Suppression of *Plutella xylostella* and *Trichoplusia ni* in Cole Crops with Attracticide Formulations

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ABSTRACT The three key lepidopteran pests of cole, *Brassica oleracea* L., crops in North America are diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae); cabbage looper; *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae); and imported cabbageworm, *Pieris rapae* (L.) (Lepidoptera: Pieridae). Two species-specific pheromone-based experimental attracticide formulations were evaluated against these pests: LastCall DBM for *P. xylostella* and LastCall CL for *T. ni*. No LastCall formulation was available against *P. rapae*. Laboratory toxicity experiments confirmed the effectiveness of each LastCall formulations in killing conspecific males that made contact. In replicated small plots of cabbage and collards in central Alabama, over four growing seasons (fall 2003, spring 2004, fall 2004, and spring 2005), an attracticide treatment receiving the two LastCall formulations, each applied multiple times at the rate of 1,600 droplets per acre, was compared against *Bacillus thuringiensis* subspecies *kursatki* (Bt) spray at action threshold and a negative untreated control. Efficacy was measured by comparing among the three treatments male capture in pheromone-baited traps, larval counts in plots, and crop damage rating at harvest. LastCall provided significant reductions in crop damage comparable to Bt in three of the four seasons. Efficacy of LastCall was dependent upon lepidopteran population densities, which fluctuated from season to season. In general, reduction in crop damage was achieved with LastCall at low-to-moderate population densities of the three species, such as typically occurs in the fall in central Alabama, but not in the spring when high *P. rapae* population pressure typically occurs in central Alabama. Significant reductions in pheromone trap captures did not occur in LastCall plots, suggesting that elimination of males by the toxicant (permethrin), rather than interruption of sexual communication, was the main mechanism of effect.

KEY WORDS diamondback moth, cabbage looper, imported cabbageworm, attract-and-kill

Diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae); cabbage looper, *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae), and imported cabbageworm, *Pieris rapae* (L.) (Lepidoptera: Pieridae), are the key pests of cruciferous plants (*Brassica* spp.) in North America. The larvae feed on the foliage and cause direct damage to the marketable leaves of cole, *Brassica oleracea* L., crops (Harcourt et al. 1955, Shelton et al. 1982, Talekar and Shelton 1993, Tabashnik 1994). The three species are usually managed together as a single caterpillar complex, commonly referred to as the cabbage caterpillar complex (Shelton et al. 1982, Mahr et al. 1993, Hines and Hutchison 2001).

Traditionally, vegetable growers in North America have managed the cabbage caterpillar complex in their fields by using calendar-based applications of broad-spectrum insecticides, including carbamates (e.g., Sevin and Lannate), organophosphates (e.g., Thiodan), and pyrethroids (e.g., Danitol) (Hines and Hutchison 2001, Liu et al. 2002). However, many of these insecticides have been lost due to governmental regulation (Food Quality Protection Act 1996) or the development of pest resistance. The most widely used biologically based control strategy in cole crops is formulated sprays of *Bacillus thuringiensis* subspecies *kurstaki* (Bt) (Biever et al. 1994). However, Bt-resistant field populations of *P. xylostella* have been reported in various locations worldwide (Mahr et al. 1993, Rueda and Shelton 1995, Tabashnik et al. 1997). Furthermore, Bt sprays are directed against pest larvae and thus allow some level of feeding damage to take place before mortality occurs. These concerns have prompted renewed interests in the development of alternative pest management tactics against the cabbage caterpillar complex. Integrating Bt sprays with another biologically based tactic (such as the use of semiochemicals) may have the potential of reducing the risk of resistance to Bt, through a reduction in the number of sprays per season.

Semiochemical-based strategies, including mating disruption and attracticides (attract-and-kill or lure-and-kill) can potentially be used to manage two of the

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three key lepidopteran pests of cole crops: *P. xylostella* and *T. ni.* The sex pheromone of both species has been characterized (Berger 1966, Tamaki et al. 1977, Bjostad et al. 1984), and studies have demonstrated the efficacy of mating disruption of *P. xylostella* and *T. ni* (Gaston et al. 1967, Farkas et al. 1974, McLaughlin et al. 1994, Mitchell et al. 1997, Mitchell 2002). However, Schroeder et al. (2000) reported that mating disruption was not effective in suppressing *P. xylostella* density in cabbage. Recently, there has been some focused interest in the potential use of semiochemicals as attracticides for pest management (Charmillot and Hofer 1997; Brockerhoff and Suckling 1999; Losel et al. 2000; Krupke et al. 2002; Evenden and McLaughlin 2004a, b, 2005). The attracticide technology incorporates an attractant (e.g., synthetic pheromones) with an insecticide (e.g., permethrin), and its utility is based on the attraction of individuals of the target species to a hydrophobic matrix containing an insecticide where they are killed without insecticide runoff or drift, thereby limiting contamination of the crop and the ecosystem. The tactic is considered useful and promising because, unlike mass trapping, traps do not have to be deployed and serviced, and unlike mating disruption, males are actually killed, rather than temporarily confused. This technology has shown significant promise for the control of several key lepidopteran pest species, including *Pectinophora gossypiella* (Saunders) (Haynes et al. 1986, Hofer and Angst 1995), *Epiphyas postvittana* (Walker) (Brockerhoff and Suckling 1999), *Cydia pomonella* (L.) (Charmillot and Hofer 1997, Charmillot et al. 2000, Losel et al. 2000, Krupke et al. 2002, Evenden and McLaughlin 2005), and *Grapholita molesta* (Busck) (Evenden and McLaughlin 2004a, b, 2005). Mitchell (2002) reported on the initial development of attracticide formulations against *P. xylostella* and *T. ni,* whereas Mullan (2003) evaluated some experimental attracticide formulations against *T. ni* in commercial vegetable greenhouses. The results of both studies demonstrated the potential of the attracticide technology for managing both pests in cole crops (Mitchell 2002, Mullan 2003).

