

Using IPM-CPR as a Management Program for Apple Orchards

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Abstract

We have demonstrated how management of key orchard pests including the insect invasive species *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) can be accomplished using a systems-level approach termed IPM-CPR (Integrated Pest Management-Crop Perimeter Restructuring) in apple. We conducted on-farm comparisons of IPM-CPR to standard management program for managing *H. halys*, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae), and *Lygus lineolaris* Palisot de Beauvois (Hemiptera: Miridae) in commercial apple orchards in 2014, 2016, and 2017 in New Jersey, Maryland, and Virginia. The presence and abundance of key pests and fruit injury at harvest were used as a measure of success of the program. We compared the amount of insecticide applied for each management program. In majority of instances, there were no differences in the IPM-CPR and the standard management program in terms of *H. halys* numbers in baited pyramid traps and stink bug injury at harvest. Damage from *C. pomonella* and *G. molesta* in the IPM-CPR treatment was significantly lower than the standard management program in 2014 and 2017. Amount of active ingredient used was on average 62.1% lower in the IPM-CPR treatment compared with standard management program. Despite a reduction in insecticide use, there were minimal impacts on beneficial insects. Overall, IPM-CPR in apples successfully managed key orchard pests, including *H. halys*, and used significantly less insecticide than a standard insecticide-based management program and could be adopted as a systems-level approach for pest population reduction.

Key words: *Halyomorpha halys*, *Malus domestica*, Mid-Atlantic, border sprays, systems-level management

Like most crops, tree fruit production is constrained by a number of problems, including insect pest damage (Agnello et al. 2009). Orchard management practices are constantly evolving to include new tactics and pest issues. Tree fruit crops constitute a major component of specialty crop production in the United States, and particularly, in the Mid-Atlantic region (USDA-NASS 2016). Insects like codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), oriental fruit moth, *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) (Brunner et al. 2005, Knight 2007), plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae) (Vincent et al. 1999, Leskey et al. 2010), and apple maggot (*Rhagoletis pomonella* Walsh [Diptera: Tephritidae]) (Prokopy et al. 1971, Rull and Prokopy 2000) are key primary pests that can cause significant yield losses and reduction in fruit quality if not managed properly. Secondary arthropod pests including *Tetranychus* spp. mites (Trombidiformes:

Tetranychidae), and San Jose scale *Quadraspidiotus perniciosus* Comstock (Hemiptera: Diaspididae) (Van Den Bosch et al. 1971, Chiappini and Negri 2004) can drastically increase in population when their predators are disrupted by broad-spectrum insecticides. These secondary and indirect pests are managed with integrated pest management (IPM) programs in the Mid-Atlantic and other regions. However, orchard pest complexes and their management approaches have shifted since the establishment of the invasive *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) as a critical pest in the Mid-Atlantic region (Rice et al. 2014, Leskey and Nielsen 2018).

Halyomorpha halys is a difficult insect to manage because of its high mobility in the landscape and polyphagous feeding behavior, allowing it to colonize new areas very quickly. Even a few observed individuals in tree fruits can cause up to 25% injured fruit (Nielsen and Hamilton 2009). Additionally, because tree fruits are a high value crop,

there is a low threshold for pest injury (Wolfe et al. 2008, Akotsen-Mensah et al. 2011). To combat this, growers use broad-spectrum materials for *H. halys* with broad-spectrum insecticides, specifically pyrethroids, that often result in secondary pest outbreaks and concerns over pollinator health (Leskey et al. 2012, Rice et al. 2014). Due to the use of broad-spectrum materials for *H. halys*, many growers in the Mid-Atlantic region shifted from using IPM tactics such as mating disruption for *C. pomonella* and *G. molesta* in lieu of insecticide-based programs (D. Polk, personal communication).

Aside from the economic impact of invasive insects, management approaches using broad-spectrum insecticides may also expedite resistance (Agnello et al. 2009, Mota-Sanchez et al. 2008), disrupt natural enemies (Cisneros et al. 2002, Moscardini et al. 2013, Rodriguez-Saona et al. 2016), and intensify food safety concerns. These concerns have resulted in renewed interest in the use of sustainable programs to mitigate the impact of *H. halys* and other key pests of apples. The economic sustainability of tree fruit production in the Mid-Atlantic and other regions, therefore, will depend largely on the identification and implementation of effective management programs emphasizing less dependence on insecticides, but at the same time effectively control *H. halys* and other such pests that attack and damage tree fruit.

Blaauw et al. (2015) introduced the IPM-CPR (Integrated Pest Management-Crop Perimeter Restructuring) concept in peaches and found the strategy was comparable to standard management programs in reducing impacts of *H. halys* and other key pests. This strategy was developed based on work demonstrating the dispersal behavior of *H. halys* which occurred most frequently at the border of peaches (Blaauw et al. 2016) and can be exploited to help growers more efficiently and effectively manage *H. halys* in other crops. IPM-CPR was also developed based on the premise that a long-term sustainable solution can be achieved through restructuring of agroecosystems in a way that inherent forces will function via a feedback mechanism such as enhanced biological control and protection of native and exotic pollinators (Van Den Bosch et al. 1971, Altieri et al. 1983, Lewis et al. 1997, Ekström and Ekbohm 2011). IPM-CPR is a multitactic approach consisting of 1) insecticide applications restricted to the outer two row/trees (i.e., border sprays) for *H. halys*; 2) removal of broadleaf weeds such as white clover, *Trifolium repens* L. (Fabales: Fabaceae) and leguminous weeds from the understory groundcover using herbicides that serve as alternative hosts for tarnished plant bugs *Lygus* spp. and endemic stink bugs (i.e., *Euschistus*

spp.); and 3) mating disruption for *G. molesta* and *C. pomonella*. Although mating disruption is a demonstrated effective management tactic, it is included as part of the management tactic to increase the sustainability of pest management in orchards and assess its compatibility with the other management tools. Further, we expanded on the approach in peaches to include a baited pheromone trap-based treatment threshold (Short et al. 2017) to trigger the onset of border sprays and estimated the impact on natural enemies.

Materials and Methods

Experimental Apple Blocks

Experiments were conducted in commercial apple orchards to compare IPM-CPR with the standard management program for management of *H. halys* and key orchard pests during the 2014, 2016, and 2017 seasons. Participating farms in 2014 were designated NJ 1, 2, and 3 (Supp Table 1 [online only]) in New Jersey. The study was expanded in 2016 and 2017 to include a commercial apple orchard in Virginia (Farm VA) and Maryland (Farm MD), and two farms were selected in New Jersey (NJ 1 and NJ 4) (Table 1). Orchards were selected based on their known history of *H. halys* incidence and injury. At each farm, two blocks of similar size (~2 ha) were randomly assigned to implement the IPM-CPR strategy or the standard management program (i.e., what the grower does normally for *H. halys* and lepidopteran pests management). Preference was given for blocks bordering a wooded habitat. The majority of the orchards consisted of different apple varieties but the most common varieties at all locations were ‘Golden Delicious’, ‘Gala’, ‘Jonagold’, ‘Granny Smith’, and ‘Empire’ (Supp Table 1 [online only]). The standard management program was managed without mating disruption, with the exception of NJ in 2017, and by using whole-block or alternate row middle (ARM) sprays to manage key pests (e.g., *C. pomonella*, *G. molesta*), and catfacing insects including *H. halys*. All plots were managed with standard fungicide program per growers discretion (Rutgers Pest Management Guide and Mid-Atlantic Fruit Management Guide).

