Integrating Chemical and Biological Control of European Corn Borer in Bell Pepper

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ABSTRACT Using multiple locations and a series of field trials over 2 yr, we evaluated an integrated pest management program for *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) management in peppers involving biorational chemistries, inundative releases of *Trichogramma ostriniae* (Pang & Chen), and conservation of generalist predators. In small plot trials, three biorational insecticides (spinosad, indoxacarb, and methoxyfenozide) provided comparable control of *O. nubilalis* as two broad-spectrum conventional insecticides (acephate and lambda-cyhalothrin). However, lambda-cyhalothrin at most locations, and indoxacarb at one location, resulted in outbreaks of green peach aphids. We also observed significant effects on the generalist predator community: beneficial communities in methoxyfenozide-treated plots were most similar to untreated controls, and acephate-treated plots were the least similar. Management systems comparing untreated controls, inundative release of *T. ostriniae* with methoxyfenozide applied when lepidopterans exceeded thresholds, or weekly applications of acephate or lambda-cyhalothrin, showed no effects on marketable fruit or percentage of fruit damaged, but the conventional insecticide approach caused aphid flares. Inundative releases of *T. ostriniae* and biorational chemistries provide a more environmentally sound approach to managing *O. nubilalis* in peppers, due, in part, to conservation of generalist predators.

KEY WORDS *Ostrinia nubilalis*, *Trichogramma ostriniae*, pepper, biocontrol, IPM

Sweet bell pepper (*Capsicum annuum* L.) is a valuable vegetable crop, grossing nearly $500 million annually in the United States (NASS 2006). Commercial growers have a large financial investment once plants begin to set fruit, and they often apply insecticides preventatively to protect the pepper fruit from insect pests. Pepper growers in the Mid-Atlantic United States generally apply the organophosphate acephate for two sprays (maximum allowed per crop per season) and then apply a pyrethroid insecticide every 5–10 d until final harvest. This conventional (preventative spraying) approach may result in five to 10 insecticide applications per crop. Although it is generally effective (Welty 1995, Kuhar and Speese 2002, Kuhar et al. 2003), it has numerous drawbacks associated with unwarranted applications, including potential buildup of pesticide residues, destruction of important natural enemies in the agroecosystem, environmental and human health risks, and reduced profits.

For pepper growers in the northeastern and central United States, European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae), is the primary target of insecticide sprays (Welty 1995, Hazzard et al. 2001). The insect has two to three generations per year and is a season-long risk to bell pepper. Egg masses are deposited on the undersides of leaves (Barlow and Kuhar 2004). After a brief period of leaf feeding, larvae bore into fruit if available or stems if no fruit or only very small immature fruit are present (Hitchner and Ghidiu 2006). Direct damage is caused by the tunneling larvae that feed on the pericarp, placenta, and seeds of developing fruit. Moreover, tunnel holes frequently are entry points for fruit-rotting pathogens such as *Erwinia caratovora* (Hazzard et al. 2001). Fruit damage can range from 40 to 60% (Welty 1995, Kuhar and Speese 2002, Kuhar et al. 2003, Welty and Vitanza 2005). Even greater fruit damage can occur to mature (colored) bell peppers because of the increased time that fruit are in the field. *O. nubilalis* is particularly difficult to control because larvae are only exposed to insecticide sprays from egg hatch until tunneling.

Other insects that may infest pepper fruit include the noctuid pests *Helicoverpa zea* (Boddie); *Spodopt-*

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era exigua Hübner; *Spodoptera frugiperda* (J.E. Smith); and pepper maggot, *Zonosemata electa* (Say) (Diptera: Tephritidae) (Boucher and Ashley 2001). However, Kuhar et al. (2004) found that this complex of pests only accounted for ≈5% of insects found attacking bell pepper fruit in Virginia, with most (95%) being *O. nubilalis.* In addition, green peach aphid, *Myzus persicae* (Sulzer), can be an important indirect pest of peppers by feeding on plant phloem sap, reducing plant vigor, vectoring viruses, and depositing honeydew, where black sooty mold fungus may grow. Green peach aphid has a tremendous reproductive capability, and it can quickly build to damaging levels if populations are not contained (van Emden et al. 1969).

Biological control of *O. nubilalis* eggs using augmentative releases of *Trichogramma* parasitoids may provide an alternative to reliance on insecticides (Smith 1996), and thus help conserve beneficials that could regulate aphid densities. *Trichogramma ostriniae* Pang & Chen (Hymenoptera: Trichogrammatidae) was introduced into the United States from China in the early 1990s (Hoffmann et al. 1995), and it has shown promise for controlling *O. nubilalis* in corn (Wang et al. 1999, Hoffmann et al. 2002, Kuhar et al. 2002, Wright et al. 2002) and solanaceous crops (Kuhar et al. 2004). After four to five inundative releases of *T. ostriniae* in bell pepper, *O. nubilalis* egg parasitism averaged ≈50%, and cumulative fruit damage was reduced almost 70% compared with nonrelease control plots (Kuhar et al. 2004). However, under heavy pest pressure, pepper fruit damage still exceeded 10% in the *T. ostriniae* release plots.