In this paper, we report on laboratory and field experiments conducted to further evaluate the potential of attracticide formulations for managing *P. xylostella* and *T. ni* on cole crops. We tested two species-specific pheromone-based experimental attracticide formulations (one formulation for *P. xylostella* and one formulation for *T. ni*) supplied by IPM Development Company, Marylhurst, OR (formerly known as IPM Tech, Inc.), which holds the global license rights to an attracticide matrix gel (LastCall). Laboratory experiments were conducted to determine the toxicity of LastCall formulations to laboratory-reared *P. xylostella* and *T. ni* males. We then evaluated over multiple field seasons the efficacy of LastCall formulations for suppression of lepidopteran pest infestation and damage in crucifer plots, in comparison with Bt and an untreated control. Ultimately, we were interested in determining whether the attracticide technology could provide significant reductions in crop damage by the cabbage caterpillar complex comparable with Bt, despite that LastCall formulations are not currently available against *P. rapae,* a key member of the cabbage caterpillar complex in Alabama.

Materials and Methods

Attracticide Formulations. The LastCall formulations used in the laboratory and field experiments were formulated and supplied by IPM Development Company which holds the global license rights to an attracticide matrix gel. The LastCall formulation consisted (in addition to pheromone and insecticide) of a clear viscous paste (gel) with a base proprietary product plus other inert ingredients. Two species-specific experimental formulations were evaluated: 1) LastCall DBM for *P. xylostella* consisting of 0.16% pheromone and 6% permethrin by weight) and 2) LastCall CL for *T. ni* consisting of 1.6% pheromone and 6% permethrin by weight. The sex pheromone of *P. xylostella* consists of three components: (Z)-11-hexadecanal, (Z)-11-hexadecen-1-ol acetate, and (Z)-11-hexadecanol (Tamaki et al. 1977). The *T. ni* sex pheromone is also multicomponent (Berger 1966, Bjostad et al. 1984), but only the major component, (Z)-7-dodecen-1-ol acetate, was used in the LastCall CL formulation. The sex pheromone of each species was purchased from Bedoukian Research Inc. (Danbury, CT) and used as attractant in the proprietary formulations (IPM Development Company). The LastCall formulations were dispensed from an applicator tube with a calibrated pump that deposits metered droplets. Each 50-μl droplet of the gel formulation weighed $\approx$50 mg. Formulations were kept in a -20°C freezer until use.

Laboratory Experiments. Simple "touch" toxicity tests were conducted to determine the toxicity of both experimental attracticide formulations by comparing exposure of insecticide-susceptible strains of adult *P. xylostella* and *T. ni* to conspecific LastCall formulations versus a double blank formulation (with no insecticide or pheromone). The starting culture of *T. ni* was obtained from Dr. K. Haynes (University of Kentucky, Lexington, KY), whereas that of *P. xylostella* was obtained from Dr. M. Eubanks (Auburn University, Auburn, AL). Both species had been maintained in the laboratory for >100 generations and were reared in our laboratory on artificial diets (Bio-Serv, Inc., Frenchtown, NJ) by using standard rearing protocols for each species (McEwen and Hervey 1960, Guy et al. 1985, Shelton et al. 1991). Pupae of each species were harvested from diet and held individually in 29.6-ml (1-oz.) plastic cups until adult emergence. Males were separated from females either as pupae (*T. ni,* Liu and Haynes 1993) or as fourth instars (*P. xylostella,* Liu and Tabashnik 1997). Before the tests, moths were chilled briefly in the refrigerator (at 5°C for $\approx$15 min) to reduce activity. For each species, 24 newly emerged (1-d-old) males were treated with their conspecific LastCall formulation. A small droplet of attracticide on a toothpick was quickly touched to the top of the thorax. Treated moths were placed individually in 29.6-ml (1-oz.) plastic cups (with lid) and provided with a 25% sugar solution (using cotton dental wicks). The cups were arranged in a random order on a tray and placed in a fume cupboard maintained at ≈ 25°C and a photoperiod of 14:10 (L:D) h. The control treatment for each species consisted of another set of males exposed to a double blank formulation (no permethrin, no pheromone). Effect of contact with LastCall was determined by checking for male mortality at two and 24 h after exposure. Individual males were scored as alive (apparently fully functional) or dead. Significant differences in the toxicity of LastCall and double blank formulations to males of each species were established using a chi-square 2 by 2 test of independence with Yates' correction for continuity (Parker 1979).

Field Evaluation of Attracticide Formulations. Field experiments were conducted in replicated small plots of cabbage and collards to evaluate the efficacy of LastCall formulations in controlling *P. xylostella* and *T. ni* infestations (LastCall formulations are not currently available against *P. rapae*). This study was conducted over four growing seasons (fall 2003, spring 2004, fall 2004, and spring 2005) at the E. V. Smith Research center in Shorter, central Alabama. Plots were 27.4 by 18.2 m with plants spaced 45 cm apart within a row and 90 cm between rows for a total of 600 plants per plot. Plots were separated by 33.5 m, and each plot was then subdivided into two equal subplots consisting of 300 cabbage plants and 300 collard plants. Plots were initially bare ground and established by transplanting cabbage (*Brassica oleraceae* L. variety *capitata* L.) and collard (*Brassica oleraceae* L. variety *acephala* L.) seedlings obtained from a nursery in western Georgia (Lewis Taylor Farms, Tifton, GA) after a preseason red imported fire ant, *Solenopsis invicta* Buren, treatment with Amdro (active ingredient hydramethylnon, BASF Corporation, Research Triangle Park, NC). In fall 2003, 'Bravo' cabbage and 'Vates' collards were mechanically transplanted on 24 September 2003. In spring 2004, Bravo cabbage and Vates collards were mechanically transplanted on 2 April 2004. In fall 2004, 'Rio Verde' cabbage and 'Top bunch' collards were mechanically transplanted on 3 October 2004. In spring 2005, Bravo cabbage and Vates collards were mechanically transplanted on 22 April 2005. Standard field preparation and crop production practices (i.e., irrigation, herbicide, and fertilizer) were used to establish and maintain cabbage and collard plants in all four growing seasons (Kemble 1999). In each season, three treatments were evaluated: 1) attracticide treatment involving applications of *P. xylostella* and *T. ni* LastCall formulations, 2) Bt spray at action threshold, and 3) untreated control. Treatments were arranged in a randomized complete block design with three replicates (blocks) in each season. Blocks were separated by ≈60 m. In each season, each attracticide plot received multiple applications of the two formulations: LastCall DBM and LastCall CL. One droplet (50 mg) of each LastCall formulation was applied to an unmarketable outer leaf of 100 plants per plot (50 plants per subplot), translating to a low rate of ≈3954 droplets per hectare (≈1,600 droplets per acre). This application rate translated to ≈0.14 and 1.4 g of pheromone per acre for *P. xylostella* and *T. ni*, respectively, and was shown to be effective in preliminary experiments (Mitchell 2002, J.M, unpublished data). The treated plants were evenly distributed in the plot. LastCall applications were made at 2-wk intervals during the first month of each growing season to accommodate early season leaf drop, and at 3–4-wk intervals thereafter, for a total of three to four applications per season.