Insect Monitoring in Orchards

The population of *C. pomonella* and *G. molesta* was monitored weekly using two orange delta traps per species in each block

Table 1. Mean (\pm SE) percent *C. pomonella* or *G. molesta* and other insect damage in commercial farms

Year	Treatment	<i>C. pomonella</i> + <i>G. molesta</i>	San Jose scale	Tarnished plant bug
2014	IPM-CPR	0.2 \pm 0.1b	0.7 \pm 0.7	0.9 \pm 0.4
	Standard management program	1.9 \pm 0.6a	1.5 \pm 0.9	1.7 \pm 0.7
	<i>t</i>	8.8	0.5	0.9
	df	1, 142	1, 16	1, 16
	<i>P</i>	0.0036	0.5536	0.3456
2016	IPM-CPR	0.0 \pm 0.0	0.7 \pm 0.3	—
	Standard management program	0.1 \pm 0.1	2.4 \pm 0.7	—
	<i>t</i>	1.00	2.4	—
	df	1, 122	1, 122	—
	<i>P</i>	0.3193	0.1240	—
2017	IPM-CPR	4.3 \pm 1.3b	5.8 \pm 2.7	1.3 \pm 0.5
	Standard management program	17.9 \pm 3.4a	4.2 \pm 1.7	2.0 \pm 0.7
	<i>t</i>	14.1	0.26	0.68
	df	1, 70	1, 70	1, 70
	<i>P</i>	0.0003	0.6064	0.4130

Means followed by different letters are significantly different from each other ($P = 0.05$).

(CM-DA lure and L2, respectively [Trècè Inc., Adair, OK]). The traps were placed in a transect with two in the interior and two at the edge. Additional insecticide applications were triggered when the weekly threshold of 5 adults per trap for *C. pomonella* and 20 adults per trap for *G. molesta* is reached. Chlorpyralid herbicide (Stinger, Dow Agrosciences, Indianapolis, IN) was applied to the orchard groundcover at a rate of 9 oz/ha in early May to remove broad-leaf weeds which serve as alternate hosts for endemic sucking insects *L. lineoralis*, *Euschistus servus* (Say), and *Chinavia bilare* (Say) (Blaauw et al. 2015). These bugs were monitored using an insect sweep net (38.1 cm diameter bag, BioQuip Products, Compton, CA) with 25 sweeps of the groundcover between each pair of the marked trees. This sampling was performed weekly in 2014 and monthly in 2016–2017.

Black coroplast pyramid traps (1.22 m tall; DEAD-INN Pyramid Trap AgBio Inc., Westminster, CO), baited with commercial formulation (Trècè Inc. and AgBio Inc.) of *H. halys* aggregation pheromone: mixture of 3.5:1 ratio of (3S,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol and (3R,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol (Khirmian et al. 2008) and pheromone synergist: methyl (2E,4E,6Z)-decatrionoate (MDT) (Weber et al. 2014, 2018) were installed in mid-May in all blocks. Lures were replaced every 4 wk. In 2014, one trap was deployed in each orchard border row ($n = 4$) corresponding to each cardinal direction (Fig. 1A). In 2016 and 2017, two additional traps were installed in the orchard interior in each block (Fig. 1B). A 5-cm insecticide strip containing 10% 2,2-dichlorovinyl dimethyl phosphate (DDVP) (Vaportape II, Hercon, Emigsville, PA) was deployed inside the trap top and used as a killing agent in 2014 and 2016 but in 2017, a 50 × 50 cm piece of deltamethrin-incorporated long-lasting insecticide netting (Vestergaard-Fransen, Washington, DC) (Kuhar et al. 2017) was used as the killing agent. Traps were checked weekly for *H. halys* adults and nymphs until

apple harvest. Note that in all years and at all locations, lures were changed every 4 wk.

Management Programs

For blocks in the IPM-CPR treatment, Isomate OFM/CM TT (CBC America Corp., Commack, NY) was used to disrupt *G. molesta* and *C. pomonella* mating (490 dispensers per hectare applied post bloom) (Blaauw et al. 2015, Short et al. 2017) orchard blocks. *Halyomorpha halys* was managed by applying insecticides to the border row plus the first full row on either end of the block using effective materials (Rutgers Pest Management Guide and Mid-Atlantic Fruit Management Guide). In 2016 and 2017, border sprays were initiated based on the trap-based threshold developed for *H. halys* (Short et al. 2017), though protocols were modified slightly. When threshold was met in the early season (until ~mid-July when populations are typically low), a single full block treatment (or two ARM) was applied. After this early season period, the threshold was reset. Weekly border sprays were initiated through harvest to manage larger populations found in the later part of the season when the threshold was subsequently reached (Khirmian et al. 2008, Leskey et al. 2015, Morrison et al. 2015). Additionally, traps deployed at the interior of orchard blocks were used to indicate that *H. halys* had dispersed beyond the IPM-CPR border treatments, thereby initiating a whole-block (or two ARM sprays).

The standard management program used by growers for insect management was based on their personal preferences and experiences, but in general, followed recommended materials and rates published in various regional management guides (Rutgers University Fruit Management Guidelines and Mid-Atlantic Fruit Management Guide). A typical grower's standard application for insect pest control is shown in Supp Table 2 (online only).