Reduced-risk (biorational) insecticides offer an alternative to organophosphates and pyrethroids for controlling *O. nubilalis* in pepper. In recent years, a few narrow-spectrum (more lepidopteran specific) insecticides have been registered for use on bell pepper, including spinosad (Spintor, Dow AgroSciences LLC, Indianapolis, IN), methoxyfenozide (Intrepid, Dow AgroSciences LLC), and indoxacarb (Avaunt, E. I. DuPont de Nemours and Co., Wilmington, DE). These insecticides provide effective control of most lepidopteran pests, whereas generally having greatly reduced toxicity to natural enemies (Brunner et al. 2001; Elzen 2001; Baur et al. 2003; Hewa-Kapuge et al. 2003; Hill and Foster 2003; Schneider et al. 2003; Studebaker and Kring 2003a, 2003b; Carton et al. 2003; Haseeb et al. 2004, 2005; Villanueva and Walgenbach, 2005).

Here, we evaluated strategies to reduce broad-spectrum insecticide use on bell pepper in the Mid-Atlantic United States. In one experiment, the efficacy and relative impact on beneficial arthropods of spinosad, methoxyfenozide, and indoxacarb were compared with the conventional broad-spectrum insecticides acephate and lambda-cyhalothrin; and in a second experiment, the efficacy of a *T. ostriniae*-based biological control program was compared with a conventional insecticide-based program.

Materials and Methods

Biorational Insecticide Trials. We evaluated the effects of biorational chemistries on *O. nubilalis* damage and natural enemy communities in 2005, by using small-plot field experiments at four locations: Virginia Tech Eastern Shore Agricultural Research and Extension Center (AREC), Painter, VA; University of Delaware REC, Georgetown, DE; University of Maryland Wye REC, Queenstown, MD; and the Russell E. Larson Research Farm, Rock Springs, PA. Each field consisted of treatments in a randomized complete block design with four replications of six insecticide treatments. Individual plots were four rows wide by 6 m long with >3-m alleys between plots. Crops were established and maintained using standard agricultural procedures including fertilizer, herbicide, and fungicide applications according to a commercial vegetable production manual for the Mid-Atlantic United States (Kuhar et al. 2006b, see Table 1 for details at each location). Insecticide treatments included 1) indoxacarb at 0.072 kg (AI)/ha (Avaunt 30 WG; E. I. du Pont de Nemours and Co.); 2) methoxyfenozide at 0.112 kg (AI)/ha (Intrepid 2 F; Dow AgroSciences LLC); 3) spinosad at 0.026 kg (AI)/ha (SpinTor 2 SC, Dow AgroSciences LLC); 4) acephate at 1.09 kg (AI)/ha (Orthene 97SG; Valent USA Corporation, Walnut Creek, CA); 5) lambda-cyhalothrin at 0.03 kg (AI)/ha (Syngenta Crop Protection Inc., Greensboro, NC); and 6) an untreated control. Insecticides were applied with a CO_2 backpack sprayer with a one-row boom having three hollow-cone nozzles per row (one over the top and one drop nozzle on each side) delivering 39 gpa at 40 psi. Treatments were applied weekly from first fruit until final harvest. Dates of applications for each location are presented in Table 1. On three postspray sample dates, aphids were counted on 50 randomly picked leaves per plot. Relative density of natural enemies (generalist arthropod predators and parasitoid species) were estimated by slowly walking the entire length of one middle row per plot while vacuuming plants using a Craftsman 200 mph leaf blower-vac. Samples were collected using a fine mesh bag fitted on the intake tube of diameter 12 cm. After each sample was collected, bags were tied shut and frozen. Any dirt or plant debris was removed and all insects were stored in 70% ethanol for later identification and sorting into seven natural enemy groups: ladybird beetles; predatory bugs; parasitic hymenoptera; lacewings; predatory Diptera; spiders, and other.

On three separate dates during a one month span in late summer (Table 1), all market-sized fruit were harvested from the middle two rows of each plot and assessed for insect damage. *O. nubilalis* damage to bell pepper can manifest itself as either reduced number of harvested fruit from rotting, or percentage of harvested fruit exhibiting damage. The cumulative number of marketable fruit and the percentage damaged by insects were recorded. Damaged fruit were dissected and inspected for any insects present.