Plots were evaluated weekly for pest infestation by sampling 10 randomly selected plants per plot, five plants from each subplot, for larvae of *P. xylostella*, *T. ni*, and *P. rapae*. The species, numbers, and size (instar) of caterpillars per plant were counted and recorded. Eggs and pupae of the three species also were sampled, but only larval data are presented. For the Bt treatment, Dipel (a formulation of *B. thuringiensis* subspecies *kurstaki*) was applied, because it is currently the most commonly used microbial insecticide on Alabama vegetable crops (personal observation).

Applications of Dipel (Valent Biosciences, Libertyville, IL) were made only when larval counts exceeded a threshold of 0.5 cabbage looper equivalents (CLE) per plant (Shelton et al. 1982). The CLE method accounts for the varying levels of feeding damage caused by the three species. In this method, 1 CLE = 20 *P. xylostella* larvae = 1.5 *P. rapae* larva = 1 *T. ni* larva (Shelton et al. 1982). Dipel applications were made at the recommended rate of 1.1 kg/hectare (1 lb/acre) with a CO_2-pressurized backpack sprayer by using a 0.91-m (3-ft) boom with three nozzles calibrated to deliver ≈233.4 liters/ha (25 gpa) at 276.4 kPa (40 psi). On average, each Bt plot received two to three applications of Dipel per season. Populations of adult males of *P. xylostella* and *T. ni* were monitored weekly by placing in the center of each plot two wing traps baited with the commercial pheromone lures one for each species (IPM Development Company). The two traps were spaced apart by ≈10 m. Because no pheromone-baited traps are currently available for monitoring *P. rapae*, adult population of this species was monitored weekly using a visual scheme. This was done weekly by an observer (E.M.M.) standing in the center of each plot and counting the number of adult *P. rapae* seen in the plot during a 5-min observation period.

At harvest, 10 plants were randomly selected from each subplot and rated for caterpillar feeding damage and marketability using the method of Greene et al. (1969). In this method cabbage plants were rated based on insect feeding damage on a scale of 1–6 as follows: 1, no apparent insect damage on head or inner wrapper leaves; 2, no head damage, but minor feeding on wrapper leaves with 0–1% leaf area consumed; 3, no damage on head, but moderate feeding damage on wrapper leaves with 2–5% leaf area consumed; 4, minor feeding on head (but no feeding through outer head leaves), but moderate feeding on wrapper or outer leaves with 6–10% leaf area consumed; 5, moderate-to-heavy feeding damage on wrapper and head leaves and a moderate number of feeding scars on

Table 1. Percentage of mortality of male *P. xylostella* and *T. ni* after exposure to attracticide (LastCall) or double blank formulations

Formulation treatment	% *P. xyllostella* males dead		% *T. ni* males dead	
	2-h exposure	24-h exposure	2-h exposure	24-h exposure
Attracticide (LastCall)	70.8a	95.8a	62.5a	100a
Double blank control	0b	8.3b	0b	8.3b

Twenty four males were exposed to each formulation. Percentages within the same insect column having no letters in common are significant at $P < 0.05$.

head with 11–30% leaf area consumed; and 6, severe feeding damage to head and wrapper leaves with heads having numerous feeding scars with ≥30% leaf area consumed (Greene et al. 1969). A similar method was used to assess marketability of collards with damage rating based solely on the percentage of leaf area consumed (because collard is not a head-producing plant). A damage rating of ≤3 is considered marketable under normal conditions (Leibee et al. 1995).

For each field season, mean seasonal numbers of larvae and adults of each species and mean damage rating at harvest were calculated for each treatment. Data were checked for normality, and if necessary, they were transformed by using the square-root method $\sqrt{(x + 0.5)}$ and analyzed for significant treatment effects by using analysis of variance (ANOVA) with the replicate plots (or subplots) considered as blocks. Means were compared using the Tukey–Kramer honestly significant difference (HSD) comparison for all pairs (JMPIN version 4.0.2, SAS Institute 1998). Significant differences were established at the 95% confidence level ($P < 0.05$).

Results

Laboratory Experiments. LastCall formulations were significantly more toxic to adult *P. xylostella* and *T. ni* than the double blank formulation both at 2-h and 24-h exposure periods (Table 1). Approximately 71% of *P. xylostella* males and 63% of *T. ni* males were killed within 2 h of exposure to conspecific LastCall formulations, whereas none of the males exposed to the double blank control died within this period. At the end of a 24-h exposure period to the formulations, 96% of *P. xylostella* males and 100% of *T. ni* males were killed, compared with the significantly lower 8% mortality recorded for males of both species exposed to the double blank control.

Field Evaluation of Attracticide Formulations. In general, attracticide formulations provided significant suppression of *P. xylostella* and *T. ni* populations and crop damage in certain situations: efficacy of LastCall varied from season to season and was much less effective at higher densities of the three lepidopteran pest species, which fluctuated from season to season. Generally, no significant block effects were detected on any of the key parameters (variables), suggesting that the blocks (replicate plots) were similar in pest abundance and treatment efficacy.

