Research Article

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IPM-CPR for peaches: incorporating behaviorally-based methods to manage *Halyomorpha halys* and key pests in peach

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Abstract

BACKGROUND: The invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), has emerged as a key pest in mid-Atlantic peach production. Current management of *H. halys* has disrupted IPM programs by relying exclusively on frequent, repeated, season-long insecticide applications. We developed a behaviorally-based tactic termed IPM-CPR (Crop Perimeter Restructuring) that utilizes border sprays for *H. halys*, groundcover management for *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae) and mating disruption for *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae).

RESULTS: IPM-CPR reduced insecticide usage by 25–61%. Generally there was less, and at times significantly less, catfacing injury (attributable to *H. halys*) in peaches in the IPM-CPR blocks relative to the standard, and minimal differences in injury due to *G. molesta* or *L. lineolaris*. These results suggest that perimeter applications of insecticides exploit the border-arrestment behavior of *H. halys* by controlling them at the orchard edge, reducing damage throughout the block.

CONCLUSION: IPM-CPR significantly reduces the area managed by growers for control of *H. halys*, while simultaneously managing key pests at levels equal to current grower standard practices. This approach brings IPM tactics back into the orchard system after disruption by the invasive *H. halys* and potentially supports beneficial insects.

Supporting information may be found in the online version of this article.

Keywords: brown marmorated stink bug; tree fruit; perimeter; mating disruption; groundcover

1 INTRODUCTION

The invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), has proven to be one of the most devastating pests of northeastern United States agriculture. Since its introduction in the mid-1990s,[1] *H. halys* has spread across North America and is now present in 40 states and eastern Canada, causing the greatest crop damage in the mid-Atlantic region.[2] Damage in New Jersey peaches from the invasive *H. halys* was first documented in 2006,[3] but widespread economic injury was not reported until 2009–2010. In 2010, high populations of *H. halys* severely damaged tree fruit, with up to 90% of the peach crop at some mid-Atlantic farms damaged and an estimated $US 37 million loss to mid-Atlantic tree apples.[4,5] Since then, *H. halys* has established itself as a primary pest in tree fruit crops, and population pressure currently remains high.

Unlike many of the other important tree fruit pests, all mobile stages of *H. halys* feed on the host plant, which results in corked, deformed fruit,[6] considerably reducing its marketability. Peaches are an ideal host of *H. halys*, supporting populations of stink bugs from mid-late May as they emerge from overwintering through harvest of the fruit.[7] *H. halys* has 1–2 generations annually in the mid-Atlantic region of the United States[3,8] and frequently disperses throughout the season between the surrounding environment and peach orchards, causing repeated surges in *H. halys* abundance within orchards, particularly along crop perimeters.[9,10] Peaches are also one of the few hosts on which *H. halys* can solely complete development (Acebes A, private communication).

The continued injury and threat of crop loss due to *H. halys* and its highly mobile behavior have required frequent insecticide applications. Research has identified insecticides that are effective against *H. halys*,[8,11,12] which are primarily limited to compounds in the pyrethroid and neonicotinoid classes. Most compounds have short residual activity against *H. halys*, necessitating repeated applications at 7–10 day intervals, actions that have resulted in an up to fourfold increase in insecticide applications.[9,12] Tree fruit crops in the mid-Atlantic region are susceptible to dozens of other insect pests, which prior to the introduction of *H. halys* were managed through integrated pest management (IPM) programs that focused on threshold-based applications of reduced-risk insecticides, mating disruption, phenology models and groundcover management.[13] One such pest, the oriental fruit moth, *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae), has long been a major

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pest of stone fruits in North America.[14] Previous IPM strategies managed *G. molesta* at levels equal to or better than conventional peach pest management programs through the use of selective insecticides or mating disruption,[15,16] which have improved natural enemy activity against pest eggs.[17] Mating disruption works through multiple mechanisms that result in modifying male moth behavior to prevent mating with females within an orchard.[18] Additionally, piercing-sucking insects, such as native stink bugs (*Euschistus* spp.) and *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae), which cause catfacing damage, can also be important pests of peaches in the mid-Atlantic region.[19] Management of broadleaf weeds, such as clover, in the orchard groundcover reduces catfacing pest populations, as well as damage to the crop.[15] The insecticides used to control *H. halys* are generally also effective against other catfacing insects and *G. molesta*. Thus, mating disruption and other IPM tactics have been eliminated from many growers' management programs as they return to weekly, calendar-based, broad-spectrum insecticide applications.[20] It is essential to develop management tactics in peach that incorporate *H. halys*, but that reduces insecticide use and the adverse impacts on the orchard agroecosystems.

To mitigate the systems-level impacts and perimeter-focused attack from *H. halys*, we propose to bring IPM back to peach production by restructuring management programs in peach orchards using minimally disruptive options to manage *H. halys*, *L. lineolaris* and *G. molesta*. We have termed these tactics collectively IPM-CPR (Integrated Pest Management – Crop Perimeter Restructuring). IPM-CPR comprises multiple IPM tactics, which include: (1) treatment only of the perimeter row/trees and the first full row for *H. halys* (i.e. border sprays) (see supporting information Fig. S1); (2) removal of broadleaf weeds within groundcover, such as clover and other legumes that can harbor populations of tarnished plant bugs and other native catfacing insect populations; (3) mating disruption for *G. molesta*. We have used herbicides to maintain turf-only groundcover, which may also help mitigate insecticide impacts on foraging pollinators present in the orchard after bloom. Thus, our objectives for this project are (1) to investigate the effectiveness of managing *H. halys* and key fruit pests with border sprays, mating disruption and groundcover management, and (2) to determine the expected costs of a 'restructured' IPM program. The IPM-CPR strategy was evaluated by establishing a field trial in commercial peach orchards in cooperation with growers who had expressed an immediate need for *H. halys* management strategies to reduce insecticide inputs.