Table 1. Crop and pest management information for each location of bell pepper management systems experiments in the Mid-Atlantic Region of the United States in 2005 and 2006

Location	Variety	Transplant date	Crop production method	Insecticide application dates in conventional plots	*T. ostriniae* release dates in IPM plots	Harvest and fruit damage evaluation dates
2005						
Painter, VA*	Paladin	14 June	Ground with overhead irrigation	21, 28 July, and 3, 9, 16, 23, 31 Aug.	21 July, and 2, 12 Aug.	11, 22 Aug., and 7 Sept.
Virginia Beach, VA	Paladin	6 June	Ground with drip-line irrigation	22, 29 July, and 4, 12, 19, 30 Aug.	22 July, and 3, 12 Aug.	26 July, 4, 16 Aug., and 1 Sept.
Georgetown, DE*	Aristotle	27 May	Single rows on black plastic with drip-line irrigation	16, 22, 28 June, 6, 13, 20, 27 July, and 5 Aug.	29 June, and 12, 19 July	12, 26 July, and 15 Aug.
Queenstown, MD*	Paladin	16 June	Single rows with overhead irrigation	24 July, 1, 8, 15, 21, 29 Aug., and 8 Sept.		19, 26 Aug., and 16 Sept.
Rock Springs, PA*	King Arthur	13 June	Double-staggered rows on black plastic with drip irrigation	25 July, and 1, 9, 15, 22, 29 Aug.	25 July, and 3, 12, 20 Aug.	20 Aug., and 1, 16 Sept.
2006						
Painter, VA	Paladin	7 June	Ground with overhead irrigation	28 July, and 4, 11, 18, 25 Aug., and 5 Sept.	3, 10, 17 Aug.	14, 24, and 5 Sept.
Virginia Beach, VA	Paladin	7 June	Single rows on black plastic with drip-line irrigation	29 July, and 3, 11, 17, 24, 31 Aug.	3, 10, 17 Aug.	5, 17, 29 Aug.
Queenstown, MD	Paladin	6 June	Single rows with overhead irrigation	12, 20, 31 July, 17, 24 Aug., and 4 Sept.	4, 12 Aug.	27 July, 11 and 23 Aug.
Georgetown, DE	Aristotle	5 June	Single rows on black plastic with drip-line irrigation	8, 15, 22, 29 July, and 5 Aug.	19, 27 July, and 3, 14 Aug.	26 July and 8, 21 Aug.
Rock Springs, PA	Paladin	8 June	Single rows on black plastic with drip irrigation	24, 31 July, and 7, 14, 21, 28 Aug.	21, 28 July and 4 Aug.	7, 17, 24, 31 Aug. and 7 Sept.

With the exception of the *Trichogramma* release, all information for the four locations in 2005 marked by an asterisk was the same for the biorational insecticide experiments.

Data were analyzed using analysis of variance (ANOVA) (Analytical Software 2003) to test for significant treatment effects on marketable fruit yield, proportion damaged fruit, and peak density of aphids on leaves. To stabilize variances all proportion damage data were arcsine square-root transformed, and aphid density data were $\log_{10}$ x-transformed. If the treatment source of variation was significant, differences among treatment means were tested using Fisher's protected least significant difference (LSD) at the $P \leq 0.05$ level of significance.

To determine whether insecticide treatments influenced the beneficial community and to investigate patterns attributable to insecticide, we performed a redundancy analysis (RDA) by using location as a covariable with CANOCO 4.5 (ter Braak and Šmilauer 2002). RDA is an ordination technique that can be useful for identifying associations between response variables and explanatory variables when working with complex multivariate data. RDA identifies the prominent gradients (i.e., orthogonal axes) among the response variables, as constrained by the treatment variables, and determines the significance of the axes using Monte Carlo permutational procedures (ter Braak and Šmilauer 2002). To visualize trends, the response and treatment variables were plotted on the first two axes (a biplot), in which proximity indicates degree of association. Forward selection was used to identify significant treatment factors. All natural enemy data were square-root transformed in CANOCO 4.5.

Management Systems Experiments. In 2005 and 2006, we established three spatially isolated plots of peppers (each ≈0.03 ha and ≈500 plants) at each of five locations: Virginia Tech Eastern Shore AREC, Painter, VA; Virginia Tech Hampton Roads AREC, VA Beach, VA; University of Delaware AREC, Georgetown, DE; University of Maryland Wye AREC, Queenstown, MD; and the Russell E. Larson Research Farm, Rock Springs, PA (Table 1). Each location represented a replicate ($n = 5$) in a randomized complete block experiment that was analyzed separately by year. Crops were established and maintained using standard agricultural procedures including fertilizer, herbicide, and fungicide applications following a commercial vegetable production manual designed for the Mid-Atlantic United States (Kuhar et al. 2006b; details at each location are presented in Table 1).