In fall 2003, moderate larval infestations (≤0.5 larva per plant per week) of *P. xylostella* and *P. rapae* were recorded in the cabbage and collard subplots, whereas *T. ni* larval infestation was very low, averaging <0.1 larva per plant per week (Tables 2 and 3). Male *P. xylostella* capture was relatively low throughout the fall increasing near the end of the season (Fig. 1A). Also, low numbers of *T. ni* were trapped in untreated control plots (Fig. 2A), whereas moderate numbers of adult *P. rapae* were recorded in visual counts (Fig. 3A). Fewer *P. xylostella* males were captured in pher-

Table 2. Seasonal mean ± SE number of larvae of the three lepidopteran pest species sampled per plant per week in cabbage subplots treated with different treatments during different growing seasons

Season	*P. xylostella*			*T. ni*			*P. rapae*		
	LastCall	Bt	Untreated	LastCall	Bt	Untreated	LastCall	Bt	Untreated
Fall 2003	0.14 ± 0.04b	0.12 ± 0.03b	0.44 ± 0.09a	0.01 ± 0.01	0.02 ± 0.01	0.04 ± 0.01	0.12 ± 0.03ab	0.07 ± 0.03b	0.22 ± 0.04a
Spring 2004	0.20 ± 0.07b	0.16 ± 0.05b	0.46 ± 0.09a	0.01 ± 0.01	0.0 ± 0.0	0.0 ± 0.0	1.34 ± 0.18a	0.17 ± 0.04b	1.36 ± 0.18a
Fall 2004	0.41 ± 0.07a	0.17 ± 0.04b	0.47 ± 0.07a	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.20 ± 0.04a	0.09 ± 0.02b	0.21 ± 0.04a
Spring 2005	0.20 ± 0.05b	0.15 ± 0.04b	0.54 ± 0.10a	0.14 ± 0.03b	0.23 ± 0.04ab	0.34 ± 0.05a	0.15 ± 0.03ab	0.09 ± 0.03b	0.25 ± 0.04a

For each pest, means in the same row having no letters in common are significantly different ($P < 0.05$, Tukey–Kramer HSD).

Table 3. Seasonal mean ± SE number of larvae of the three lepidopteran pest species sampled per plant per week in collard subplots treated with different treatments during different growing seasons

Season	*P. xylostella*			*T. ni*			*P. rapae*		
	LastCall	Bt	Untreated	LastCall	Bt	Untreated	LastCall	Bt	Untreated
Fall 2003	0.50 ± 0.13	0.26 ± 0.09	0.39 ± 0.08	0.04 ± 0.02	0.05 ± 0.03	0.06 ± 0.02	0.18 ± 0.04ab	0.10 ± 0.03b	0.25 ± 0.06a
Spring 2004	0.24 ± 0.08	0.18 ± 0.06	0.45 ± 0.11	0.0 ± 0.0	0.01 ± 0.01	0.0 ± 0.0	1.15 ± 0.15a	0.18 ± 0.05b	1.08 ± 0.14a
Fall 2004	0.44 ± 0.08a	0.19 ± 0.04b	0.53 ± 0.08a	0.0 ± 0.0	0.01 ± 0.01	0.0 ± 0.0	0.30 ± 0.05a	0.10 ± 0.03b	0.22 ± 0.04ab
Spring 2005	0.22 ± 0.05b	0.19 ± 0.05b	0.49 ± 0.08a	0.21 ± 0.04	0.22 ± 0.04	0.28 ± 0.04	0.13 ± 0.03	0.13 ± 0.03	0.25 ± 0.05

For each pest, means in the same row having no letters in common are significantly different ($P < 0.05$, Tukey–Kramer HSD).