2 EXPERIMENTAL METHODS

2.1 Field layout and treatments

Field trials were implemented during a 2 year period to investigate the effectiveness of managing key fruit pests with border sprays, mating disruption and groundcover management. In 2012, field sites were located in three commercial peach orchards in southern New Jersey: farm 1 near Richwood, Gloucester County (39° 44′ 8.12″ N, 75° 10′ 29.42″ W), farm 2 near Salem, Salem County (39° 33′ 59.63″ N, 75° 25′ 29.61″ W), and farm 3 near Bridgeton, Cumberland County (39° 25′ 22.97″ N, 75° 15′ 34.86″ W). In 2013, the locations of farms 1 and 2 remained the same, but the third was substituted with farm 4 near Aura, Gloucester County (39° 41′ 35.59″ N, 75° 9′ 54.20″ W). All farms participate in the Rutgers IPM program and received insecticide recommendations from that program.

At each farm, an IPM-CPR treatment (border sprays + groundcover management + mating disruption) and standard block [solid block or alternate-row-middle (ARM) insecticide application] were selected for similarly aged trees of the same variety. In 2012, orchards at farms 1 and 2 were composed of the peach variety Jerseyqueen, while farm 3 was Harcrest. In 2013, sites at farms 1, 2 and 4 were all the Jerseyqueen variety, with additional sites implemented at farms 1 and 2 with the PF 24–007 variety, referred to as farms 1b and 4b respectively. All three varieties are relatively late-season peaches, with the PF 24–007 ripening roughly on 11–18 August, Harcrest on 17–23 August and Jerseyqueen on 27 August–3 September. Varieties, block areas and insecticide application type for each of the farms are given in Table 1.

Management programs were aimed at controlling *H. halys* from the end of May through harvest, early-season catfacing insects and second- and third-generation *G. molesta*. Applications for *H. halys* were initiated from a preliminary phenology model (Nielsen AL, unpublished) at 148 $DD_{14°C}$ accumulating 1 January.[3] Insecticide usage was left to the individual grower's discretion, but each grower was instructed to apply the same chemicals to each of the standard and IPM-CPR blocks. All insecticides were applied with a rear-mounted airblast sprayer. The standard blocks received insecticide applications for *H. halys* at 7–14 day intervals, based on Rutgers IPM recommendations and label requirements.

Within the IPM-CPR treatment blocks, mating disruption dispensers (2012: Isomate M-100, rate 247 dispensers ha^{-1}, 118.5 g AI ha^{-1}; 2013: Isomate OFM-TT, rate 173 dispensers ha^{-1}, 59.3 g AI ha^{-1}; CBC America Corp., Commack, NY) were applied to trees during both years in mid-May prior to the second flight of *G. molesta*, and the first generation was managed with insecticides. Each block, standard and IPM-CPR, had two delta traps baited with 0.1 mg of *G. molesta* lures (Suterra, Bend OR; Great Lakes IPM, Vestaburg, MI), placed within the orchard to assess pest activity and pressure. The orchard floor was treated with Clopyralid 40.9% (Stinger®; Dow, Indianapolis, IN) during the first week of May at a rate of 9.9 oz ha^{-1} to control broadleaf weeds such as clover and other legumes that may harbor populations of catfacing insects, such as *L. lineolaris*, and native stink bugs (*Euschistus* spp.). At DD timing for *H. halys*, insecticide applications were made to IPM-CPR blocks by treating the perimeter peach trees and the first full row of the block (i.e. border sprays) (see supporting information Fig. S1).

2.2 Sampling methods

Beginning in mid-May of 2012 and 2013, plots at each farm were scouted weekly at four sampling sites along each of four transects. Two transects were along orchard rows and two were perpendicular to the rows through each block. Each transect had four two-tree sampling sites, one on each perimeter edge, and two 6–10-tree sampling sites within the interior, for a total of 16 samples per block.

At each sampling site, two peach trees were observed for a combined 3 min period, recording visual counts for *G. molesta* flagging and *H. halys* adults, eggs and nymphs.[9,17] From each tree, 25 fruits were randomly assessed for brown rot, catfacing injury and *G. molesta* fruit injury. Additionally, we sampled for *L. lineolaris* within the row middles using 25 sweep samples with a sweep net (15″; BioQuip Products Inc., Compton, CA) at each of the 16 sampling sites. At harvest (dates in Table 1), 50 fruits sampling $site^{-1}$ (i.e. two-tree samples) for each of the 16 sampling sites were evaluated for a total of 800 fruits $block^{-1}$. Each peach was peeled and cut to assess the end-of-season insect injury due to piercing-sucking damage (*H. halys* and native stink bugs), *L.*

Table 1. Varieties, block areas, insecticide application type and harvest date for each of the six farm sites evaluated in this study (ARM stands for alternate-row-middle)

Year	Farm	Variety	Treatment	Block area (ha)	Border area (ha)	Insecticide application	Harvest date
2012	1	Jerseyqueen	IPM-CPR	3.72	0.85	Border	6 August 2012
			Standard	0.53	–	ARM	
	2	Jerseyqueen	IPM-CPR	2.30	0.63	Border	13 August 2012
			Standard	2.39	–	Solid block	
	3	Harcrest	IPM-CPR	4.01	0.88	Border	13 August 2012
			Standard	1.94	–	ARM	
2013	1	Jerseyqueen	IPM-CPR	3.35	0.72	Border	26 August 2013
			Standard	2.02	–	ARM	
	2	Jerseyqueen	IPM-CPR	2.30	0.58	Border	26 August 2013
			Standard	2.39	–	Solid block	
	4	Jerseyqueen	IPM-CPR	2.07	0.63	Border	26 August 2013
			Standard	1.16	–	ARM	
	1b	PF 24-007	IPM-CPR	2.23	0.68	Border	12 August 2013
			Standard	1.78	–	ARM	
	4b	PF 24-007	IPM-CPR	2.02	0.63	Border	12 August 2013
			Standard	1.83	–	ARM	

lineolaris and *G. molesta*. The *L. lineolaris* injury occurs early season and is distinguishable from feeding by other catfacing species.[16]

2.3 Cost of IPM-CPR

Insecticide costs for implementation of IPM-CPR were calculated on the basis of spray records for pesticide usage and material costs, including mating disruption, at the averaged suggested retail price for local distributors, area of plot and percentage border. IPM-CPR and standard blocks at each farm were not the same size, which impacts on the percentage orchard border. Using each grower's management plan, a direct cost comparison for IPM-CPR relative to ARM or solid sprays was estimated on the basis of the size and percentage border of the IPM-CPR orchard for each individual farm. The total quantity (kg) of active ingredient used during *H. halys* activity (mid-late May through harvest) was summed for each block (for the specific chemicals applied, see supporting information Table S1).

