

# *Halyomorpha halys* (Hemiptera: Pentatomidae) Responses to Traps Baited With Pheromones in Peach and Apple Orchards

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Subject Editor: Allan Showler

Received 14 February 2018; Editorial decision 20 June 2018

## Abstract

Monitoring insect populations is a fundamental component of integrated pest management programs. In many cropping systems, monitoring is accomplished through captures in baited traps. The aggregation pheromone and pheromone synergist for the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) are known. We compared the response of *H. halys* to commercial lures in peach and apple orchards. Two commercial pheromone formulations, PHEROCON Trécé BMSB ('Trécé') and AgBio Inc. Stink Bug Xtra Combo ('Xtra Combo'), were compared with unbaited traps in peach orchards in 2015 and 2016 and in an apple orchard in 2016. In both crops and years, more *H. halys* responded to the Trécé lure, and fruit from trees near baited traps had correspondingly higher injury. In both years, peach fruit near Trécé baited traps had significantly higher feeding injury ( $52.2 \pm 4.5\%$ ) than fruit near Xtra Combo baited and unbaited traps ( $35.2 \pm 4.5\%$  and  $22.2 \pm 3.4\%$ , respectively). Injury to apple fruit near baited traps in 2016 was significantly different from fruit near unbaited traps (Trécé:  $93.0 \pm 3.8\%$ , Xtra Combo:  $74.1 \pm 5.1\%$ , and unbaited:  $19.0 \pm 2.7\%$ ). A field response index, which quantifies attraction of *H. halys* to each lure, demonstrated an equal response to both lures in 2015 peach and a higher response to Trécé lure in 2016 in both crops, which suggests the lure is pulling bugs from a larger area. We conclude that formulation differences, population pressure, and host plant species influence *H. halys* populations' response and resulting injury, and should be considered for trap-based decision management.

**Key words:** brown marmorated stink bug, monitoring, injury, aggregation pheromone, pyramid trap

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive agricultural pest in North America (Leskey et al. 2012a). Since its detection in Allentown, PA in the mid-1990s (Hoebeke and Carter 2003), *H. halys* has become a global invader (Leskey and Nielsen 2018) with the potential to threaten agricultural production beyond the United States and Europe (Zhu et al. 2012, Haye et al. 2015, Kriticos et al. 2017). The rapid spread of *H. halys* in North America has occurred in part because of its high mobility (Wiman et al. 2014, Lee and Leskey 2015), polyphagous feeding behavior (Bergmann 2016), and an ability to withstand climatic conditions present in much of continental North America (Cira et al. 2016, Nielsen et al. 2016, Kriticos et al. 2017). In the mid-Atlantic region of the United States, where invasive *H. halys* populations are the most abundant and damaging in North America (Rice et al. 2014), adults disperse from overwintering sites in spring, typically when temperatures begin to rise in April (Bergh et al. 2017), in search of suitable host plants. Indeed, adults

can disperse into peaches (*Prunus persica* (L.) Batsch) (Rosales: Rosaceae) and apples (*Malus domestica* Borkh) (Rosales: Rosaceae) after emergence from overwintering, and dispersal into crops is continued throughout the growing season (Leskey and Nielsen 2018).

Direct monitoring of *H. halys* is primarily done using traps baited with attractive olfactory stimuli, which capture both adult and nymphal life stages, and has been utilized to determine the seasonality of *H. halys* in a wide variety of crops and wild host habitats (Leskey et al. 2012b, 2012c; Morrison et al. 2015; Leskey et al. 2015a, 2015b). Currently, the black coroplast pyramid trap with the attractive aggregation pheromone mixture of 3.5:1 ratio of (3S,6S,7R,10S)-10,11-epoxy-1-bisabolene-3-ol and (3R,6S,7R,10S)-10,11-epoxy-1-bisabolene-3-ol (Khrimian et al. 2008, Khrimian et al. 2014) and pheromone synergist methyl (2E,4E,6Z)-decatrienoate (MDT; Weber et al. 2014, 2017) is used in most monitoring efforts. Pheromone traps allow for population assessment of some hemipteran insects that have nocturnal (Krupke et al. 2001, Cambridge 2016)

and avoidance behaviors that complicate visual monitoring approaches. To date, management of *H. halys* has relied principally on calendar-based (Leskey et al. 2012a) or border-based application of insecticides (Blaauw et al. 2015). A pheromone trap-based threshold has been developed for management decisions in apple; the application of which can significantly decrease the total amount of insecticide applied during the growing season (Short et al. 2017). However, the relationships between captures in traps, fruit injury, and absolute field densities of *H. halys* are not well understood. Understanding the response of *H. halys* to baited traps within a crop can lead to better trap-based decision management approaches through correlating estimates of crop risk through trapping. Moreover, commercial formulations of pheromone lures vary in composition, release rates, and other inherent product characteristics that may influence the relationship of captures in traps (Weber et al. 2017) to absolute insect density and the efficiency of lures in different crop contexts. Our principal aim in this study is to determine a relationship between the numbers of *H. halys* responding to a specific pheromone lure and fruit injury. We hypothesize that this relationship between the responding populations (i.e., captures of *H. halys* in traps plus spillover of individuals) and crop injury is influenced by lure type and crop type.