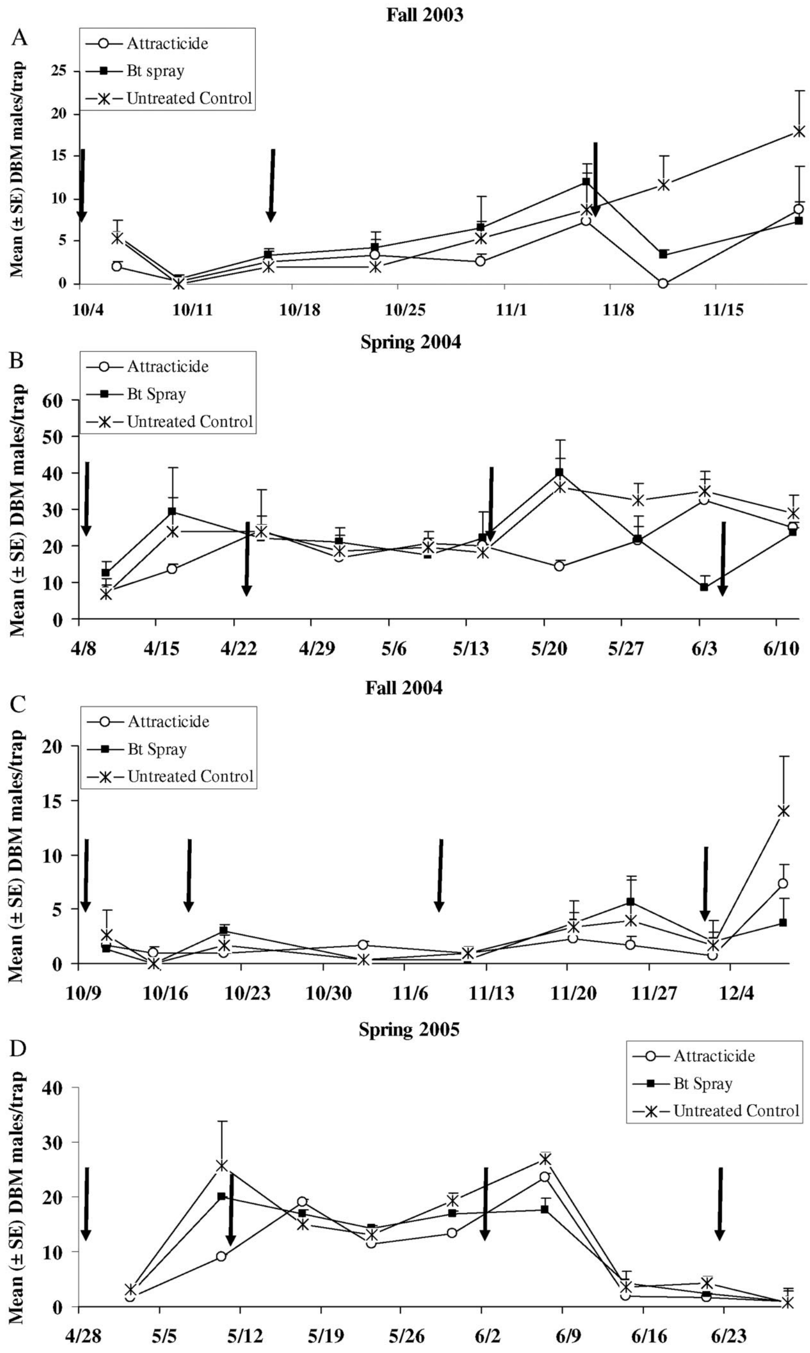

Fig. 1. Mean ± SE trap capture of diamondback moth (DBM) in pheromone-baited wing traps for each of three treatments during fall 2003 (A) spring 2004 (B), fall 2004 (C), and spring 2005 (D). Arrows indicate dates of application of LastCall formulations.

omone traps located in LastCall plots (seasonal mean ± SE, 3.4 ± 0.9) than in Bt (seasonal mean ± SE, 5.4 ± 0.9) or untreated (seasonal mean ± SE, 6.6 ± 1.4) plots (Fig. 1). However, this ≈49% reduction of trap capture in LastCall plots relative to untreated plots was not significant ($F = 2.6$, df = 2, $P = 0.08$). Similarly, trap captures of *T. ni* in LastCall plots were not significantly different than captures in the other two treatments ($F = 0.1$, df = 2, $P = 0.91$). Nonetheless, *P. xylostella* larval counts were significantly lower in cabbage subplots treated with LastCall or Bt compared with untreated subplots ($F = 8.3$, df = 2, $P =$

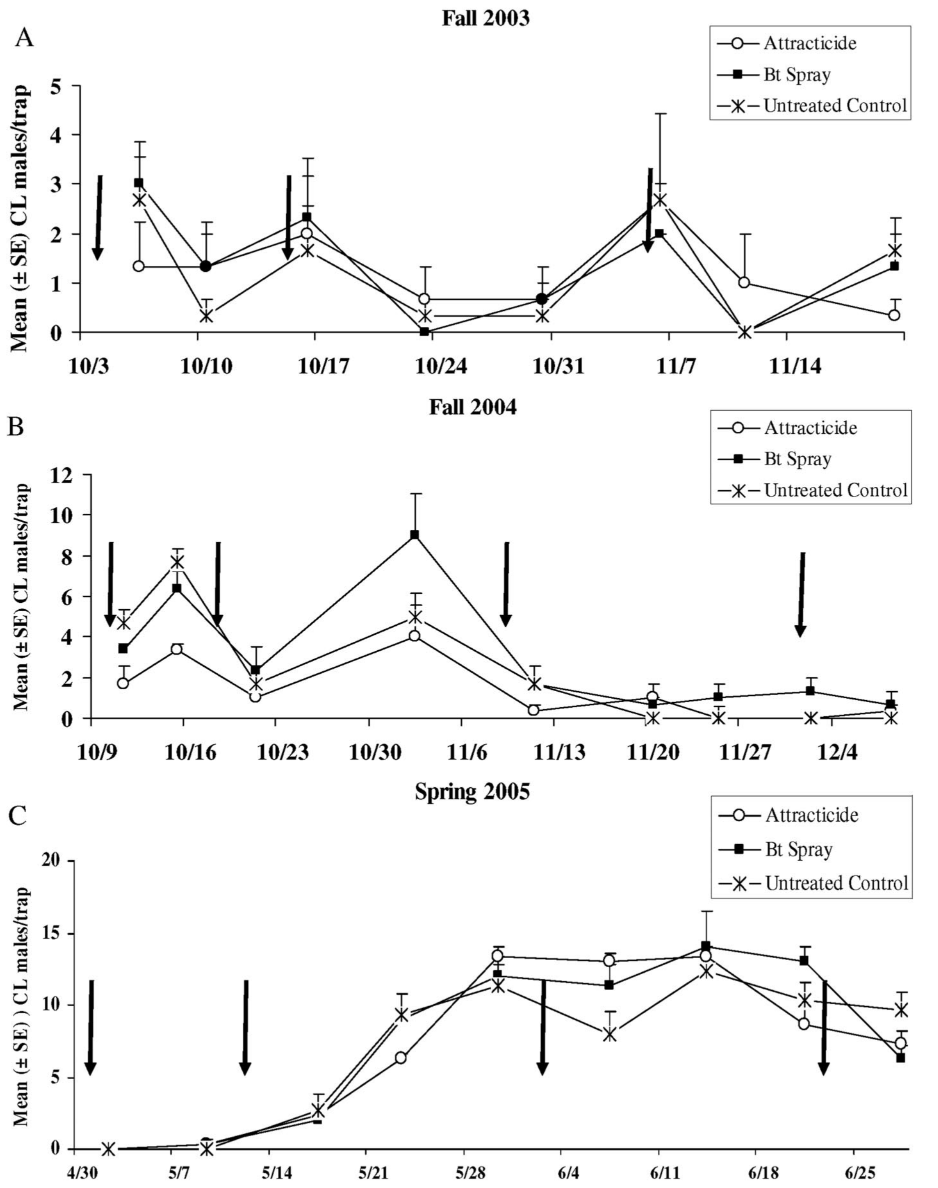

Fig. 2. Mean ± SE trap capture of cabbage looper (CL) in pheromone-baited wing traps for each of three treatments during fall 2003 (A), fall 2004 (B), and spring 2005 (C). Arrows indicate dates of application of LastCall formulations.

