DBM populations occurring on the southern plains of the Island.

Intercropping has been recommended as a conservation practice for parasitoids and other beneficial insects because this cultural practice increases their effectiveness in the agroecosystem compared with their effectiveness in pure stands, or with the use of conventional blanket sprays of insecticides (Altieri, 1994; Talekar, 1992; Vandermeer, 1989). However, parasitism by *C. plutellae* was apparently deterred in the cabbage/tomato substitutive dicultures. This result contrasts with findings by Bach and Tabashnik (1990), who reported that tomato as neighboring nonhost plants enhanced *C. plutellae* parasitism of DBM on cabbage, but it agrees with results of a three-year field study made by González (1998) where parasitism of *Diadegma insulare* (Cresson) on DBM was deterred in cabbage/tomato additive dicultures. Odors emitted by tomato plants in the cabbage/tomato dicultures may have interfered with host-habitat and host-finding cues of the searching female parasitoids, all of which may have reduced the frequency and duration of visits to tomato-containing patches. Parasitoid females use synamones emitted by their host's host plants to locate appropriate food for their progeny (Price, 1997). The aphid parasitoid, *Diaeretiella rapae* (McIntosh), for example, uses allyl isothiocyanate, a secondary compound product of the hydrolisis of glucosinolates from crucifer plants, as a synamone to locate its host's habitat (Read et al., 1970). Cabbage plants also stimulate searching behavior of the DBM larval parasitoids *D. insulare* and *Microplitis plutellae* (Muesbeck) females (Bolter and Laing, 1983).

Thus, two hypotheses are proposed to explain the lower parasitism rates in the C/T diculture: 1) The resource concentration hypothesis (Root, 1973)—A specialist parasitoid will be most abundant in pure stands where its host's host plant and its host densities are more abundant. Higher concentrations of the synamones and kairomones required for the parasitoid to locate its habitat and host, respectively, occur in pure stands. The parasitoid's residence time will be increased under these conditions; 2) The associational interference hypothesis—A specialist parasitoid will be less abundant in a polyculture where odors from companion plants interfere or in some way dilute the plumes of synamones and kairomones required to locate its habitat and host. The parasitoid's residence time will be decreased under these conditions. These hypotheses are not necessarily mutually exclusive, but may be complementary. The parasitoid host must be a specialist herbivore for these hypotheses to apply. *Cotesia plutellae* searching behavior on crucifers should be studied to elucidate the mechanisms involved and how this behavior is affected by non-host plants.

Tomato or wedelia in close association with cabbage (1998 experiment) significantly reduces the size of cabbage plants thus resulting in smaller heads, delayed maturation and lower yield. Even with considerable plant spacing (1999 experiment), significant reduction in yield (>25%) may occur from a grower's standpoint. Firmness of the heads seems to be reduced by the shady conditions in the C/T diculture. Reduction in plant size is common in polycultures compared with size in monocultures (Bach and Tabashnik, 1990; Bach, 1988; Lawrence and Bach, 1989), but cabbage/tomato intercrops are a commercial practice to reduce DBM population densities on crucifers in India (Chelliah and Srinivasan, 1986). For these to be effective in reducing DBM densities, relay-type intercrops must be established by planting tomato ahead of the crucifer crop. A close association between cabbage and tomato and good canopy coverage by the companion crop appears to be necessary for this approach to be effective against DBM (González, 1998). From a commercial grower's standpoint, this dilemma will most probably be solved in favor of establishing a monoculture if DBM can be effectively controlled with insecticides.

Conclusions: 1) Intercropping cabbage with tomato could reduce *P. xylostella* (a specialist herbivore) densities in the main crop, but this companion plant showed some competition with cabbage, which was reflected in reduced head size and fewer heads ready for harvest. 2) Products containing the delta endotoxins of *B. thuringiensis* are still effective in reducing *P. xylostella* densities, but under high population pressure the reduction is not sufficient to avoid economic damage. Some levels of resistance to these products are apparently present in DBM populations in southern Puerto Rico, but other operational factors such as inappropriate timing and coverage of Bt sprays may have reduced spray efficacy. Bt-containing products must be alternated with more effective insecticides during the critical stages of cupping and head formation. 3) The resource concentration and the associational interference hypotheses are proposed to explain the lower parasitism rates of a specialist parasitoid in a polyculture. 4) In screening trials to evaluate the effectiveness of Bt products, which are decomposed rapidly in the environment, sprayed plots should be located away from control plots to reduce colonization of dispersing DBM adults.

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