The objectives of this study were to 1) compare the number of *H. halys* in traps baited with two commercial formulations of aggregation pheromone + pheromone synergist in tree fruit and 2) determine the relationship between captures in traps and injury in peach and apple.

## Materials and Methods

### Experimental Blocks

Experiments were conducted at Rutgers University Agricultural Research and Extension Center (RAREC), Bridgeton, NJ (39°31'3.21"N and 75°12'12.57"W) and Rutgers Fruit and Ornamental Research Extension Center (FOREC), Cream Ridge, NJ (39°36'28.63"N and 74°20'26.19"W). In 2015, four peach blocks at RAREC were used: Block 1 (variety-John Boy, 1.19 ha, tree spacing 6 × 7.62 m), Block 2 (varieties-Encore, Fantasia and Harrow Beauty, 1.76 ha, tree spacing 7.62 × 7.62 m), Block 3 (variety-Fantasia nectarine, 1.62 ha, tree spacing 7.62 × 7.62 m), and Block 4 (variety-Blushing Star, 1.55 ha, tree spacing 6 × 6 m). Blocks 2 and 3 were separated by 20-m grassy area containing a drainage area, whereas block 1 was separated by other peach blocks, field crops, vegetable crops, and fallow ground. Experiments were repeated in 2016 at RAREC in blocks 1 and 2 and one peach (mixed variety-PF-24, 27, 32, 0.75 ha, tree spacing 6 × 7.62 m) and one apple block (variety-Red Delicious, 0.55 ha, tree spacing 7.62 × 7.62 m) at FOREC were included. The apple block was added in 2016 to allow better interpretation between crops at FOREC. Each block was maintained using standard agronomic practices without management for endemic stink bugs or *H. halys* (Rutgers 2016). All orchards were managed for plant diseases according to the Rutgers Commercial Tree Fruit Production Guide. Generally, plots were not managed for insect pests. If they were, Isomate OFM TT mating disruption (70 dispensers/acre) and applications of Imidan, Asana, or Avaunt were used to manage insects prior to *H. halys* activity.

### Responses of *H. halys* and Endemic Pentatomids to Commercial Lures in Peach and Apple

We evaluated the olfactory response of *H. halys* and endemic pentatomids to two commercial lures deployed in a 1.22-m high by

base width 0.5-m black pyramid traps obtained from AgBio, Inc., Westminster, CO, similar to those used and described in Leskey et al. (2012b) and Joseph et al. (2014), but with slight modifications between 2015 and 2016. In 2015, the plastic tops were vented with insect screening on all four sides and the lures hung inside, whereas in 2016, unmodified trap tops were used and the lures hung on the outside of the tops. The traps were spaced at a minimum of 18 m and a maximum of 50 m apart. Each trap was 60 cm from a peach or apple tree trunk (associated tree). Half of a Hercon Vaportape II (Hercon Environmental, Emigsville, PA) that contained 10% 2, 2 dichlorovinyl dimethyl phosphate (DDVP) was placed in the collection top as a killing mechanism. The aggregation pheromone lures evaluated were 1) Stink Bug Xtra Combo (AgBio Inc., Westminster, CO), herein referred as Xtra Combo lure, and 2) PHEROCON Trécé BMSB (low dose; Trécé, Inc., Adair, OK), herein referred as Trécé lure. Both lures contain ~5-mg 10, 11-epoxy-1-bisabolene-3-ol, which includes the two-component *H. halys* aggregation and the pheromone synergist MDT (Weber et al. 2014). Xtra Combo also contains 50-mg (2E, 4E, 6Z) methyl decadienoate (MDD); the aggregation pheromone of endemic *Euschistus* spp. Lures were replaced every 4 wk.