0.0003), whereas no significant differences were recorded among the treatments in collard subplots ($F = 1.8$, df = 2, $P = 0.17$). Larval counts of *T. ni* in cabbage and collard subplots were too low to detect any significant differences among treatments (cabbage: $F = 1.0$, df = 2, $P = 0.37$; collard: $F = 0.49$, df = 2, $P = 0.61$). As expected, significantly lower numbers of *P. rapae* larvae were found in cabbage and collard subplots treated with Bt compared with untreated subplots (cabbage: $F = 5.5$, df = 2, $P = 0.004$; collard: $F = 2.9$, df = 2, $P = 0.05$), whereas larval counts were not significantly different between LastCall subplots and untreated or Bt subplots (Tables 2 and 3). Significantly higher damage ratings were recorded in untreated subplots than in LastCall or Bt subplots (cabbage: $F = 14.9$, df = 2, $P < 0.0001$; collard: $F = 14.5$, df = 2, $P < 0.0001$); marketable cabbage and collards were produced in both LastCall and Bt subplots, but not in untreated subplots (Fig. 4A).

In spring 2004, *P. rapae* infestation was very high both in terms of larval pressure (Tables 2 and 3) and adult visual counts (Fig. 3B). Similarly, high numbers of male *P. xylostella* were captured in pheromone traps (Fig. 1B), whereas larval pressure was moderate (Tables 2 and 3). In contrast, *T. ni* larval pressure was extremely low in the subplots (Tables 2 and 3),

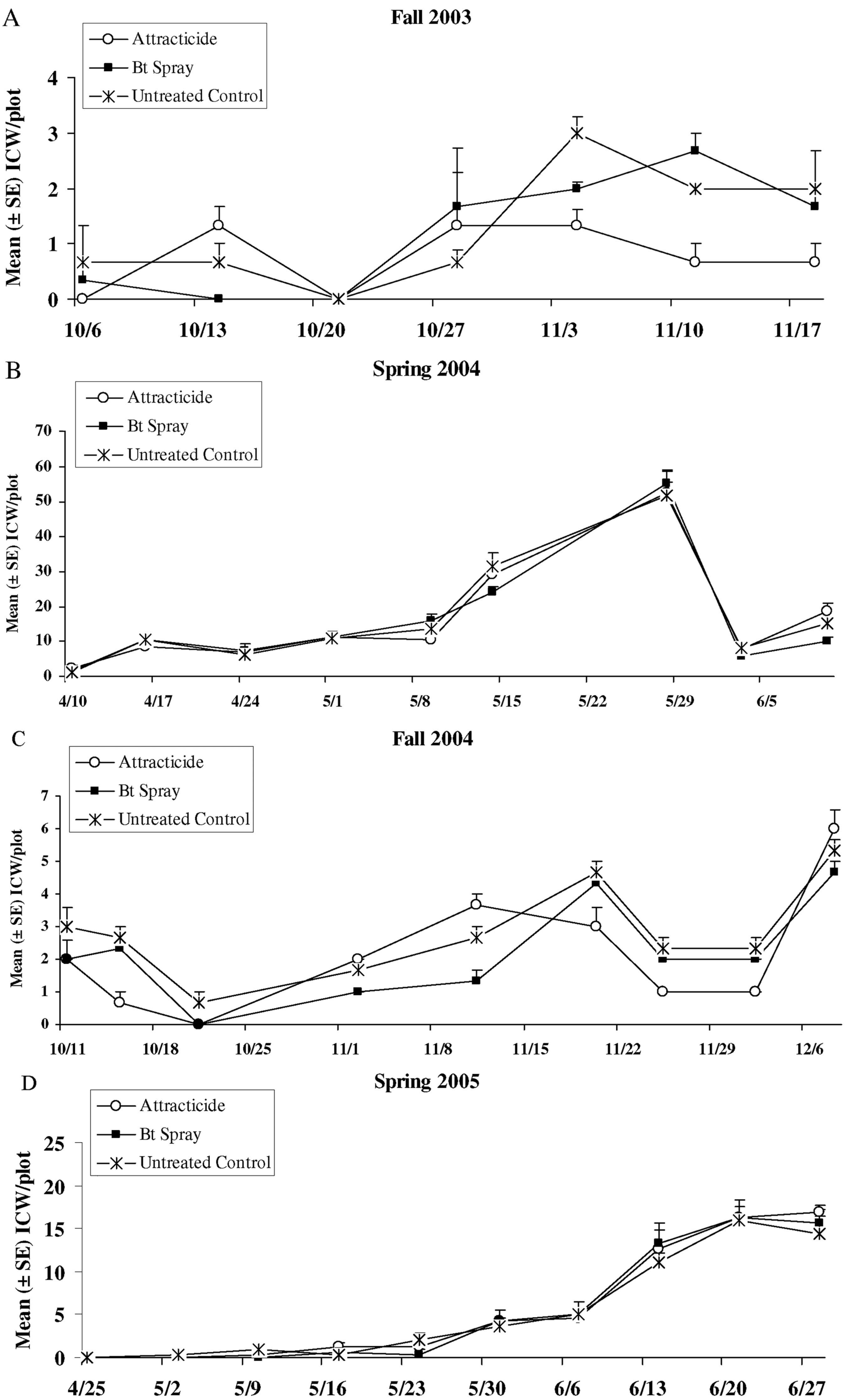

Fig. 3. Mean ± SE number of adult imported cabbageworm (ICW) counted during 5-min observation period in untreated and treated plots during fall 2003 (A) spring 2004 (B), fall 2004 (C), and spring 2005 (D).

whereas adult trap catch was nearly zero. Traps captures of male *P. xylostella* in pheromone traps were not significantly different among the three treatments ($F = 1.0$, df = 2, $P = 0.36$), although slightly lower in LastCall plots. Significantly higher numbers of *P. xylostella* larvae were found in untreated cabbage subplots than in LastCall or Bt subplots ($F = 5.6$, df = 2, $P = 0.0004$), whereas significant differences were not