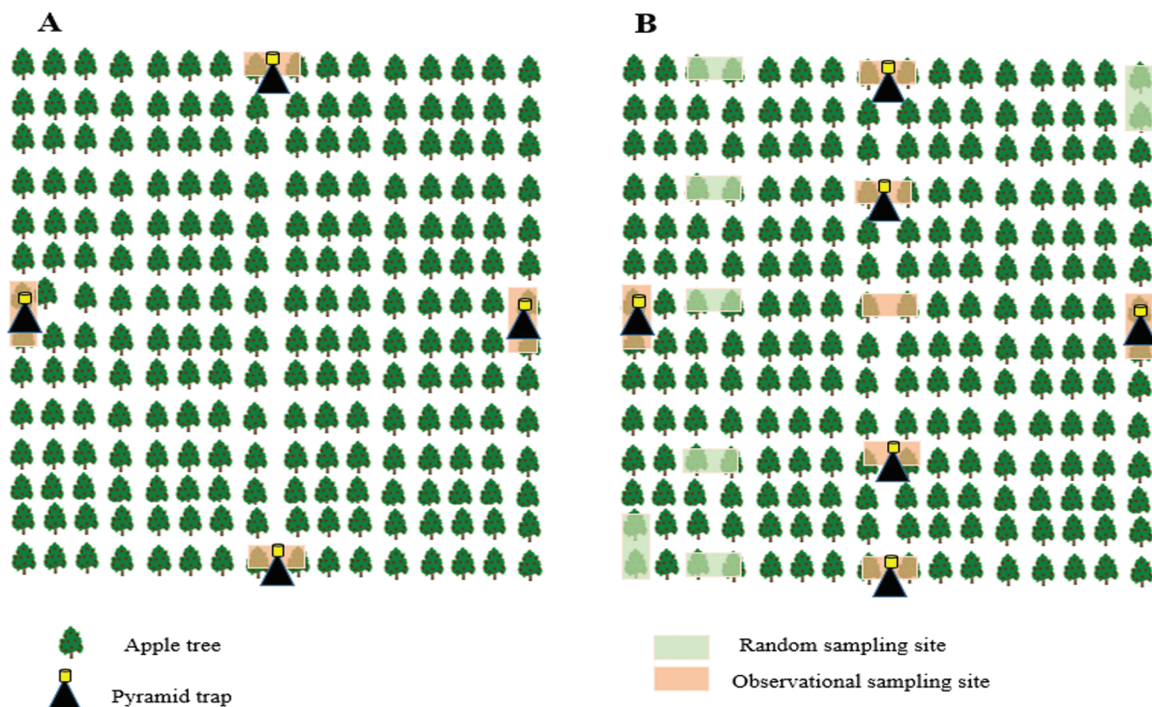


Fig. 1. Field schematic for (A) 2014 and (B) 2016 and 2017. Unbroken edge rectangle indicates sites of visual sampling and natural enemy monitoring; broken edge rectangle indicates sites for random sampling and damage assessment. Black pyramid indicates location of traps. In 2014, traps were set out at only the border, whereas in 2016 and 2017, two additional traps were set up in the interior.

Abundance and Impact on Natural Enemies

Natural enemy abundance and diversity were monitored with yellow sticky cards and in some locations, sentinel *H. halys* eggs. Natural enemies were sampled using 4.5 × 5.5 cm, double-sided yellow sticky cards (Alpha Scents Inc., West Linn, OR) in all blocks. At each time point, sticky cards were hung at ~3 m from the ground within the canopy of two trees along the orchard border and two trees in the interior (approximately 10 trees from the edge) for four samples per treatment and time point (Fig. 1B). The sticky cards were left in the trees for 7 d, after which they were retrieved and evaluated for abundance of major natural enemy taxa including: Coccinellidae, Chrysopidae, Nabidae, Geocoridae, *Orius* spp., Syrphidae, and parasitoids.

Fresh sentinel *H. halys* egg masses (<1 d old) were used to measure predation and parasitism along the same transects as the yellow sticky cards, but on the opposite side of the tree canopy. Egg masses were examined prior to deployment to count the total number of eggs per egg mass. Egg masses were placed on white cardstock with nontoxic glue (Elmer's Products, Columbus, OH) or double-sided sticky tape and clipped to the underside of a leaf for 48 h. Sentinel egg masses were deployed 2–3 times per year per farm in both treatment plots (Supp Table 3 [online only]). Upon retrieval, we recorded the number of eggs remaining and number of eggs with sucking predation (indicated by stylet sheaths), and chewing predation following Morrison et al. (2016). If the entire egg mass was missing upon retrieval it was counted as a missing data point, not as predation. Predation rates were calculated as the proportion of the sum of missing eggs, sucking predation, and chewing predation relative to the starting number of eggs per egg mass. Egg masses were then held in a controlled-environment chamber (25°C; 16:8 [L:D] h, 50–60% RH) for ~6 wk and monitored for hymenopteran egg parasitoid emergence.

Fruit Injury Assessment

Sample trees were selected away from trees with *H. halys* pheromone traps, where fruit can have higher injury (Akotsen-Mensah et al. 2018). At harvest, for each block, 50 fruits per sampling site (two-tree sample) for each of the eight sampling sites were randomly picked from the entire canopy for a total of 800 fruits per block. The random trees were within a transect at least two trees away from any *H. halys* pheromone trap. Fruit was externally evaluated for injury from early season sucking pests and San Jose scale. Each fruit was then peeled and scored for the presence or absence of stink bug feeding, and/or internal feeding due to *C. pomonella* or *G. molesta*.

Determination of Amount of Active Ingredient Used

We followed approaches by Blaauw et al. (2016) and Morrison et al. (2018) with some modification to calculate the amount of active ingredient used in the IPM-CPR approach and the grower standard. The percent border area was calculated using GIS images of each orchard. We collected pesticide records from some of the cooperating growers (NJ, MD, and VA) to calculate the total amount of active ingredients applied per hectare in each treatment.

Statistical Analysis

All analyses were conducted using JMP Pro (JMP Pro v. 14; SAS Institute, Cary, NC). For each year and location, weekly averages were calculated for adult and nymphal *H. halys* captured in pyramid traps and the data were used to determine the seasonal abundance per treatment. Trap capture data were accumulated across weeks and subjected to analyses based on the assumptions of analysis of

variance (ANOVA) after transformation using $\log(X)$. Transformed data were then analyzed using a mixed model with treatment type (IPM-CPR vs standard management program), orchard section (edge vs interior), and the interaction between treatment type and orchard section as fixed effects and location (farms) as a random effect. If the interaction between treatment type and orchard section was not significant, the data were pooled (seasonal total) and analyzed by treatment and orchard section. A mixed model analysis was also used to analyze the proportion of fruit injury per treatment after transformation using arcsine (square root(x)). Further analysis using a *t*-test was conducted on factors showing significant differences using the mixed model.

Predation on sentinel egg masses was analyzed for treatment effects by farm and within field location, for each year as a generalized linear model for arcsine (square root(x)) transformed data, assuming a normal distribution. Similarly, abundance of parasitoids and predatory taxa on yellow sticky cards was compared separately for each year between IPM-CPR and standard management program using a generalized linear model with Poisson distribution and overdispersion parameter. The total amount of active ingredient between the treatments was compared using chi-square.