At each location, the three pepper plots were randomly designated as 1) conventional, which involved two applications of acephate at 1.09 kg (AI)/ha initiated at first fruiting followed by four or five weekly applications of lambda-cyhalothrin at 0.03 kg (AI)/ha from first fruit until final harvest; 2) IPM, which included three or four weekly inundative releases of *T. ostriniae* starting with first fruiting and an application of methoxyfenozide at 0.112 kg (AI)/ha only if lepidopteran pests exceeded action thresholds; and 3) an untreated control. In the IPM plot, we released 100,000 *T. ostriniae* per acre on three or four dates (Table 1) by using perforated cardboard release cartons and methods described in Kuhar et al. (2004). The parasitoids were obtained from M. P. Hoffmann (Cor-

Table 2. Influence of insecticide applications on green peach aphid on bell peppers at four locations in the Mid-Atlantic United States

Treatment[a]	Rate kg (AI)/ha	Mean ± SE no. green peach aphids per 10 leaves								
		Georgetown, DE			Rock Springs, PA			Painter, VA		
		After 4 sprays	After 6 sprays	After 7 sprays	After 2 sprays	After 5 sprays	After 6 sprays	After 3 sprays	After 6 sprays	After 7 sprays
Lambda-Cyhalothrin	0.03	44.2 ± 33.2a	81.2 ± 23.8a	139.4 ± 38.0a	0.1 ± 0.1a	21.9 ± 10.4a	35.9 ± 7.9a	0.6 ± 0.4a	76.3 ± 25.6a	158.0 ± 46.7a
Acephate	1.09	0.0 ± 0.0b	0.2 ± 0.1b	0.2 ± 0.2b	0.0 ± 0.0a	0.0 ± 0.0b	0.0 ± 0.0b	0.0 ± 0.0a	0.0 ± 0.0b	0.0 ± 0.0b
Spinosad	0.026	0.8 ± 0.4b	0.8 ± 0.4b	3.4 ± 0.7b	0.5 ± 0.2a	4.6 ± 1.2b	4.6 ± 4.2b	0.2 ± 0.1a	0.0 ± 0.0b	0.5 ± 0.5b
Indoxacarb	0.072	7.1 ± 5.2ab	55.3 ± 39.7a	139.8 ± 84.5a	0.5 ± 0.3a	1.9 ± 1.0b	0.3 ± 0.1b	0.2 ± 0.1a	0.8 ± 0.3b	3.2 ± 1.7b
Methoxyfenozide	0.112	0.7 ± 0.4b	0.5 ± 0.4b	2.9 ± 1.1b	0.4 ± 0.3a	2.4 ± 0.5b	13.0 ± 12.2b	0.2 ± 0.2a	0.3 ± 0.3b	0.7 ± 0.7b
Untreated control		0.9 ± 0.5b	1.0 ± 0.3b	2.0 ± 0.4b	0.4 ± 0.3a	0.4 ± 0.2b	0.0 ± 0.0b	0.7 ± 0.6a	0.0 ± 0.0b	0.4 ± 0.4b

Means within a column with a letter in common are not significantly different according to ANOVA and Fisher's protected LSD at the P = 0.05 level of significance.

[a] All insecticides were applied ≈weekly beginning at first appearance of fruit.

nell University, Ithaca, NY), details on the *T. ostriniae* colony maintenance can be found in Hoffmann et al. (1995). Insect monitoring followed guidelines outlined in Boucher and Ashley (2001), and involved blacklight or pheromone trap monitoring of *O. nubilalis* and *S. frugiperda* and *S. exigua* moths (Lepidoptera: Nocutidae). Weekly inspections of 40 plants per plot involved looking for aphids and eggs on the underside of leaves and examining any present fruit for tunnels or frass, indicating the presence of larvae of lepidopteran pest species. As described in Boucher and Ashley (2001), insecticide applications for *O. nubilalis* were applied on IPM plots 1 wk after pheromone trap counts reached seven moths per week and the pepper crop had reached bloom stage. Insecticide spray dates at each location are shown in Table 1.

When they reached marketable size, pepper fruit were hand-harvested and evaluated for damage from July to October (specific dates are listed in Table 1). Data were pooled across the five locations and analyzed by year using ANOVA (Analytical Software 2003) to test for significant treatment effects on marketable fruit yield, proportion damaged fruit, and peak density of aphids on leaves. Proportion data were square-root transformed before analysis to stabilize variance. Differences among treatment means were tested using Fisher Protected LSD at the $P \leq 0.05$ level of significance.

Results

Biorational Insecticide Trial. Green peach aphid infested pepper plots at all four locations, but it did not reach damaging levels in the untreated control plots on any sample date at any location. However, after four or more insecticide applications, there was a highly significant treatment effect on numbers of aphids at three of the four locations: Virginia (F = 23.43; df = 5, 23; $P < 0.0001$), Pennsylvania (F = 6.35; df = 5, 23; $P < 0.0024$), and Delaware (F = 7.99; df = 5, 23; $P < 0.0008$). In Virginia and Pennsylvania, aphid densities were significantly higher in the lambda-cyhalothrin plots compared with any other insecticide treatment or the control, and in Delaware, aphid densities were significantly higher in the lambda-cyhalothrin and indoxacarb plots compared with any other insecticide or the control (Table 2). Additional applications of these insecticides resulted in even greater aphid densities, whereas aphid densities remained low in control plots (Table 2).