Insecticide selection and application method (ARM or solid block) were left to the individual grower's discretion, so the cost per hectare for insecticide application varied among farm sites and years. Growers were instructed to manage the IPM-CPR blocks with the same insecticide formulations (plus solid block herbicide for clover control), but to apply it only to the borders, which amounted to approximately a 25–61% reduction in area that required management with insecticides.

2.4 Statistical analyses

Pest abundance and fruit injury throughout the season, averaged by treatment for each sampling date, were compared between the grower standard and IPM-CPR treatments for each year using a one-way analysis of variance (ANOVA). Season-long accumulations of catfacing damage in the grower standard and IPM-CPR blocks were compared for each year using repeated-measures ANOVA, testing within-subject differences between cumulative catfacing damage from weekly samples. Catfacing injury, *L. lineolaris* abundance and *G. molesta* trap counts from each year were totaled for each sampling site separately for each farm and then compared between treatments using a generalized linear mixed model (GLMM) with treatment (IPM-CPR or grower standard) as the fixed factor, orchard as a random factor, Poisson distribution and a log link function.[21] Similarly, post-harvest fruit injury assessment was compared between the treatments and separately for within-orchard location (edge and interior) for each year and variety, using a GLMM as described above. For all tests, treatments were considered significantly different at $P < 0.05$. The calculated costs and amounts of active ingredient used in the IPM-CPR and grower standard ARM applications were compared within years using a two-sample *t*-test. Additionally, the relationship between catfacing injury at harvest and kg active ingredient used during *H. halys* activity was analyzed with a linear regression. Statistical analyses were performed with SPSS v.20.0 (IBM Corp., Armonk, NY).

3 RESULTS

3.1 Season-long insect abundance and fruit injury

Our null hypothesis was that catfacing injury between treatments would be equal because the primary difference was the area that was treated. In 2012, on-tree assessment of catfacing injury in both grower standard and IPM-CPR-treated orchards showed a significant difference in injury over time (IPM-CPR: $F_{1,12} = 11.15$, $P = 0.029$; standard: $F_{1,12} = 7.31$, $P = 0.04$) and no significant differences between the treatments ($F_{1,12} = 0.12$, $P = 0.75$) (Fig. 1). Similarly, in 2013, on-tree catfacing injury significantly increased over time (IPM-CPR: $F_{1,13} = 23.49$, $P = 0.04$; standard: $F_{1,13} = 28.01$, $P = 0.03$), but no difference between the grower standard and IPM-CPR treatments was identified ($F_{1,13} = 0.003$, $P = 0.96$) (Fig. 1). Because we were primarily concerned with abundances of *H. halys* and its associated damage, only the season-long data for catfacing are shown (Fig. 1).

Overall, observed densities of *H. halys* were low in 2012; however, when all life stages of *H. halys* were combined, there were significantly higher densities ($F_{1,94}$=17.48, $P = 0.001$) observed in the IPM-CPR blocks (Fig. 2A). Conversely, there was significantly more catfacing injury ($F_{1,94} = 4.15$, $P = 0.04$) observed on trees in the blocks under the standard treatment (Fig. 2B). In 2013 there were significantly ($F_{1,94} = 11.19$, $P = 0.001$) more *H. halys* observed in the standard blocks for the Jerseyqueen variety, and although not significant ($F_{1,62} = 0.86$, $P = 0.36$), there was a trend for