Results

Numbers of *H. halys* in Baited Pyramid Traps

In 2014, there was no significant difference in the total number of *H. halys* adults captured in blocks managed using IPM-CPR and standard management programs ($F = 0.02$; $df = 1, 90$; $P = 0.8995$) (Fig. 2A) but captures were significantly higher in the orchard border ($F = 28.7$; $df = 1, 90$; $P < 0.0001$) (Fig. 2B). Treatment versus

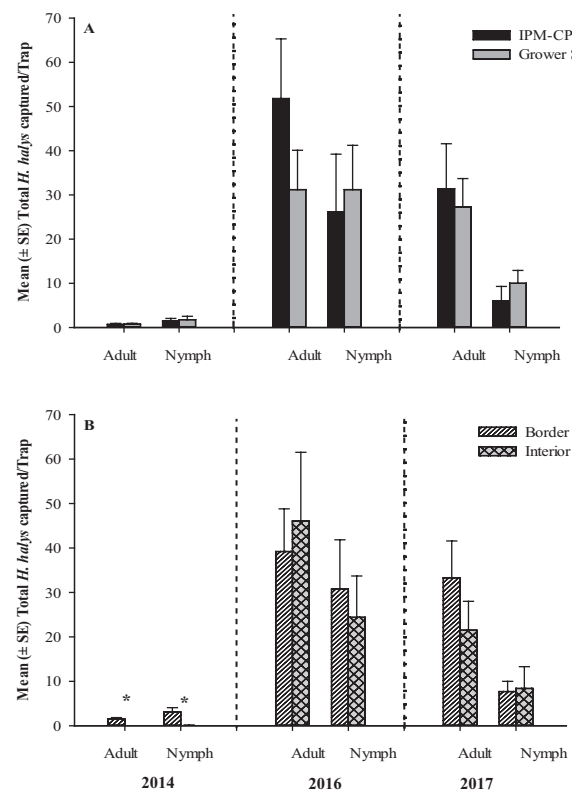


Fig. 2. Mean (± SE) seasonal total number of *H. halys* captured per trap per (A) treatment (IPM-CPR vs standard management program) and (B) orchard section (border vs interior) during 2014, 2016, and 2017.

orchard section interaction was not significant ($F = 0.02$; $df = 1, 90$; $P = 0.8995$). For *H. halys* nymphs, there was a significant difference in the total number captured between orchard sections ($F = 15.8$; $df = 1, 90$; $P = 0.0001$) but captures did not differ significantly between treatments ($F = 0.05$; $df = 1, 90$; $P = 0.8281$) (Fig. 2B). Treatment versus orchard section interaction was not significantly different ($F = 0.06$; $df = 1, 90$; $P = 0.8043$). In 2016, there were no significant differences in the total number of adults captured between orchard sections ($F = 0.75$; $df = 1, 90$; $P = 0.6651$), treatment ($F = 0.02$; $df = 1, 90$; $P = 0.8995$), and treatment versus orchard section interaction ($F = 0.02$; $df = 1, 90$; $P = 0.8995$). Similarly, total nymph captures were not different between orchard sections ($F = 15.8$; $df = 1, 90$; $P = 0.0001$), treatments ($F = 0.05$, $df = 1, 90$; $P = 0.8281$), and treatment versus orchard section interaction ($F = 0.06$; $df = 1, 90$; $P = 0.8043$). In 2017, there was no significant differences in the total number of adults captured between orchard sections ($F = 0.11$; $df = 1, 41$; $P = 0.7443$), treatments ($F = 0.02$; $df = 1, 41$; $P = 0.8912$), and treatment versus orchard section interaction ($F = 0.005$; $df = 1, 41$; $P = 0.9434$). Similarly, total nymph captures were not different between orchard sections ($F = 1.12$; $df = 1, 41$; $P = 0.2971$) and treatments ($F = 0.42$; $df = 1, 41$; $P = 0.5212$). However, treatment and orchard section interaction was significant ($F = 5.99$; $df = 1, 41$; $P = 0.0188$). Total captures of adult and nymphal *H. halys* were 60 and 40 times greater in 2016 and 2017, respectively, than in 2014.

Stink Bug Injury

In 2014, there were no significant differences in stink bug injury found in blocks managed with either IPM-CPR or standard management programs ($F = 0.29$; $df = 1, 138$; $P = 0.5866$) (Fig. 3A) but

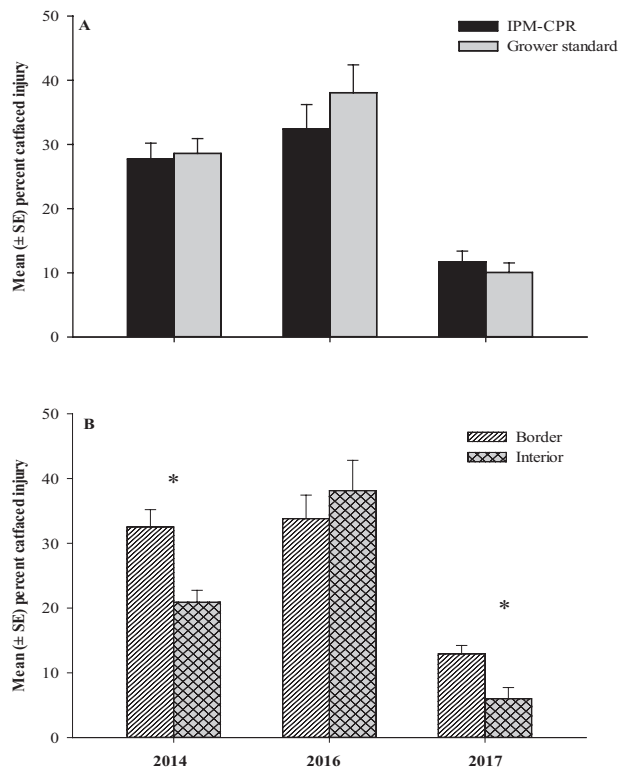


Fig. 3. Mean (\pm SE) percent stink bug injury recorded in (A) treatment and (B) orchard section during 2014, 2016, and 2017. Asterisks indicated significant difference between treatments at $P < 0.05$.

injury was significantly higher along the border ($F = 14.6$; $df = 1, 138$; $P = 0.0002$) (Fig. 3B) compared to the interior. The treatment and orchard section interaction was not significantly different ($F = 0.06$, $df = 1, 138$; $P = 0.7608$). In 2016, no significant differences were found in injury between the treatments ($F = 0.53$; $df = 1, 89$; $P = 0.4665$), orchard section ($F = 1.79$; $df = 1, 89$; $P = 0.1843$), and treatment and orchard section interaction ($F = 0.37$; $df = 1, 89$; $P = 0.5427$) (Fig. 3A). In 2017, injury was not significant between treatments ($F = 1.7$; $df = 1, 69$; $P = 0.1991$) but it was significantly higher in the border sections ($F = 10.3$; $df = 1, 69$; $P = 0.0020$). Treatment and orchard section interactions were not significantly different ($F = 2.12$; $df = 1, 69$; $P = 0.1417$).

Internal Lepidopteran Pests (*G. molesta* and *C. pomonella*) and Other Insects

Internal feeding due to *G. molesta* and *C. pomonella* was significantly greater (feeding injury and live larvae in apples) in blocks managed using the standard management program than IPM-CPR treatments 2014 and 2017 (Table 1). Damage due to San Jose scale and tarnished plant bug was not significantly different between management programs in all years (Table 1), although damage was generally lower in the IPM-CPR treatments.