Lepidopteran pest pressure was relatively low across all locations, and there was no significant treatment effect on cumulative number of marketable (undamaged) fruit in Maryland (F = 0.67; df = 5, 23; P = 0.6534), Pennsylvania (F = 1.80; df = 5, 23; P = 0.1730), and Virginia (F = 0.27; df = 5, 23; P = 0.9243); however, there was a consistent numeric trend toward the untreated control plots yielding the least number of marketable fruit (Fig. 1A). There was a significant treatment effect on the percentage of fruit damaged by *O. nubilalis* in Pennsylvania (F = 6.35; df = 5, 23; $P < 0.0024$) and Virginia (F = 7.56; df = 5, 23; $P <$ 0.0010), where the untreated control plots at both locations had more damage than any of the insecticide treatments, and no differences were found among the insecticide treatments (Fig. 1B). No significant treatment effect on fruit damage was found at the Maryland location (F = 1.56; df = 5, 23; P = 0.2308). Fruit damage and concomitant number of marketable fruit was not assessed at the Delaware location.

The predominant natural enemies were parasitic Hymenoptera (mostly Chalcidoidea, Braconidae, and Ichneumonidae), predatory bugs (mostly Anthocoridae, *Orius* spp.), ladybird beetles (Coccinellidae), and spiders (Aranea). RDA identified a significant primary (F = 8.78, P = 0.002) and secondary (F = 2.41, P = 0.002) gradient among the beneficial insect community as constrained by our treatment variable (i.e., insecticide) and together they explained 11.6% of the variance in the community data. The biplot (Fig. 2) indicates that the communities associated with lambda-cyhalothrin and acephate differed from the other treatments along the first axis, and forward selection identified lambda-cyhalothrin as the predominant variable influencing this gradient (F = 4.57, P = 0.002). Lacewings, spiders, and predatory bugs responded positively to indoxacarb, methoxyfenozide, and the untreated control, and they were negatively correlated to lambda-cyhalothrin and acephate (Fig. 2). The second axis represented community differentiation between lambda-cyhalothrin and acephate (F = 5.26, P = 0.002). Ladybird beetles, braconids, and other hymenopterans (excluding ichneumonids)

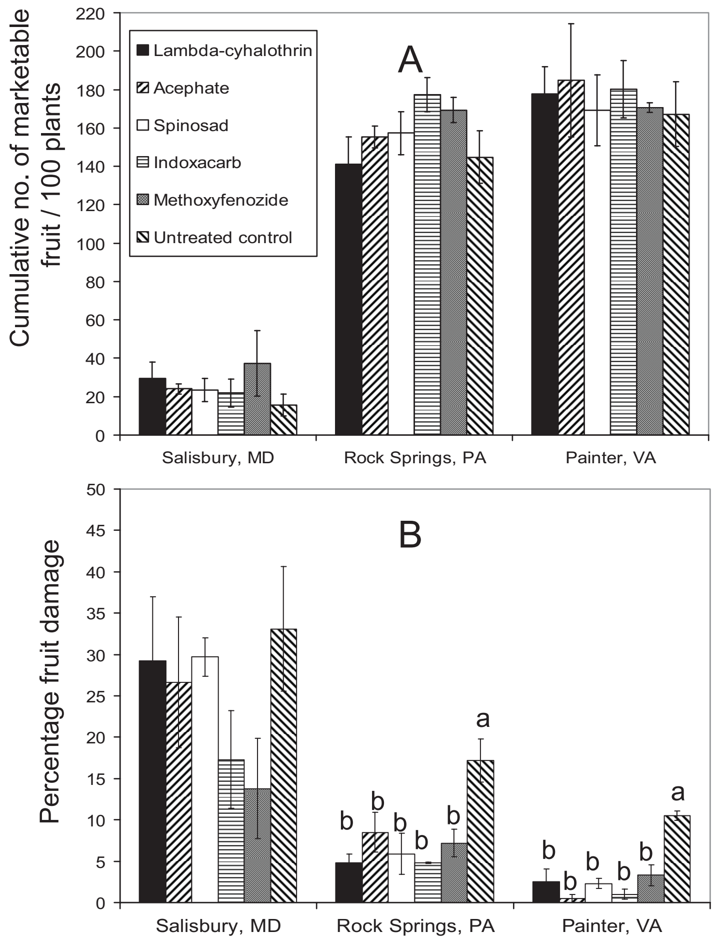

Fig. 1. Influence of insecticide applications on marketable fruit yield (A) and percentage of fruit damaged by lepidopteran pests (B) on bell peppers at three locations in the Mid-Atlantic United States in 2005. All insecticides were applied approximately weekly beginning at first appearance of fruit. Means within a location with a letter in common are not significantly different according to ANOVA and Fisher's protected LSD at the $P = 0.05$ level of significance.