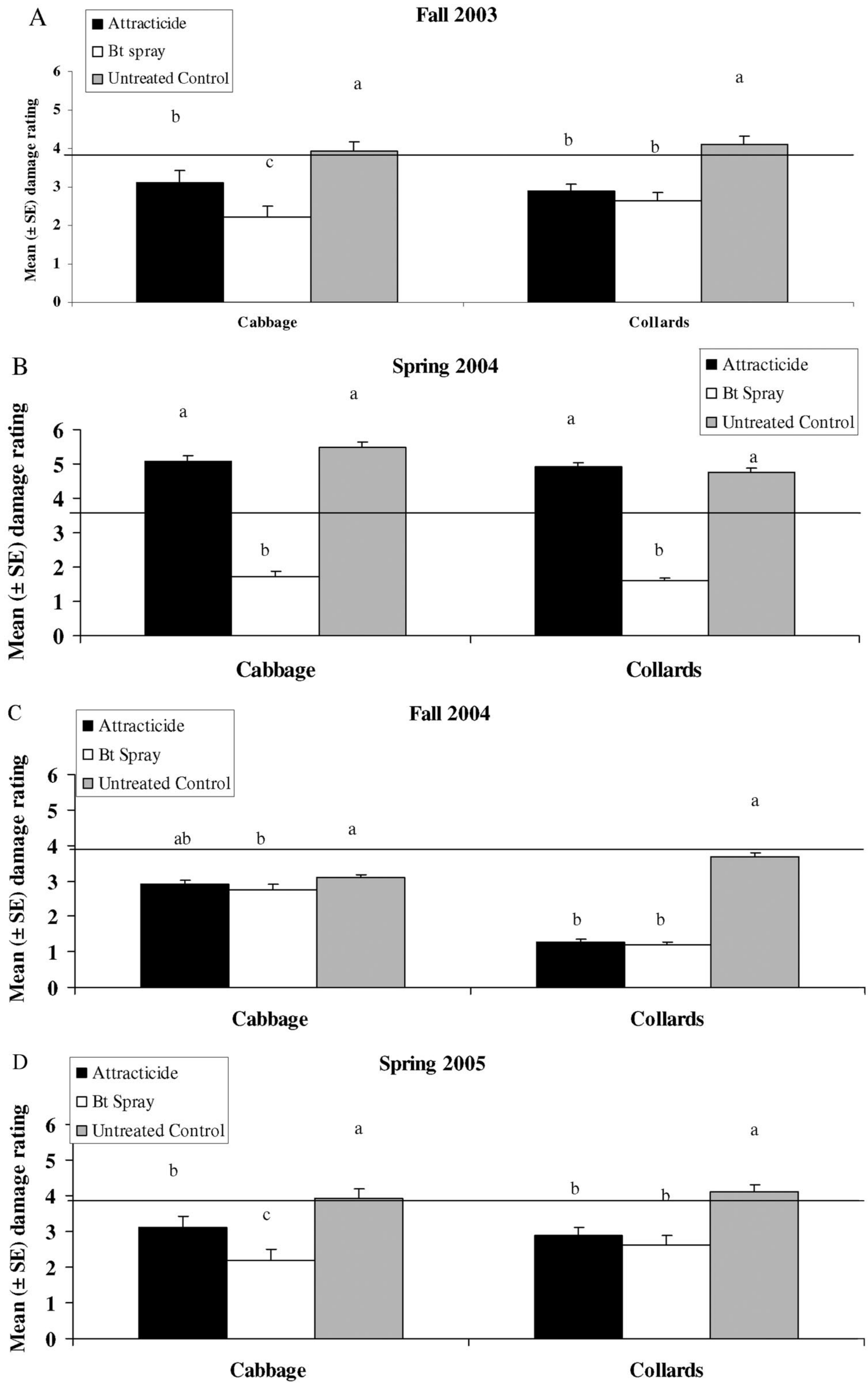

Fig. 4. Mean ± SE damage ratings of plants harvested from plots of each of three treatments during fall 2003 (A) spring 2004 (B), fall 2004 (C), and spring 2005 (D). Line indicates marketability threshold of three above which produce is considered unmarketable (Leibee et al. 1995). Means followed by the same letter are not significantly different ($P < 0.05$, Tukey–Kramer HSD).

recorded among the treatments in collard subplots ($F = 2.8$, df = 2, $P = 0.06$). As observed in fall 2003, *T. ni* infestation was too low to detect any significant difference between treatments (cabbage: $F = 1.0$, df = 2, $P = 0.37$; collard: $F = 1.0$, df = 2, $P = 0.37$). Expectedly, *P. rapae* larval counts were significantly lower in cabbage and collard subplots treated with Bt compared with untreated or LastCall subplots (cabbage: $F = 26.8$, df = 2, $P < 0.0001$; collard: $F = 21.7$, df = 2, $P < 0.0001$). Damage ratings were significantly higher in untreated and LastCall subplots than in Bt subplots (cabbage: $F = 190$, df = 2, $P < 0.0001$; collard: $F = 273$, df = 2, $P < 0.0001$), and marketable cabbage and collards were produced only in the Bt subplots (Fig. 4B).

The results obtained in fall 2004 were generally similar to those of fall 2003 in terms of pest pressure, species abundance, and treatment efficacy. In this season, *P. xylostella* and *P. rapae* pressure was moderate (Tables 2 and 3; Figs. 1C and 3C). *T. ni* larval infestation was not detected in the subplots (Tables 2 and 3), although low numbers of males were captured in pheromone traps (Fig. 2B). A modest (≈34%) reduction in trap capture was recorded in LastCall plots in comparison with untreated control plots, but this was not significant ($F = 0.15$, df = 2, $P = 0.87$). Similarly, the ≈43.5% reduction in trap capture of *T. ni* males in LastCall plots was not significant ($F = 2.3$, df = 2, $P = 0.11$). Larval counts of *P. xylostella* were significantly lower in subplots treated with Bt, compared with LastCall or untreated subplots (cabbage: $F = 6.3$, df = 2, $P = 0.002$; collard: $F = 6.3$, df = 2, $P = 0.002$). Similarly, numbers of *P. rapae* larvae found in subplots treated with Bt were significantly lower than in LastCall or untreated subplots (cabbage: $F = 3.4$, df = 2, $P = 0.04$; collard: $F = 5.3$, df = 2, $P = 0.005$). Nevertheless, damage ratings were significantly lower in LastCall and Bt subplots than in untreated subplots (cabbage: $F = 3.2$, df = 2, $P = 0.05$; collard: $F = 210$, df = 2, $P < 0.0001$); marketable crops were produced both in LastCall and Bt subplots but not in untreated subplots (Fig. 4C).