Abundance and Incidence of Natural Enemies in Orchard

Parasitism of sentinel egg masses was not analyzed due to low numbers. Adventive populations of *Trissolcus japonicus*, a primary parasitoid of *H. halys*, that has adventive populations in the United States, were not found during these surveys. Two parasitoids, both *Telenomus* spp., emerged from the MD site in 2017.

There was a significant treatment effect at NJ farms in 2014 where predation of *H. halys* egg masses being significantly higher in blocks managed using IPM-CPR compared to standard management programs ($df = 2$; Treatment: $\chi^2 = 9.73$; $P = 0.002$, Farm: $\chi^2 = 0.006$; $P = 0.941$). There was no effect of treatment on predation in 2016 ($df = 2$; Treatment: $\chi^2 = 0.909$; $P = 0.340$, Farm: $\chi^2 = 0.088$; $P = 0.767$) or 2017 ($df = 3$; Treatment: $\chi^2 = 0.882$; $P = 0.348$, Farm: $\chi^2 = 10.069$; $P = 0.006$). The MD site had significantly lower predation than the NJ farms in 2017 (Fig. 4).

Yellow sticky cards were used to measure the abundance and diversity of beneficial insect morphotaxa. In 2014, natural enemy abundance on NJ farms using IPM-CPR was significantly higher than

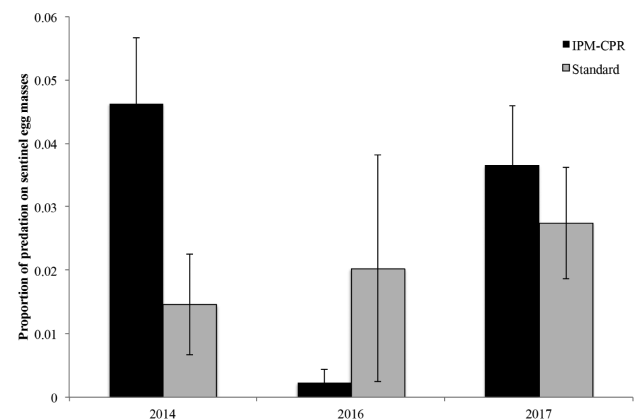


Fig. 4. Mean (\pm SE) proportion of predation on sentinel *H. halys* egg masses placed in apple orchards under IPM-CPR or standard management program. Asterisks indicated significant difference between treatments at $P < 0.05$.

standard management (Treatment: $\chi^2 = 19.14$; $df = 1$; $P < 0.001$; Farm: $\chi^2 = 32.18$; $df = 2$; $P < 0.001$) (Table 2). No effect of treatment programs was observed in 2016 (Treatment: $\chi^2 = 1.29$; $df = 1$; $P = 0.25$; Farm: $\chi^2 = 4.28$; $df = 3$; $P = 0.23$) or 2017 (Treatment: $\chi^2 = 0.50$; $df = 1$; $P = 0.48$; Farm: $\chi^2 = 112.91$; $df = 3$; $P < 0.001$) (Table 2).

Amount of Active Ingredient Used

There were significant reductions in the amount of active ingredient used in the IPM-CPR treatments in three of the six locations where insecticide data were available (Table 3). In these locations the percent active ingredient reduction ranged from 20.0 (NJ 2 in 2014) to 74.8% (MD in 2016). The results show some farms (particularly, those in VA) had higher amount of active ingredient use mainly due to higher numbers of *H. halys* recorded in 2016 and 2017, which means that frequent application were made because thresholds were frequently reached during the growing season (Supp Figs. S2 and S3 [online only]).

Discussion

In this regional multiyear study in commercial apple orchards, our results suggest that while using significantly less insecticide, fruit quality was not reduced under IPM-CPR for management of key orchard pests, including *H. halys*. In general, *H. halys* seasonal total numbers in traps and injury were not statistically different between the IPM-CPR treatment and standard management program. These

results provide additional support for IPM-CPR as an effective systems-level IPM approach, aiming to manage critical pests by exploiting insect behavior and reducing reliance broad-spectrum synthetic toxins (pesticides) (Lewis et al. 1997).

Fundamentally, many insects exhibit edge-biased distribution—a behavior which the IPM-CPR approach exploits (Nguyen and Nansen 2018 and references therein). Johnson (1950) showed that black bean aphids, *Aphis fabae* Scop. (Hemiptera: Aphididae) exhibited edge-biased distribution on twigs of *Euonymus europaeus* L. (Celastrales: Celastraceae) and *Viburnum opulus* L. (Dipsacales: Adoxaceae) around agricultural systems. However, infestation of these insects quickly spread throughout the field, although field edges had highest aphid density. In particular, *H. halys* and other hemipteran insects exhibit strong edge effect behavior and their damage is also higher along the borders in peaches (Blaauw et al. 2015), apple (Joseph et al. 2014), citrus (Sétamou and Bartels 2015), and field crops (Tillman et al. 2009, Tillman 2011, Venugopal et al. 2014, 2015a,b). Blaauw et al. (2016) utilized border-focused insecticide applications for *H. halys*, groundcover management for *L. lineolaris*, and mating disruption for *G. molesta* demonstrating comparable injury compared with standard management programs and a reduction in seasonal active ingredient application by 25–61%. The IPM-CPR approach bears some similarity with an attract and kill strategy (Morrison et al. 2016, 2019) because both strategies involve the management of *H. halys* in a confined area using *H. halys* attractants after which foraging populations can be removed with an insecticide. Morrison et al. (2019) which is an example of IPM-CPR, reported 2–7 times less damage in an attract and kill strategy

Table 2. Comparison of specific insect groups collected via yellow sticky cards (mean \pm SEM) from apples managed with the IPM-CPR or grower standard treatment