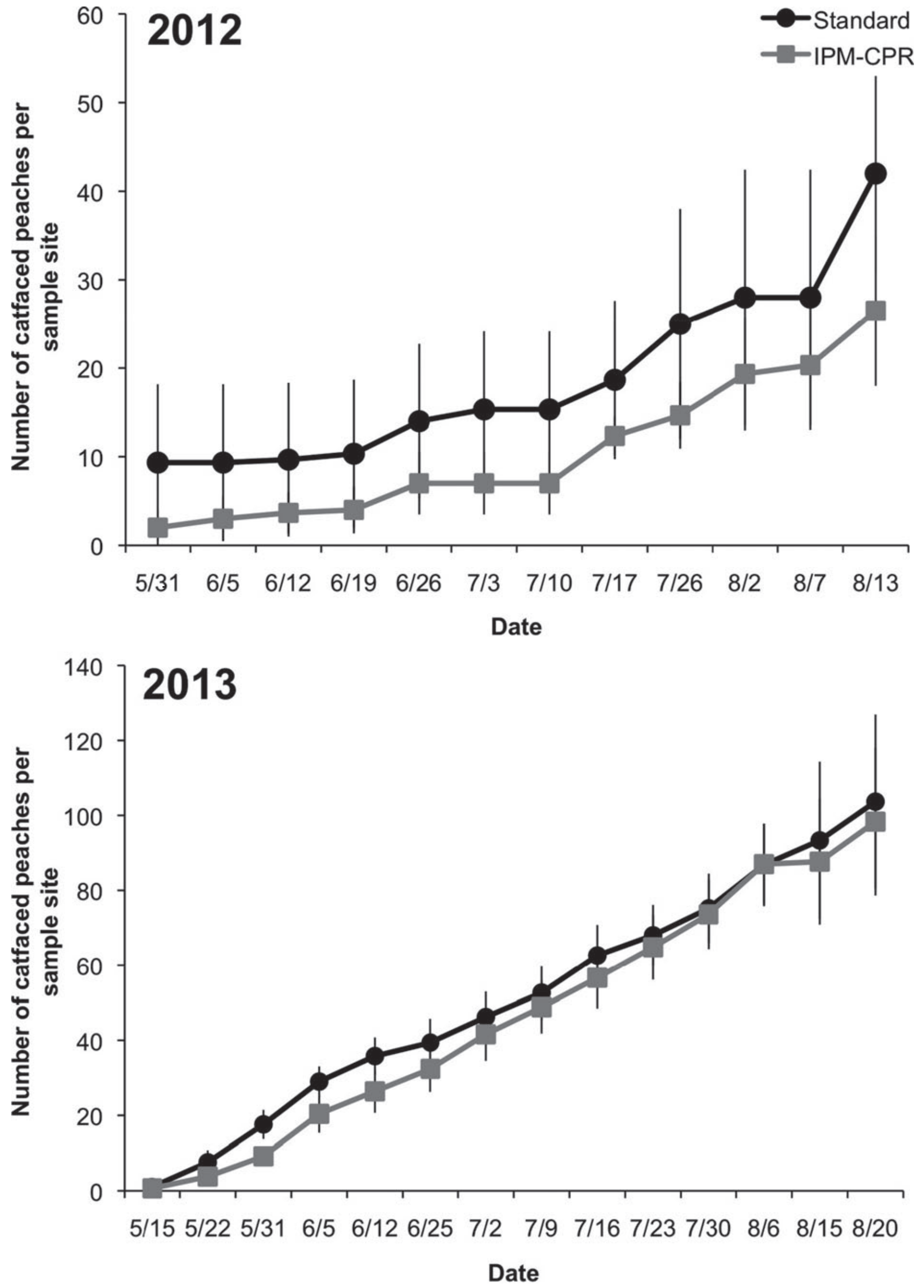

Figure 1. The average number of catfaced peaches (mean ± SEM) per 50 peaches sampled on-tree, cumulated throughout the season comparing IPM-CPR-treated orchards to standard grower practices over a 2 year period (2012 and 2013).

higher observed *H. halys* in the standard blocks for the PF 24–007 orchards as well (Fig. 2A). Additionally, for both varieties in 2013, there was no significant difference in the amount of catfacing damage observed on the trees in either of the treatments (Jerseyqueen: $F_{1,94} = 0.78$, $P = 0.38$; PF 24–007: $F_{1,62} = 0.22$, $P = 0.64$) (Fig. 2B).

Groundcover management in the IPM-CPR blocks was used to control early-season catfacing insects, such as *L. lineolaris*. In 2012, marginally higher densities of *L. lineolaris* ($F_{1,94} = 3.12$, $P = 0.08$) were captured in sweep net samples from the groundcover in the standard blocks (Fig. 3B). Although under the same management, in 2013 there was significantly more *L. lineolaris* ($F_{1,94} = 11.02$, $P = 0.001$) collected from IPM-CPR blocks in the Jerseyqueen variety, with a similar trend found in the PF 24–007 orchards ($F_{1,62} = 3.5$, $P = 0.07$) (Fig. 3A).

Pheromone-baited delta traps were used to monitor *G. molesta* occurrence within both treatment orchards at each farm. In both years and within both varieties, significantly higher numbers of *G. molesta* moths were captured in pheromone traps in the standard blocks when compared with the IPM-CPR blocks (2012: $F_{1,154} = 13.01$, $P = 0.002$; 2013 Jerseyqueen: $F_{1,154} = 6.61$, $P = 0.01$; 2013 PF 24–007: $F_{1,102} = 4.32$, $P = 0.04$) (Fig. 4A).

3.2 Post-harvest fruit injury

Peaches were collected from all study sites and then peeled and cut to assess total-season fruit injury associated with catfacing (i.e. *H. halys*), early-season catfacing from *L. lineolaris* and internal feeding from *G. molesta*. In 2012, peaches harvested from the standard blocks had significantly more catfacing damage than