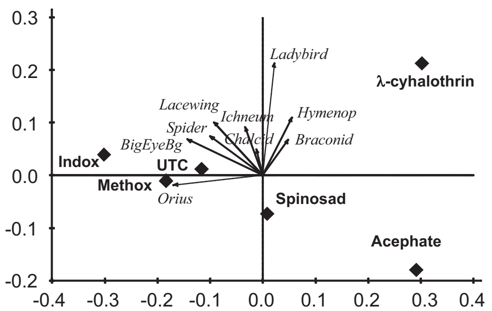

Fig. 2. Redundancy analysis bipolot, depicting associations between beneficial insect taxa (vectors) and six insecticide programs (black diamonds). Abbreviations used in the figure were as follows: Indox, indoxacarb; Methox, methoxyfenozide; UTC, untreated control; Ladybird, Coccinellidae adults and larvae; Lacewing, larvae of Chrysopidae and Hemerobiidae; Ichneum, adult Ichneumonidae; BigEyeBg, *Georcoris* spp. adults and nymphs; Chalcid, adult Chalcidoidea; Braconid, adult Braconidae; Hymenop, all adult Hymenoptera; and Orius, *Orius* spp. adults and nymphs.

were more highly associated with lambda-cyhalothrin and not acephate (Fig. 2). Ichneumonids and chalcidids were negatively correlated with acephate and spinosad and uncorrelated with the remaining treatments (i.e., found equally among them).

Management Systems Experiments. In both years, lepidopteran pest pressure to bell peppers was moderately low to low at all five Mid-Atlantic locations. *O. nubilalis* was the primary insect pest encountered, and weekly moth catch at each location and year is shown in Fig. 3. In 2005, conventional plots averaged seven insecticide applications (two acephate sprays + five pyrethroid sprays) compared with less than one insecticide spray of methoxyfenozide in the IPM plots. In 2006, conventional plots averaged 5.8 insecticide applications (two acephate sprays + additional pyrethroid sprays) compared with no insecticide sprays in the IPM plots.

There was no significant treatment effect on cumulative number of marketable fruit in 2005 ($F = 1.37$; df = 2, 6; $P = 0.3035$) or 2006 ($F = 0.7$; df = 2, 6; $P =$

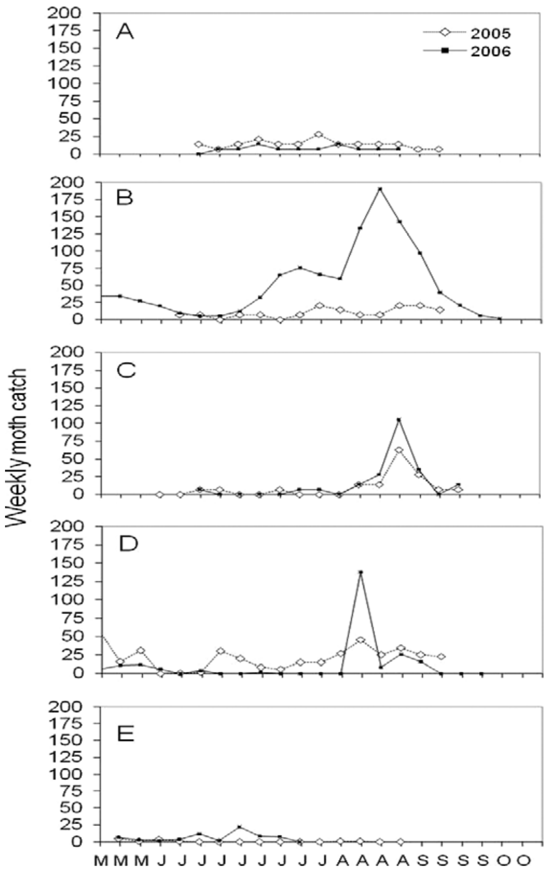

Fig. 3. Weekly moth catch of *O. nubilalis* in blacklight or pheromone traps located at Rock Springs, PA (A), Queenstown, MD (B), Georgetown, DE (C), Painter, VA (D), and Virginia Beach, VA (E), in 2005 and 2006.