Taxa	2014				2016				2017			
	IPM-CPR	Standard	χ^2	<i>P</i>	IPM-CPR	Standard	χ^2	<i>P</i>	IPM-CPR	Standard	χ^2	<i>P</i>
Coccinellidae	0.18 \pm 0.06a	0.04 \pm 0.03b	4.65	0.03	0.25 \pm 0.08	0.19 \pm 0.10	0.37	0.54	0.44 \pm 0.09	0.27 \pm 0.07	2.22	0.14
Syrphidae	0.06 \pm 0.04	0.06 \pm 0.04	0.00	1.00	0.11 \pm 0.07	0.08 \pm 0.06	0.20	0.65	2.71 \pm 0.59	2.75 \pm 0.46	0.01	0.95
Neuroptera	0.06 \pm 0.04a	0.00 \pm 0.00b	13.19	<0.01	0.11 \pm 0.05b	0.28 \pm 0.10a	4.80	0.03	0.23 \pm 0.07	0.29 \pm 0.08	0.32	0.57
Aranea	1.19 \pm 0.23	0.79 \pm 0.13	2.56	0.11	0.56 \pm 0.18	1.25 \pm 0.29	5.84	0.20	1.48 \pm 0.24	1.96 \pm 0.42	2.07	0.15
<i>Orius</i> sp.	0.00 \pm 0.00	0.00 \pm 0.00	—	—	1.14 \pm 0.33a	0.11 \pm 0.05b	33.93	<0.01	1.06 \pm 0.30	0.92 \pm 0.24	0.17	0.68
Geocoridae	0.00 \pm 0.00	0.00 \pm 0.00	—	—	0.00 \pm 0.00	0.00 \pm 0.00	—	—	0.02 \pm 0.02	0.00 \pm 0.00	—	—
Reduviidae	0.00 \pm 0.00	0.00 \pm 0.00	—	—	0.00 \pm 0.00	0.00 \pm 0.00	—	—	0.00 \pm 0.00	0.04 \pm 0.03	—	—
Nabidae	0.00 \pm 0.00	0.00 \pm 0.00	—	—	0.14 \pm 0.07a	0.00 \pm 0.00	74.90	<0.01	0.06 \pm 0.04	0.02 \pm 0.02	1.73	0.19
Dolichopidae	12.39 \pm 5.50a	1.44 \pm 0.38b	18.61	<0.01	1.11 \pm 0.77	0.53 \pm 0.15	1.38	0.24	0.96 \pm 0.32	1.35 \pm 0.46	1.15	0.28
Hymenopteran parasitoid	27.89 \pm 8.23	20.19 \pm 5.10	0.79	0.37	45.42 \pm 11.6	59.25 \pm 16.29	0.88	0.35	27.33 \pm 6.62	51.35 \pm 12.30	7.45	<0.01
Natural enemy taxa	13.90 \pm 5.50	2.33 \pm 0.38	19.14	<0.01	3.17 \pm 0.69	2.33 \pm 0.43	1.29	0.25	7.00 \pm 0.90	7.60 \pm 0.95	0.50	0.48

Bolded values indicate significant difference between treatments ($P < 0.05$).

Table 3. Amount of active ingredient used in insecticide treatments in commercial orchards

Farm	IPM-CPR	Standard management program	% AI reduction (increase)	Chi-square	<i>P</i> -value
Total AI (kg/ha)					
2014	NJ 1	0.60	0.84	15.8	<0.01
	NJ 2	0.15	0.18	1.6	0.20
	NJ 3	0.47	0.64	10.9	<0.01
2016	MD	1.63	6.47	1,168.2	<0.01
	VA	0.14	0.10	0.007	0.93
2017	VA	0.19	0.17	0.001	0.97

AI = active ingredient. Bolded italic values indicate significant difference between treatments ($P < 0.05$).

compared with grower standard plots. This study reported 97% reduction in the crop area treated with insecticide against *H. halys* similar to the IPM-CPR.

The seasonal patterns of *H. halys* captures in baited pyramid traps were similar across years and treatments (Supp Figs. S1–S3 [online only]), and the pyramid traps were able to capture both adults and nymphs all season long (Leskey et al. 2015; Morrison et al. 2016, 2017; Leskey and Nielsen 2018). Overall, higher seasonal total captures in traps were observed in 2016 and 2017, relative to 2014, which may be due to improvements in lure technology, not necessarily higher pest pressure. Reproductively immature *H. halys* adults ('overwintering' adults) gradually emerge from overwintering sites in early spring (April to May) and do not produce offspring until mid-May to early June (Nielsen et al. 2016, 2017). The pheromone trap which were deployed at the edges and interior of the orchard detected this initial movement and subsequent dispersal of *H. halys* into apples. A single insecticide treatment which was made in advance before the border sprays was started. As *H. halys* does not cause significant feeding injury in the early season (Acebes-Doria et al. 2016), management during the initial host-search phase is expected to reduce oviposition within the orchard and pest pressure later in the growing season. Following the spring emergence movement into apples, we observed a lag in activity of *H. halys* because damage was very low during the initial migration into the orchard. Incorporation of the modified threshold allowed fewer insecticide applications targeting *H. halys* during this period of lower risk (Short et al. 2017). As lure and trapping technologies continue to improve, adjustments to the trap-based threshold may be required. The trap-based threshold, however, presents an important IPM decision tool for initiating border sprays.

The results showed that internal feeding due to *G. molesta* and *C. pomonella* was significantly higher (feeding injury and live larvae in apples) in the standard program than IPM-CPR treatments in 2014 and 2017, which is consistent with previous work showing the effectiveness of mating disruption (Agnello et al. 2009). However, it is important to demonstrate that mating disruption is compatible with border-based sprays for management of key pests of apple. The addition of groundcover management as an IPM tool reduced annual broad-leaved flowering plants and resulted in numerical reduction of injury from tarnished plant bug.

We hypothesized the IPM-CPR would positively influence natural enemies population and impact as seen through the increases in the beneficial insect community and lower secondary pest injury (San Jose scale). There was no observed benefit to management of secondary pests observed in this study. Using sentinel egg masses and yellow sticky cards to sample the natural enemy population showed varied results. Overall, there was a slight positive effect of IPM-CPR on natural enemies, in 2 yr there was numerically higher predation on sentinel egg masses and in 1 yr higher beneficial taxa abundance. Impacts of treatment programs on the natural enemy community may have been obscured by variability in initial natural enemy populations and landscape factors that are independent from management (Del-Claro and Oliveira 2000, Chaplin-Kramer et al. 2011, Frost et al. 2014). Predatory families including Neuroptera (2014), Dolichopidae (2014), *Orius* sp., and Nabidae (2016) were significantly more abundant in the IPM-CPR treatment although Neuroptera (2016) and parasitic Hymenoptera (2017) were significantly higher in the standard management programs. Although we did not detect *T. japonicus*, in our trial, natural enemies are contributing to *H. halys* population reduction at the landscape level (Ogburn et al. 2016, Morrison et al. 2018). While the level of biological control is currently insufficient to regulate *H. halys* populations below economic injury in orchards (Leskey and Nielsen 2018,

Kaser et al. 2018) we do not discount differences in the local heterogeneity among the study sites in terms of landscape features, climate, and other management practices.

In general, we found IPM-CPR methods to use less insecticide active ingredient than conventional management programs without sacrificing fruit quality. There are likely additional ecological and health benefits to the beneficial insect community and agroecosystem health from reductions in insecticide use. We were able to reduce amount of active ingredient by up to 74% (MD location) by exploiting insect behavior through multiple pest management tactics (Short et al. 2017). Even though the natural enemy and parasitoid communities in both strategies were variable in diversity and abundance, we believe an IPM-CPR approach offers significant benefits to overall health and sustainability of the apple agroecosystem.