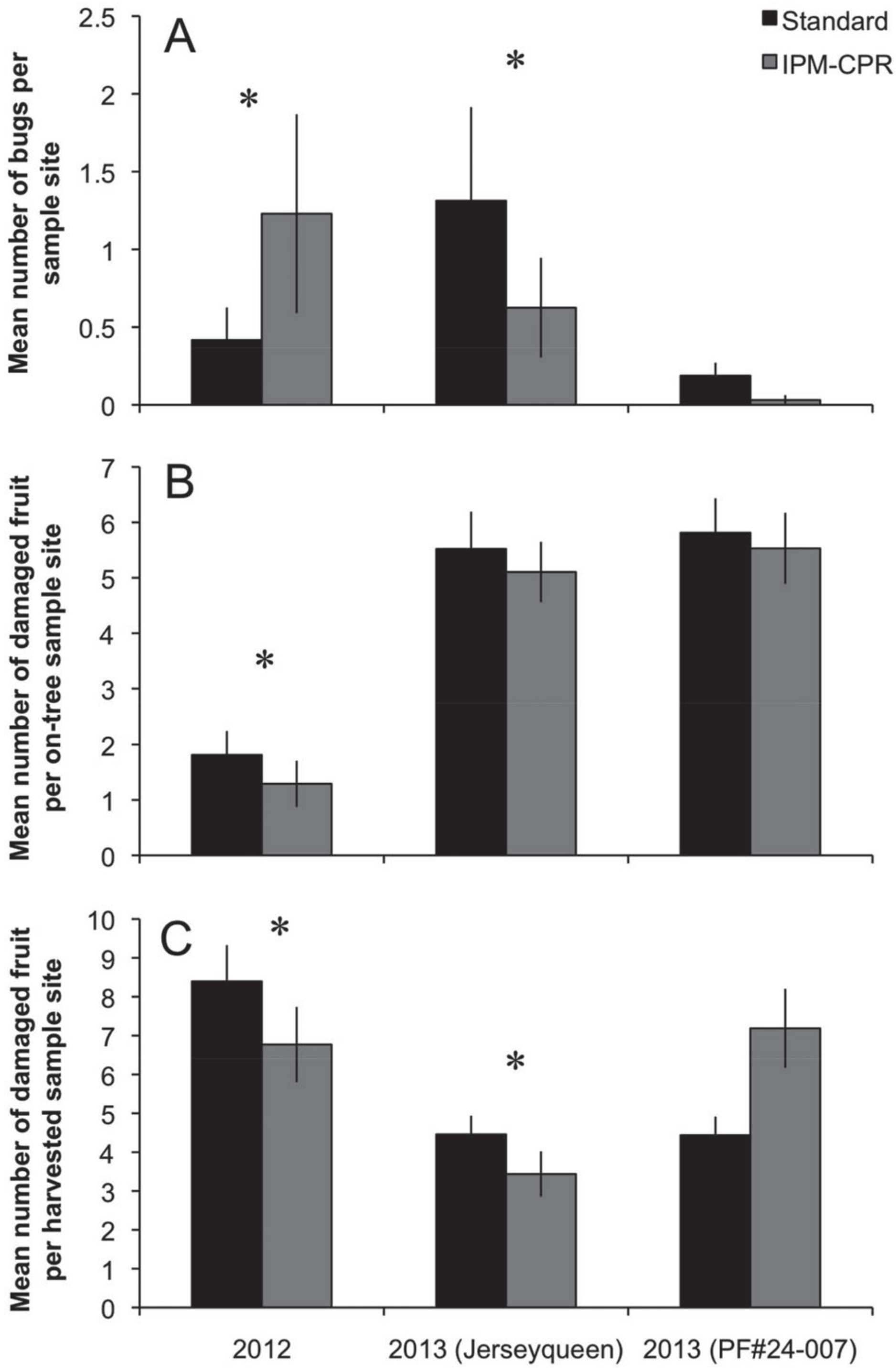

Figure 2. The average (mean ± SEM) number of (A) observed *Halyomorpha halys* per 3 min visual sample, (B) on-tree catfaced fruit due to stink bug injury from season-long totals and (C) catfaced fruit due to stink bug injury assessed at harvest. Data are compared between IPM-CPR-managed orchards and standard grower practices during 2012 and 2013. Asterisks indicate statistical significance ($P < 0.05$).

those from the IPM-CPR blocks ($F_{1,94} = 5.36$, $P = 0.02$) (Fig. 2C). Similarly in 2013, Jerseyqueen peaches from the standard blocks had significantly more damage ($F_{1,94} = 11.02$, $P = 0.001$) than those from the IPM-CPR blocks, whereas harvested PF 24–007 peaches had the opposite trend with more damage measured in the IPM-CPR blocks ($F_{1,62} = 2.58$, $P = 0.11$).

Relative to catfacing due to stink bug injury, early catfacing damage, attributed to *L. lineolaris*, and internal feeding from *G. molesta* were low in both treatments during both years. In 2012, *L. lineolaris* damage was not significantly different between the two treatments ($F_{1,94} = 0.39$, $P = 0.53$) (Fig. 3B). Although not significant, in 2013 harvested Jerseyqueen peaches ($F_{1,94} = 0.55$, $P = 0.46$) from the standard blocks had slightly higher injury due to *L. lineolaris* than the IPM-CPR peaches, whereas PF 24–007 peaches ($F_{1,62} = 1.9$, $P = 0.17$) had more injury in the IPM-CPR peaches (Fig. 3B). Damage due to *G. molesta* was not significantly different in either

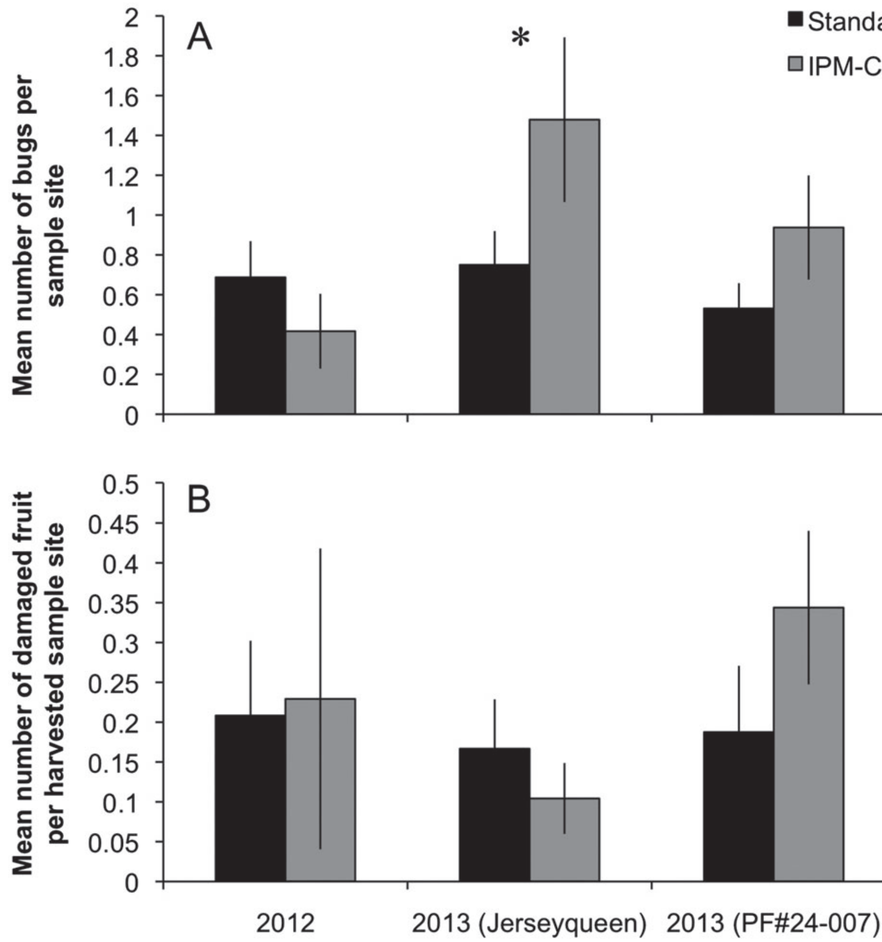

Figure 3. The average (mean ± SEM) number of (A) *Lygus lineolaris* from season-long totals caught in sweep net sampling and (B) early catfaced fruit due to *L. lineolaris* injury assessed at harvest. Data are compared between IPM-CPR-treated orchards and standard grower practices during 2012 and 2013. Asterisks indicate statistical significance ($P < 0.05$).

year or variety (2012: $F_{1,94} = 0$, $P = 1$; 2013 Jerseyqueen: $F_{1,94} = 1$, $P = 0.32$; 2013 PF 24–007: $F_{1,62} = 1$, $P = 0.32$); nevertheless, internal feeding damage with live larvae was only detected in peaches harvested from the standard blocks (Fig. 4B).