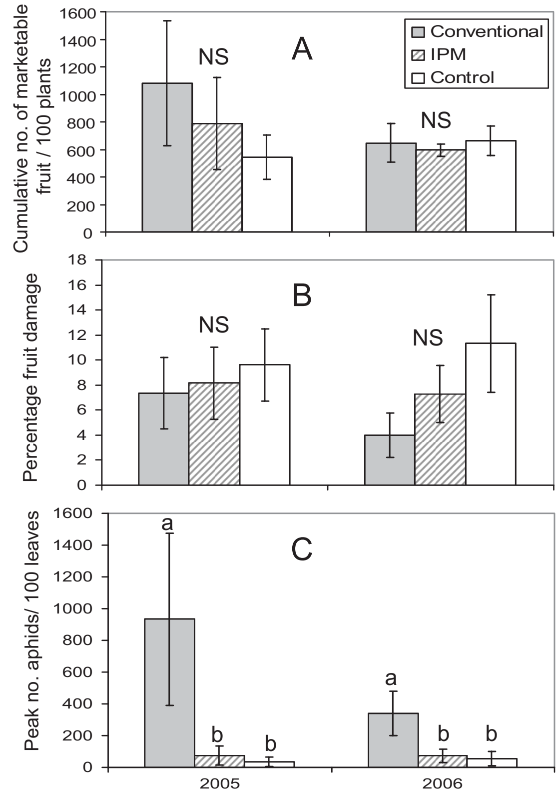

Fig. 4. Cumulative yield of marketable fruit (A), percentage of fruit damaged by lepidopteran pests (B), and peak green peach aphid densities (C) from bell pepper in the Mid-Atlantic States (n = 5 locations per year) under three pest management systems: 1) a conventional system of weekly acephate or lambda-cyhalothrin applications from first fruiting until final harvest; 2) an IPM system of three or four inundative releases of *T. ostriniae* to control *O. nubilalis* plus zero, one, or two applications of the insect growth regulator (IGR) insecticide methoxyfenozide; and 3) an untreated control. Means within the same year with a letter in common are not significantly different according to ANOVA and Fisher's protected LSD at the P = 0.05 level of significance.

0.5239). However, in 2005, across the five locations, conventional plots tended to have the most marketable fruit followed by the IPM plots and then the untreated control plots (Fig. 4A). There was also no treatment effect on percentage of fruit damaged by lepidopteran larvae in either 2005 (F = 0.15; df = 2, 6; P = 0.8649) or 2006 (F = 2.60; df = 2, 6; P = 0.1351). Percentage of damaged fruit averaged between 4 and 12% among the treatments with the untreated control plots typically having the most damage numerically (Fig. 4B).

There was a significant treatment effect on peak density of green peach aphids in 2005 (F = 5.71; df = 2, 6; P < 0.041) and nearly a significant effect in 2006 (F = 3.70; df = 2, 6; P < 0.0896). In both years, the conventional insecticide plots had the most aphids, and no differences were found between the IPM and untreated control plots (Fig. 4C).

Discussion

In the 2 yr of our study, the biorational insecticides spinosad, indoxacarb, and methoxyfenozide provided similar control of *O. nubilalis* in bell pepper as the conventional acephate or lambda-cyhalothrin treatments. However, lepidopteran pest pressure was relatively low in our study. Nonetheless, similar efficacy results with some or all of the aforementioned insecticides on bell peppers have been shown by Nault and Speese (2000), Kuhar and Speese (2002), Kuhar et al. (2003, 2006a), and Sorensen and Cooke (2004). In contrast, Welty and Vitanza (2005) found acephate to be the superior insecticide under extreme *O. nubilalis* pest pressure on mature red bell pepper in Ohio. Timing of the insecticide applications is critical for *O. nubilalis* control. Most do not kill the egg stage, and after hatch, larvae quickly tunnel into plants where they are protected from chemical sprays. A systemic insecticide such as acephate could exhibit greater efficacy against *O. nubilalis* because of a longer residual in the field compared with the newer biorationals.

Green peach aphid did not reach damaging levels in the untreated control plots, or in plots treated with acephate, spinosad, or methoxyfenozide. In contrast, at most locations, multiple sprays of the pyrethroid lambda-cyhalothrin caused severe aphid outbreaks. Also at one location, multiple sprays of indoxacarb caused similar aphid flares. Destruction of arthropod natural enemies by insecticides was likely the cause for the aphid outbreaks (van Emden et al. 1969, Croft and Brown 1975). lambda-Cyhalothrin and acephate are highly toxic to most arthropod natural enemies (Baur et al. 2003). However, acephate provides excellent control of green peach aphid, but pyrethroid insecticides, such as lambda-cyhalothrin, do not (Speese 1994 and 1995). Therefore, multiple sprays of lambda-cyhalothrin or any pyrethroid will typically exacerbate green peach aphid problems. Our data showed that at least in one field, multiple sprays of indoxacarb could result in similar aphid outbreaks. Indoxacarb does not control aphids, and is moderately toxic to some natural enemies including predatory hemipterans (Baur et al. 2003) and ladybeetles (Kuhar, unpublished data). Several factors can influence the nontarget impact of an insecticide in the field. For example, spinosad was extremely toxic to the hymenopteran parasitoid *Diadegma insulare* (Cresson) in leaf dip assays (Hill and Foster 2000); however, in field experiments *D. insulare* parasitism of diamondback moth larvae was not affected by spinosad applications (Hill and Foster 2003). In addition, the aforementioned insecticides may have sublethal effects on natural enemies, such as parasitoid oviposition rate and emergence (Brunner et al. 2001, Schneider et al. 2004). However, although sublethal effects of both indoxacarb and spinosad have been documented under lab conditions, it is difficult to know to what extent these effects may occur in the field. Moreover, rapid degradation of insecticide surface residues in the field would improve their compatibility with natural enemies. This would likely be the case with spinosad degradation by photolysis (Viktorov et al. 2002). In addition, the translocation and translaminar properties of some insecticides make them available in the host plant tissues for control of leaf feeders, but surface residues disappear quickly, thus making them safe for parasitoids and most natural enemies (Hoy and Cave 1985, Brunner et al. 2001).