In conclusion, the detailed comparisons of results from field trials suggest IPM-CPR management strategies reduced stink bug injury to levels comparable to standard management programs and successfully managed lepidopteran larvae with the use of mating disruption.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

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References Cited

- Acebes-Doria, A. L., T. C. Leskey, and J. C. Bergh. 2016. Injury to apples and peaches at harvest from feeding by *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) nymphs early and late in the season. *Crop Prot.* 89: 58–65.
- Agnello, A. M., A. Atanassov, J. C. Bergh, D. J. Biddinger, L. J. Gut, M. J. Haas, J. K. Harper, H. W. Hoggire, L. A. Hull, L. F. Kime, et al. 2009. Reduced-risk pest management programs for eastern U.S. apple and peach orchards: a 4-year regional project. *Am. Entomol.* 55: 184–197.
- Akotsen-Mensah, C., R. T. Boozer, and H. Y. Fadamiro. 2011. Field evaluation of reduced insecticide spray programs for managing plum curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae), in Alabama peaches. *Pest Manag. Sci.* 67: 626–632.
- Akotsen-Mensah, C., J. M. Kaser, T. C. Leskey, and A. L. Nielsen. 2018. *Halyomorpha halys* (Hemiptera: Pentatomidae) responses to traps baited with pheromones in peach and apple orchards. *J. Econ. Entomol.* 111: 2153–2162.
- Altieri, M. A., P. B. Martin, and W. J. Lewis. 1983. A quest for ecologically based pest management systems. *Environ. Manage.* 7: 91–99.
- Blaauw, B. R., D. Polk, and A. L. Nielsen. 2015. IPM-CPR for peaches: incorporating behaviorally-based methods to manage *Halyomorpha halys* and key pests in peach. *Pest Manag. Sci.* 71: 1513–1522.
- Blaauw, B. R., V. P. Jones, and A. L. Nielsen. 2016. Utilizing immunomarking techniques to track *Halyomorpha halys* (Hemiptera: Pentatomidae) movement and distribution within a peach orchard. *PeerJ* 4: e1997.

- Brunner, J. F., E. H. Beers, J. E. Dunley, M. Doerr, and K. Granger. 2005. Role of neonicotinyl insecticides in Washington apple integrated pest management. Part I. Control of lepidopteran pests. *J. Insect Sci.* 5: 14.
- Chaplin-Kramer, R., M. E. O'Rourke, E. J. Blitzer, and C. Kremen. 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecol. Lett.* 14: 922–932.
- Chiappini, E., and I. Negri. 2004. Flagellar sensilla of *Quadraspidiotus permiciosus* Comstock (Rhynchota: Diaspididae) male. *Micron.* 35: 597–605.
- Cisneros, J., D. Goulson, L. C. Derwent, D. I. Penagos, O. Hernández, and T. Williams. 2002. Toxic effects of spinosad on predatory insects. *Biol. Control.* 23: 156–163.
- Del-Claro, K., and P. S. Oliveira. 2000. Conditional outcomes in a neotropical treehopper-ant association: temporal and species-specific variation in ant protection and homopteran fecundity. *Oecologia.* 124: 156–165.
- Ekström, G., and B. Ekbom. 2011. Pest control in agro-ecosystems: an ecological approach. *CRC Crit. Rev. Plant Sci.* 30: 74–94.
- Frost, C. M., R. K. Didham, T. A. Rand, G. Peralta, and J. M. Tylianakis. 2014. Community-level net spillover of natural enemies from managed to natural forest. *Ecology.* 96: 193–202.
- Johnson, C. 1950. Infestation of a bean field by *Aphis fabae* Scop. in relation to wind direction. *Ann. Appl. Biol.* 37: 441–450.
- Joseph, S. V., J. W. Stallings, T. C. Leskey, G. Krawczyk, D. Polk, B. Butler, and J. C. Bergh. 2014. Spatial distribution of brown marmorated stink bug (Hemiptera: Pentatomidae) injury at harvest in mid-Atlantic apple orchards. *J. Econ. Entomol.* 107: 1839–1848.
- Kaser, J. M., C. Akotsen-Mensah, E. J. Talamas, and A. L. Nielsen. 2018. First Report of *Trissolcus japonicus* parasitizing *Halyomorpha halys* in North American agriculture. *Fla. Entomol.* 101: 680–683.
- Khrimian, A., P. W. Shearer, A. Zhang, G. C. Hamilton, and J. R. Aldrich. 2008. Field trapping of the invasive brown marmorated stink bug, *Halyomorpha halys*, with geometric isomers of methyl 2,4,6-decatrienoate. *J. Agric. Food Chem.* 56: 197–203.
- Knight, A. L. 2007. Adjusting the phenology model of codling moth (Lepidoptera: Tortricidae) in Washington State apple orchards. *Environ. Entomol.* 36: 1485–1493.
- Kuhar, T. P., B. D. Short, G. Krawczyk, and T. C. Leskey. 2017. Deltamethrin-incorporated nets as an integrated pest management tool for the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae). *J. Econ. Entomol.* 110: 543–545.
- Leskey, T. C., and A. L. Nielsen. 2018. Impact of the invasive brown marmorated stink bug in North America and Europe: history, biology, ecology, and management. *Annu. Rev. Entomol.* 63: 599–618.
- Leskey, T. C., T. J. Hancock, and S. E. Wright. 2010. Host-tree-related differences in trap captures and electroantennogram activity of *Conotrachelus nemophar* (Coleoptera: Curculionidae). *Can. Entomol.* 142: 284–293.
- Leskey, T. C., B. D. Short, B. R. Butler, and S. E. Wright. 2012. Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in mid-Atlantic tree fruit orchards in the United States: case studies of commercial management. *Psyche (New York)*. 2012: 535062.
- Leskey, T. C., A. Agnello, J. C. Bergh, G. P. Dively, G. C. Hamilton, P. Jentsch, A. Khrimian, G. Krawczyk, T. P. Kuhar, D. H. Lee, et al. 2015. Attraction of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) to traps baited with semiochemical stimuli across the United States. *J. Econ. Entomol.* 44: 746–756.
- Lewis, W. J., J. C. van Lenteren, S. C. Phatak, and J. H. Tumlinson. 1997. A total system approach to sustainable pest management. *Proc. Natl. Acad. Sci. USA.* 94: 12243–12248.
- Morrison, W. R., J. P. Cullum, and T. C. Leskey. 2015. Evaluation of trap designs and deployment strategies for capturing *Halyomorpha halys* (Hemiptera: Pentatomidae). *J. Econ. Entomol.* 108: 1683–1692.
- Morrison, W. R., D. H. Lee, B. D. Short, A. Khrimian, and T. C. Leskey. 2016. Establishing the behavioral basis for an attract-and-kill strategy to manage the invasive *Halyomorpha halys* in apple orchards. *J. Pest Sci.* (2004). *Sci.* 89: 81–96.
- Morrison, W. R., C. G. Park, B. Y. Seo, Y. L. Park, H. G. Kim, K. B. Rice, D. H. Lee, and T. C. Leskey. 2017. Attraction of the invasive *Halyomorpha halys* in its native Asian range to traps baited with semiochemical stimuli. *J. Pest Sci.* 90: 1205–1217.
- Morrison, W. R., B. R. Blaauw, A. L. Nielsen, E. Talamas, and T. C. Leskey. 2018. Predation and parasitism by native and exotic natural enemies of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) eggs augmented with semiochemicals and differing host stimuli. *Biol. Control.* 121: 140–150.
- Morrison, W. R., B. R. Blaauw, B. D. Short, A. L. Nielsen, J. C. Bergh, G. Krawczyk, Y. L. Park, B. Butler, A. Khrimian, and T. C. Leskey. 2019. Successful management of *Halyomorpha halys* (Hemiptera: Pentatomidae) in commercial apple orchards with an attract-and-kill strategy. *Pest Manag. Sci.* 75: 104–114.
- Moscardini, V. F., P. da C. Gontijo, G. A. Carvalho, R. L. Oliveira, J. B. Maia, and F. F. Silva. 2013. Toxicity and sublethal effects of seven insecticides to eggs of the flower bug *Orius insidiosus* (Say) (Hemiptera: Anthocoridae). *Chemosphere.* 92: 490–496.
- Mota-Sanchez, D., J. C. Wise, R. Vander Poppen, L. J. Gut, and R. M. Hollingworth. 2008. Resistance of codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), larvae in Michigan to insecticides with different modes of action and the impact on field residual activity. *Pest Manag. Sci.* 64: 881–890.
- Nguyen, H. D. D., and C. Nansen. 2018. Edge-biased distributions of insects. A review. *Agron. Sustain. Dev.* 38: 11.
- Nielsen, A. L., and G. C. Hamilton. 2009. Life history of the invasive species *Halyomorpha halys* (Hemiptera: Pentatomidae) in Northeastern United States. *Ann. Entomol. Soc. Am.* 102: 608–616.
- Nielsen, A. L., S. Fleischer, and S. Chen. 2016. Coupling developmental physiology, photoperiod, and temperature to model phenology and dynamics of an invasive Heteropteran, *Halyomorpha halys*. *Front. Physiol.* 7: 165.
- Nielsen, A. L., S. J. Fleischer, G. C. Hamilton, T. Hancock, G. Krawczyk, J. C. Lee, E. Ogburn, J. M. Pote, A. Raudenbush, A. Rucker, et al. 2017. Phenology of *Halyomorpha halys* described using female reproductive development. *Ecol. Evol.* 7: 6680–6690.
- Ogburn, E. C., R. Bessin, C. Dieckhoff, R. Dobson, M. Grieshop, K. A. Hoelmer, C. Mathews, J. Moore, A. L. Nielsen, K. Poley, et al. 2016. Natural enemy impact on eggs of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in organic agroecosystems: a regional assessment. *Biol. Control.* 101: 39–51.
- Prokopy, R. J., E. W. Bennett, and G. L. Bush. 1971. Mating behavior in *Rhagoletis pomonella* (Diptera: Tephritidae) I. Site of assembly. *Can. Entomol.* 103: 1405–1409.
- Rice, K., C. Bergh, E. Bergman, D. Biddinger, C. Dieckhoff, D. Dively, H. Fraser, T. Garipey, G. Hamilton, and T. Haye. 2014. Biology, ecology, and management of brown marmorated stink bug (*Halyomorpha halys*). *J. Integr. Pest Manag.* 5: A1–A13.
- Rodriguez-Saona, C., A. C. Wanunen, J. Salamanca, R. Holdcraft, and V. Kyrzencenko-Roth. 2016. Toxicity of insecticides on various life stages of two tortricid pests of cranberries and on a non-target predator. *Insects.* 7: 15.
- Rull, J., and R. J. Prokopy. 2000. Attraction of apple maggot flies, *Rhagoletis pomonella* (Diptera: Tephritidae) of different physiological states to odour-baited traps in the presence and absence of food. *Bull. Entomol. Res.* 90: 77–88.
- Sétamou, M., and D. W. Bartels. 2015. Living on the edges: spatial niche occupation of Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Liviidae), in citrus groves. *PLoS One.* 10: e0131917.
- Short, B. D., A. Khrimian, and T. C. Leskey. 2017. Pheromone-based decision support tools for management of *Halyomorpha halys* in apple orchards: development of a trap-based treatment threshold. *J. Pest Sci.* 90: 1191–1204.
- Tillman, P. G. 2011. Influence of corn on stink bugs (Heteroptera: Pentatomidae) in subsequent crops. *Environ. Entomol.* 40: 1159–1176.
- Tillman, P. G., T. D. Northfield, R. F. Mizell, and T. C. Riddle. 2009. Spatiotemporal patterns and dispersal of stink bugs (Heteroptera: Pentatomidae) in peanut-cotton farmscapes. *Environ. Entomol.* 38: 1038–1052.