As border-focused insecticide applications are a key component of IPM-CPR, we also evaluated the total fruit injury between the two treatments at two different locations within the orchard blocks: the edge and interior. As we would expect from the total orchard analysis above, there were significant differences in catfacing injury attributed to stink bug feeding between standard blocks and IPM-CPR blocks. The catfacing injury along the orchard edge in 2012 was slightly higher in the standard blocks than in the IPM-CPR blocks, whereas within the crop interior this trend was statistically significant (Table 2). In 2013, peaches harvested from the orchard edge in the Jerseyqueen IPM-CPR blocks had significantly less catfacing injury than those from the standard block, but there was no significant difference with the peaches harvested from the orchard interiors (Table 2). The peaches harvested from the edge of the PF 24–007 orchards had no discernable difference in catfacing injury between the two treatments, whereas those harvested in the interior had significantly higher occurrences of catfacing injury in the IPM-CPR blocks (Table 2).

Groundcover management and mating disruption to control *L. lineolaris* and *G. molesta*, respectively, were utilised throughout the entire IPM-CPR block at each of the farms. Thus, it is not surprising that for both years and varieties there were no significant differences between treatments when focusing on the edge and interior for either *L. lineolaris* or *G. molesta* injury of harvested peaches (Table 2).

Consistent with the season-long observational data, post-harvest injury levels varied among years and varieties, but generally there was no difference between treatments, suggesting that the IPM-CPR management tactic is an acceptable alternative to the grower standard for managing peach orchards for *H. halys*, *L. lineolaris* and *G. molesta* pests, while simultaneously reducing the amount of insecticide used within the system. In 2012, border-only insecticide applications saved growers \$US 64–84 ha^{-1} compared with ARM applications, and \$US 279 compared with solid block applications (Table 3). Owing to changes in chemical prices and usage in 2013, ARM applications cost an additional \$US 49–110 ha^{-1} over border applications, while the solid block application cost an additional \$US 510 ha^{-1} (Table 3). Applying insecticide only to the borders of orchards can potentially save growers 25–61% in application costs, which is also a substantial reduction in the amount of insecticides introduced into the farming system.

In addition to insecticide applications on the border, IPM-CPR peaches are under mating disruption and groundcover management. The average cost for mating disruption dispensers increased from \$US 94 ha^{-1} (Isomate M-100) to \$US 135 ha^{-1}

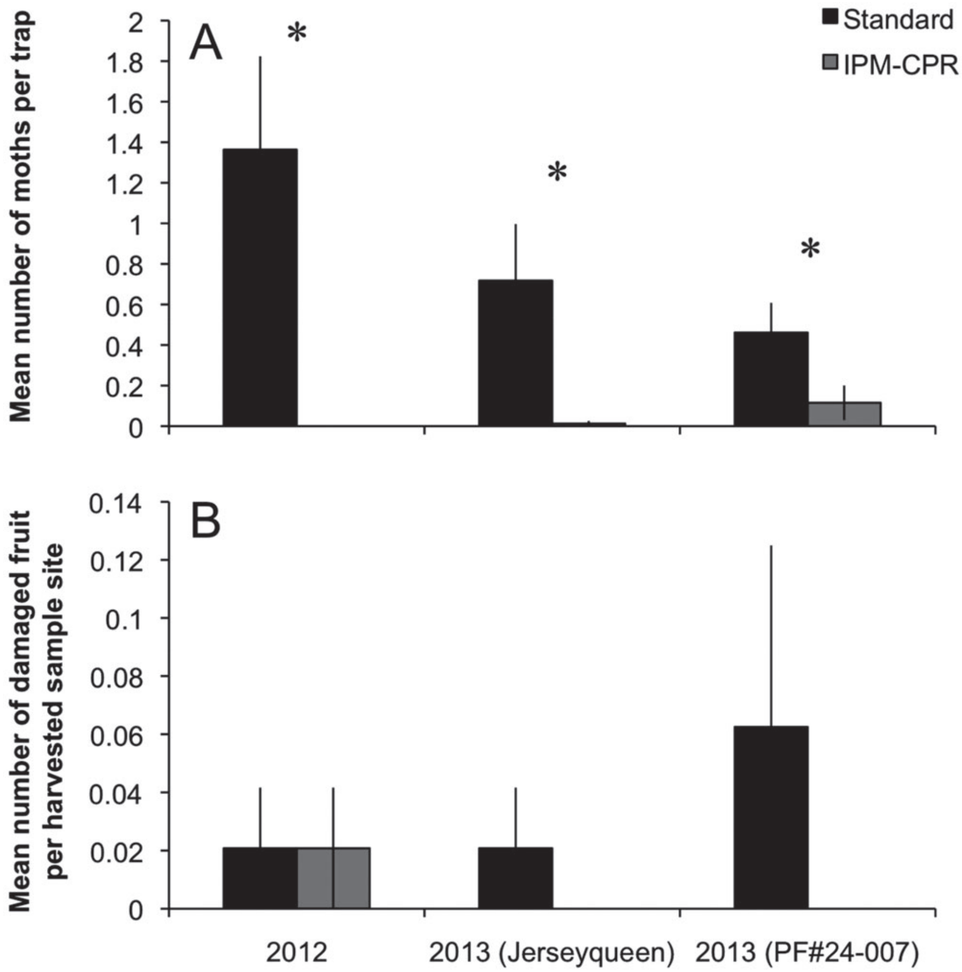

Figure 4. (A) The average number of *Grapholita molesta* from season-long totals caught in monitoring traps and (B) the average (mean ± SEM) *G. molesta* injury assessed at harvest. Data are compared between IPM-CPR-treated orchards and standard grower practices during 2012 and 2013. Asterisks indicate statistical significance ($P < 0.05$).