We worked under constraints commonly associated with efficacy trials in high-value crops, including small plots and the presence of toxins in proximity to all plots. The proximity of plots could have masked differences in mobile beneficial insects associated with treatments. Combined with small plot size, there was likely a homogenizing effect on the treatment response. Nonetheless, we were able to demonstrate significant community-scale effects (Fig. 2). Community gradients among insecticide management tactics stood out as the first axis, and showed strong similarity in beneficial communities in untreated controls and plots treated with methoxyfenozide. In both, heteropteran predator abundance and density were strongest. In contrast, beneficial communities from untreated controls or methoxyfenozide, along with indoxacarb, were most different than those treated with either of the broad-spectrum insecticides—the organophosphate (acephate) or the pyrethroid (lambda-cyhalothrin). However, there was a measurable difference in communities between these two broad-spectrum plots (shown by the significant second axis; Fig. 2). Plots treated with the systemic organophosphate acephate were not associated with any beneficial taxa in contrast with plots treated with lambda-cyhalothrin, which associated with some hymenopterans and ladybird beetles. Indeed, although lambda-cyhalothrin is known to be detrimental to beneficial insects, the highly mobile parasitic hymenopterans and ladybird beetles were more closely associated with the pyrethroid than the systemic acephate, which may have been due to recolonization (Baur et al. 2003) in response to the aphid flare documented in these plots. The microbial metabolite, spinosad, had no clear pattern of association. In general, this suggests that newer biorational insecticides, coupled with multivariate analytical tools, enable analysis of beneficial communities in vegetable entomological research, and that methoxyfenozide had the least affect on beneficial communities among the treatments we tested.

Our demonstration plots in the Mid-Atlantic Region of IPM versus conventional insecticide-based programs in bell pepper did not reveal significant treatment effects on cumulative number of marketable fruit or percentage fruit damage. This was clearly impacted by low lepidopteran pest pressure across the two years of our study. The economic implications of this study suggest a conventional insect management approach could reduce costs by adopting some IPM practices during low insect pressure. Based on typical grower practices, approximately seven insecticide sprays were made throughout the growing season on our conventional plots. Two sprays of acephate ($32/ha) followed by five sprays of lambda-cyhalothrin ($21/ha) resulted in an approximate cost of $169/ha for insect control (Knodel 2007). The IPM plots were sprayed once with methoxyfenozide ($39/ha) in 2005 and none in 2006. Combined with three scheduled releases of *Trichogramma* wasps ($50/ha) insect control totaled approximately $189/ha. Despite the weekly spray regimen, the conventional-insecticide treated plots did not have significantly more fruit or less insect damage than either the IPM or the control plots. Presumably, if a conventional insect management program adopted monitoring for European corn borer and limited insecticide sprays to when an action threshold was met, less insecticide sprays would be needed thus lowering costs. Under greater insect pressure, the cost benefit of the treatments would likely be more apparent. As it stands, future research is needed for continued improvement for the IPM systems of interest in this study. Inundative releases of the parasitoid, *Trichogramma ostriniae*, have been shown to significantly reduce *O. nubilalis* damage in bell pepper in previous studies (Kuhar et al. 2004). Unfortunately, in our study, we were unable to determine whether this pest management approach can provide comparable control of *O. nubilalis* as a conventional insecticide approach. It should be noted, however, that the conventional insecticide treatment resulted in significantly higher densities of green peach aphids on peppers compared with either the untreated control plots or the *Trichogramma*-based IPM plots. Thus, in conditions of the degree of *O. nubilalis* pressure we observed over 2 yr in the mid-Atlantic states, integration of *T. ostriniae* releases, combined with conservation of generalist predators achieved through use of biorational insecticides, provides a more environmentally sound pest management option in peppers.

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