In spring 2005, moderate-to-high infestations of all three species were recorded in the subplots both in terms of larval pressure (Tables 2 and 3) and adult counts (Figs. 1D, 2D, and 3D), resulting in a relatively higher total pest pressure than in the previous seasons. A modest (but not significant) reduction (≈26%) was recorded in trap captures of male *P. xylostella* was recorded in LastCall plots, compared with untreated plots ($F = 0.72$, df = 2, $P = 0.49$). Also, no significant differences in *T. ni* male trap capture were recorded among the treatments ($F = 0.02$, df = 2, $P = 0.98$). Seasonal mean numbers of *P. xylostella* larvae were significantly lower in LastCall and Bt subplots than in untreated subplots (cabbage: $F = 8.8$, df = 2, $P = 0.0002$; collard: $F = 6.4$, df = 2, $P = 0.0002$). Similarly, significantly lower numbers of *T. ni* larvae were found in cabbage subplots treated with LastCall or Bt than in untreated subplots ($F = 5.8$, df = 2, $P = 0.003$), whereas no significant differences were recorded among treatments in collard subplots ($F = 1.0$, df = 2, $P = 0.37$). For *P. rapae,* larval counts were significantly lower in subplots treated with Bt than in untreated or LastCall-treated subplots (cabbage: $F = 4.6$, df = 2, $P = 0.01$; collard: $F = 3.2$, df = 2, $P = 0.04$). Significantly lower damage ratings were recorded in LastCall and Bt subplots than in untreated subplots (cabbage: $F = 14.9$, df = 2, $P < 0.0001$; collard: $F = 14.5$, df = 2, $P < 0.0001$). Marketable cabbage and collards were produced in the LastCall and Bt subplots, but Bt treatment resulted in a slightly better cabbage marketability rating than LastCall (Fig. 4D). In general, similar results were obtained for cabbage and collard subplots.

Discussion

Laboratory toxicity experiments established that both experimental attracticide (LastCall) formulations will kill a large proportion of *P. xylostella* or *T. ni* males that make contact. The effect of treatment on mating ability was not tested. Field experiments further confirmed the potential utility of both LastCall formulations to suppress infestations of *P. xylostella* and *T. ni* on cabbage and collards to levels resulting in marketable crops. In the current study, LastCall provided acceptable control of *P. xylostella* and *T. ni* and yielded marketable crops similar to Bt in all but one of the four seasons (spring 2004). The efficacy of LastCall was dependent upon the population densities of the three lepidopteran species, which fluctuated from season to season. This pattern of efficacy is commonly observed with mating disruption products and attracticides. In the study plots in central Alabama, *P. xylostella* was observed in moderate numbers in all four seasons, whereas population densities of *P. rapae* and *T. ni* were greater in the spring than in the fall.

The failure of LastCall treatments to yield marketable produce in spring 2004 could be attributed to several reasons. First, *P. xylostella* infestation as indicated by adult trap captures was two- to three-fold greater in spring 2004 than in any of the other seasons (≈24 males per trap per week recorded in spring 2004). In addition, LastCall failure may be due to the relatively high *P. rapae* infestation recorded in spring 2004 coupled with the fact that this species was not the target of the LastCall treatments. Several authors have also attributed attracticide failure to very high initial pest populations (Charmillot et al. 2000, Krupke et al. 2002, Evenden and McLaughlin 2004b). Krupke et al. (2002) postulated that the effectiveness of attracticide formulations is likely to decrease as the population density of female increases, because more females will increase the competition provided by natural sources of pheromones. Disruption of sexual communication (measured by trap shutdown) has been proposed as a key operative mechanism of the attracticide tactic (Mitchell 2002, Evenden and McLaughlin 2004a, b; Evenden et al. 2005). However, we did not record significant trap shutdown in LastCall plots, yet LastCall was effective in producing marketable cabbage and collards. This suggests that elimination of males by the toxicant (permethrin), rather than male confusion or interruption of sexual communication due to multiple pheromone sources, was probably the main mechanism behind the success of the attracticide tactic in this study (Brockerhoff and Suckling 1999, Charmillot et al. 2000).

Our field study covering four growing seasons each with varying pest pressure has yielded some insights on the potential efficacy of the attracticide tactic against lepidopteran pests of cole crops and allowed us to make some predictions regarding some of the factors that may influence the effectiveness of this relatively novel technology. The results of our study suggest that LastCall, at the recommended application rate of 3,954 droplets per formulation per hectare, is effective at low-to-moderate population densities of *P. xylostella* and *T. ni* typically observed in the fall in central Alabama. The relatively greater spring population densities of *P. xylostella* and *T. ni* coupled with extremely high *P. rapae* pressure commonly observed in the spring in central Alabama may likely result in the failure of the present pheromone-based attracticide system against lepidopteran crucifer pests, which does not target *P. rapae.* It is possible that the use of a higher application rate (e.g., 3,000 droplets per formulation per acre) or frequency may likely enhance the efficacy of LastCall even at high pest population densities; however this possibility needs to be investigated. Attracticides using floral attractants instead of pheromone are currently under development (IPM Development Company), and may hold promise for utilization against *P. rapae.* Floral attractants often attract both sexes and therefore have the potential to increase the utility of attracticide tactic against other species. Furthermore, the development of attracticide formulations that use botanical insecticides (e.g., pyrethrum) instead of synthetic insecticides will likely make the tactic acceptable to organic farmers, or those interested in sustainable crop production.

In summary, the attracticide technology is potentially effective against lepidopteran pests of cole crops and can be of use in an integrated pest management program against the cabbage caterpillar complex, either as a stand alone tactic using multiple applications within a season or in rotation with Bt or other tactics. The advantages of this tactic include species specificity, little or no impact on nontarget beneficial arthropods, and requirement of less pheromone per hectare than mating disruption (Charmillot et al. 2000; Mitchell 2002; Evenden and McLaughlin 2004a, b). Additionally, because the attracticide technology targets the adult males of these insect populations, it is compatible and complementary with tactics aimed at eggs or larvae of *P. xylostella* and *T. ni.* However, it remains to be seen whether this tactic will provide a cost-effective alternative to Bt or conventional insecticides.

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