in 2013 (Isomate OFM-TT) owing to changes in formulation. Growers that use solid block applications of insecticides will still save between $US 150 and 340 ha^{-1} when mating disruption and groundcover management (Clopyralid 40.9%, 9.9 oz ha^{-1}) are included in the insecticide usage cost, but IPM-CPR may cost an additional $US 44–120 ha^{-1} over the standard ARM applications (Table 3). However, the additional costs of reintegrating common IPM tactics in either year were not significantly different than the current grower standard costs for ARM applications (2012: $t_4 = 1.91$, $P = 0.93$; 2013: $t_8 = 1.63$, $P = 0.92$) (Table 3). If one considers mating disruption and groundcover management to be proven standard IPM practices or these tactics are already being implemented, the cost analysis for border sprays for BMSB changes. Moreover, the additional benefits from IPM-CPR, such as natural enemy services, reduced fuel costs and time savings, are not included in the calculation.

Comparing kg AI inputs per hectare between IPM-CPR and ARM sprays each year revealed that there were significantly less insecticide inputs under IPM-CPR in both years (2012: $t_4 = -2.75$, $P = 0.045$; 2013: $t_8 = -3.51$, $P = 0.005$) (Table 3). Furthermore, there was no significant relationship between kg AI ha^{-1} and percentage catfacing injury at harvest across treatments (IPM-CPR: $y = 3.72x + 1.19$, $R^2 = 0.095$; standard: $y = 1.20x + 1.44$, $R^2 = 0.14$).

4 DISCUSSION

Insecticide inputs in mid-Atlantic orchards have increased up to fourfold since *H. halys* became a pest.[8] Growers have been forced essentially to abandon IPM programs, returning to an aggressive and frequent spray regime of disruptive materials.[20] Thus, through IPM-CPR we have demonstrated a systems-level IPM program that is the first to incorporate management for *H. halys* by exploiting pest behaviors. This is accomplished by utilizing border-focused insecticide applications for *H. halys*, groundcover management for *L. lineolaris* and other catfacing insects and mating disruption for *G. molesta*. During the 2 year period of this project, the implementation of the IPM-CPR tactic resulted in significantly less insecticide inputs and maintained, if not reduced, pest injury. Although *H. halys* abundance data varied according to year and peach variety, their attributed catfacing damage was generally lower in the IPM-CPR orchards compared with the grower standard orchards throughout the season. Catfacing injury may be the most reliable method to identify stink bug pressure and abundance, especially for *H. halys*, because populations may be underestimated through visual monitoring owing to evasive behaviors and nocturnal activity.[6,7] Sweep net sampling of *L. lineolaris* resulted in significantly higher captures in the Jerseyqueen IPM-CPR blocks in 2013. Conversely, in both years and varieties, early-season catfacing damage associated with

Table 2. Injury assessment per 50 fruits (mean ± SEM) of peaches harvested from the edge and interior locations within the IPM-CPR and grower standard blocks monitored over a 2 year period (GLMM with treatment as the fixed factor, orchard as a random factor, Poisson distribution and a log link function)

Year	Location	Treatment	Catfacing	*Lygus lineolaris*	*Grapholita molesta*
2012	Edge	IPM-CPR	8.37 ± 1.69	0.37 ± 0.37	0.04 ± 0.04
		Standard	9.42 ± 1.41	0.17 ± 0.08	–
		$F_{1,46}$	1.42	0.03	1.00
		P	0.24	0.86	0.32
	Interior	IPM-CPR	5.17 ± 0.87	0.08 ± 0.06	–
		Standard	7.37 ± 1.20	0.25 ± 0.17	0.04 ± 0.04
		$F_{1.46}$	5.54	0.62	1.00
		P	0.02	0.44	0.32
2013	Edge	IPM-CPR	2.63 ± 0.52	0.21 ± 0.08	–
Jerseyqueen		Standard	5.17 ± 0.75	0.21 ± 0.08	0.04 ± 0.04
		$F_{1.46}$	13.43	0	1.00
		P	0.001	1	0.32
	Interior	IPM-CPR	4.25 ± 1.03	–	–
		Standard	3.75 ± 0.57	0.13 ± 0.09	–
		$F_{1.46}$	0.14	1.98	–
		P	0.71	0.166	–
2013	Edge	IPM-CPR	4.81 ± 0.86	0.25 ± 0.11	–
PF 24-007		Standard	4.56 ± 0.80	0.19 ± 0.14	–
		$F_{1,30}$	0.03	0.33	–
		P	0.85	0.57	
	Interior	IPM-CPR	9.56 ± 1.67	0.25 ± 0.11	–
		Standard	4.31 ± 0.55	0.18 ± 0.13	0.13 ± 0.13
		$F_{1,30}$	5.78	1.7	1.00
		P	0.02	0.2	0.33

Table 3. Cost analysis and chemical usage (amount of active ingredient) per hectare for various management tactics for *Halyomorpha halys, Lygus lineolaris* and *Grapholita molesta* for the six orchards in this study

		Cost ($US ha^{-1})				AI (kg)			
Year	Farm	Border[a]	IPM-CPR[b]	ARM[a]	Solid[a]	Border[a]	IPM-CPR[b]	ARM[a]	Solid[a]
2012	1	54.22	182.18	118.39		0.84	0.98	3.69	
	2	104.18	232.14	191.52	383.03	1.07	1.19	1.96	3.92
	3	65.65	193.61	149.20		0.44	0.57	2.01	
2013	1	59.22	229.18	129.29		0.64	0.71	2.36	
	2	190.56	360.53	350.29	700.59	1.52	1.61	2.86	5.71
	4	102.86	272.82	168.06		0.93	1.03	2.25	
	1b	79.39	249.35	129.29		0.72	0.81	1.25	
	4b	49.70	219.67	159.31		0.81	0.87	1.82	