- USDA-NASS. 2016. National Agricultural Statistics Service: crop production. USDA. https://www.nass.usda.gov/Publications/Ag_Statistics/2016/Chapter05.pdf. Accessed April 2020.
- Van Den Bosch R., T. F., Leigh, L. A., Falcon, V. M., Stern, D., Gonzalez, K. S. Hagen and C. B. Huffaker. 1971. The developing program of integrated control of cotton pests in California, pp. 377–394. *In* C. B. Huffaker (ed.), Biological control. Plenum Press, New York and London.
- Venugopal, P. D., P. L. Coffey, G. P. Dively, and W. O. Lamp. 2014. Adjacent habitat influence on stink bug (Hemiptera: Pentatomidae) densities and the associated damage at field corn and soybean edges. *PLoS One*. 9: e109917.
- Venugopal, P. D., G. P. Dively, and W. O. Lamp. 2015a. Spatiotemporal dynamics of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) in and between adjacent corn and soybean fields. *J. Econ. Entomol.* 108: 2231–2241.
- Venugopal, P. D., H. M. Martinson, E. J. Bergmann, P. M. Shrewsbury, and M. J. Raupp. 2015b. Edge effects influence the abundance of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) in woody plant nurseries. *Environ. Entomol.* 44: 474–479.
- Vincent, C., G. Chouinard, and S. B. Hill. 1999. Progress in plum curculio management: a review. *Agric. Ecosyst. Environ.* 73: 167–175.
- Weber, D. C., T. C. Leskey, G. C. Walsh, and A. Khrimian. 2014. Synergy of aggregation pheromone with methyl (E,E,Z)-2,4,6-decatrienoate in attraction of *Halyomorpha halys* (Hemiptera: Pentatomidae). *J. Econ. Entomol.* 107: 1061–1068.
- Weber, D. C., A. Khrimian, M. C. Blassioli-Moraes, and J. G. Millar. 2018. Semiochemistry of Pentatomoidea, pp. 677–725. *In* J. E. McPherson (ed.), Invasive stink bugs and related Species (Pentatomoidea): biology, higher systematics, semiochemistry, and management. CRC Press, Boca Raton, FL.
- Wolfe, D. W., L. Ziska, C. Petzoldt, A. Seaman, L. Chase, and K. Hayhoe. 2008. Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. *Mitig. Adapt. Strateg. Glob. Chang.* 13: 555–575.