[a] Insecticide only.
[b] Border insecticide applications for *H. halys*, plus herbicide application to remove clover, and mating disruption (Isomate M 100 in 2012 and Isomate OFM TT in 2013) for *G. molesta*.

this pest was not significant, which is consistent with findings from Atanasov *et al.* (2012).[15] The removal of clover in orchard groundcover not only reduces *L. lineolaris* abundance and injury in orchards but also removes alternative flower resources for foraging bees, which could reduce non-target impacts of insecticide applications. Additionally, at harvest we observed typically less and in 2013 no *G. molesta* injury in the IPM-CPR orchards relative to the standard orchards, consistent with orchards under mating disruption.[15] Utilizing a border-approach for *H. halys* management likely inhibits *H. halys* dispersal into the interior of the orchard by controlling them at the orchard edge through the exploitation of their border-arrestment behavior. This suggests that the IPM-CPR management tactic is a systems-level approach of managing key peach pests post-invasion of *H. halys* and presents a significant step forward in reintroducing IPM programs in mid-Atlantic peach orchards.

The use of perimeter-focused insecticide applications in tree fruit is not a novel approach,[22,23] but using such a behaviorally-based technique for a newly invasive, highly mobile pest in peaches has not previously been done. The results from this 2 year study assessing border sprays for the management of *H. halys* produced results similar to previous work for managing plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera; Curculionidae) in apple orchards, where implementation of border sprays provided economically acceptable control,[22] with total damage in experimental plots comparable with that of standard programs.[23] Border sprays worked for *C. nenuphar* in apple because, as they disperse from overwintering sites, *C. nenuphar* attacks the border row of apple trees first before moving into the orchard interior.[24] Similarly, as with many native stink bug species,[25,26] the pattern of crop injury by *H. halys* within tree fruit indicates that it is a perimeter-driven threat,[9,10] with adults emigrating from surrounding wood lots or other cultivated hosts continuously to attack orchard borders through the season. Mark–recapture studies on *H. halys* colonization behavior in peach orchards demonstrate that 74% of adults arrested movement at the orchard border (Nielsen AL and Blaauw BR, unpublished). Current grower practices rely on either 10–14 day solid block or weekly alternate-row-middle application of insecticides to manage *H. halys*. Effective insecticides have short residual periods, as short as 3 days,[8,11] which, under the spray regimens above, leaves the orchard unprotected from immigrating *H. halys* for a long period.

Eliminating frequent applications of insecticide to the orchard interior through the IPM-CPR tactic makes this region of the orchard vulnerable to infestation by the oriental fruit moth, *G. molesta*. Thus, we incorporated mating disruption, a common IPM strategy, as part of the IPM-CPR tactic, which is known successfully to protect fruit from *G. molesta* damage in fruit orchards,[27] but has been largely abandoned by growers experiencing high injury from *H. halys*.[28] Our utilization of mating disruption generally resulted in lower moth captures in traps and lower damage due to moth pests in the IPM-CPR blocks than in the standard, and may conserve natural enemy services.[17] Focusing insecticide applications for *H. halys* to the orchard border resulted in a reduction of 0.44–4.19 kg AI ha^{-1}, making this a practical and affordable alternative to management practices since the introduction of *H. halys*. Regression analyses suggest that, in spite of increased insecticide inputs in the standard blocks, there was no improvement in protection against *H. halys* injury. Additionally, as with other moth pests, such as codling moth (*Cydia pomonella* L.) (Lepidoptera: Tortricidae),[29] mating disruption for *G. molesta* may result in lower population pressure over multiple years of utilization,[30] reducing the density of pheromone dispensers needed for adequate moth control over time. Thus, even though the cost of mating disruption causes implementation of IPM-CPR to be more expensive than some grower standard management programs, after multiple years of IPM-CPR implementation, peach growers may achieve both a reduction in the amount of insecticide used and a reduction in the cost of managing *H. halys* and *G. molesta*.

Our work was done on relatively small-scale peach orchards (0.5–4 ha), but promising border-focused work has been done on managing the green peach aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphidae), in large fields (>50 ha) of seed potato.[31] Carroll *et al.*[31] determined that border sprays in seed potato fields controlled 94% of aphids dispersing into the crop and reduced grower costs by up to $US 54.68 ha^{-1}. Increasing the overall size of the plot decreases the percentage of plot sprayed with insecticide. This shows promise that IPM-CPR could be adopted at a large scale.

The disruption of fruit IPM programs through the radical shift in pest management to control *H. halys* in peaches has also upset the natural enemy complex within orchards, leading to secondary pest outbreaks.[11] In the northeastern United States, orchards are experiencing high populations of European red mites, two-spotted spider mites, wooly apple aphids and white peach scale and the return of San Jose scale.[5] Preliminary data suggest that the IPM-CPR tactic is also beneficial for conserving insect natural enemies. The different spray programs seemed to have different effects on the natural enemy populations when egg predation was measured. While we did not find any parasitized *H. halys* eggs, there was increased evidence of egg predation in IPM-CPR blocks within the orchard interior where insecticides were not applied (Blaauw BR, unpublished). With the added benefits of protecting natural enemies through mating disruption and less insecticide applied, there is likely a significant benefit to ecosystem services by the adoption of this technique.

5 CONCLUSIONS

The continued threat of crop injury due to invasive pest insects such as *H. halys* and *G. molesta* have caused many peach growers to abandon previously successful IPM programs, replacing them with calendar-based, broad-spectrum insecticide applications. Fortunately, through the utilization of perimeter-focused insecticide treatments, groundcover management and mating disruption, our IPM-CPR tactic can reintroduce IPM strategies by controlling peach pests at levels equal to or better than current grower practices. The adoption of IPM-CPR in peach orchard management is expected to reduce overall insecticide use for *H. halys* control and may lead to increased beneficial insect activity.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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