In 2015, three treatments consisting of the two commercial lures and an unbaited control were evaluated in a randomized complete block design in the four peach blocks at RAREC. Treatments within each orchard block were replicated three times for a total of  $n = 36$  traps in 2015. Experimental units (trap plus associated tree) were sampled twice weekly from 22 June to 27 August 2015. In 2016, again using a randomized complete block design, treatments were evaluated in three peach blocks (two at RAREC and one at FOREC), and one apple block (at FOREC) with each treatment replicated four times per orchard block. There were a total of  $n = 36$  in peach and  $n = 12$  in apple. Experimental units (trap plus associated tree) were sampled twice weekly from 9 May through harvest. During each sampling date, the number of *H. halys* adults, nymphs, and endemic pentatomid species captured in the traps were counted and recorded. This was done between the hours of 0800–1000 GMT. Also, the number of *H. halys* adults, nymphs, eggs, and other endemic pentatomid species observed during a 3-min visual assessment on the associated tree was counted and recorded during the twice weekly sampling. Stink bug captures in traps and numbers observed on the associated tree were used to determine the response of *H. halys* and endemic pentatomids to the lure.

The seasonality of *H. halys* adults and nymphs in both peach and apple was determined by calculating the averages of captures in each trap and data is presented by sampling date. Seasonal total *H. halys* and endemic pentatomids (nymphs and adults) captured in traps and those observed on associated trees were analyzed using analysis of variance (ANOVA). Seasonal total nymphs and adults were  $\log(x+1)$  transformed prior to analysis for each year. Treatment effect that was not significant was removed prior to analysis of full model with a one-way or two-way ANOVA in apple and peach, respectively, and Tukey's HSD to separate treatment effects (2016).

### Field Response Index

We calculated a field response index (FRI), which measures the enhanced response of the insects to a pheromone lure by biweekly counts of bugs in traps and spillover (i.e., insects that do not enter the trap and are recorded on the visual observations on the associated tree) by looking at the relationship between baited and unbaited treatments. The FRI was calculated using equation 1,

$$FRI = \frac{\text{Trap} - \text{Trap}_{\text{CtrlTree}} + \text{Visual} - \text{Visual}_{\text{CtrlTree}}}{\text{Trap} + \text{Trap}_{\text{CtrlTree}} + \text{Visual} + \text{Visual}_{\text{CtrlTree}}}$$

where Trap = number of insects (adults or nymphs) in the baited trap; Visual = number of insects (adults or nymphs) observed in the tree associated with the baited trap;  $\text{Trap}_{\text{CtrlTree}}$  = number of insects (adults or nymphs) in the unbaited trap; and  $\text{Visual}_{\text{CtrlTree}}$  = number of insects (adults or nymphs) observed in the tree associated with the unbaited trap for each experimental unit. The FRI did not meet the assumptions of ANOVA and were transformed using  $\log(x+1)$ . Treatment differences in the FRI were analyzed using a chi-square approximation (JMP Pro 13, 2016).

### Fruit Injury at Harvest

In both years, fruit injury was assessed by randomly selecting 25 fruit per associated tree at harvest. In 2015, peach harvest assessment occurred on 27 July and 3 August. Similarly, in 2016, peaches were harvested on 19 July at RAREC and 1 August at FOREC. Apples were harvested on 1 August and 6 September 2016 for comparison with peach and harvest injury, respectively. Fruit injury assessment was done by peeling each fruit and assessing stink bug feeding injury (Nielsen and Hamilton 2009, Acebes-Doria et al. 2016a). Because feeding injury cannot be distinguished among different life stages of *H. halys* and other endemic pentatomids, injury was recorded as ‘stink bug’ injury. Percent fruit injury was calculated using the ratio of number of fruit with stink bug damage divided by the total number of fruit evaluated. Data on percent injury at harvest for peach was analyzed using a generalized linear model with estimation method using maximum likelihood and normal distribution and identity as the link function (JMP Pro 13, 2016). A likelihood-ratio chi-Square (L-R  $\chi^2$ ) was used to test for significance. For apple, injury data between treatments was analyzed with a one-way ANOVA, and Tukey’s HSD was used to separate treatment effects.

### Comparison of *H. halys* Response to Baited Traps Between Peach and Apple

In 2016, at FOREC, the peach and apple plots described above were located 186 m from each other (measured from the center of each plot) and were selected to compare the population response of *H. halys* to baited traps between the two host plants from 23 May to 1 August 2016 when peach was harvested. Each experimental unit was replicated four times per crop, as stated above. While we were unable to repeat this experiment at multiple apple orchards, and thus do not have spatial interspersions of replicates at the level of crop type (i.e., pseudoreplication; Hurlbert 1984), a comparison of *H. halys* population response between crops is still valuable and may provide insights for future studies specifically designed to test for differences between crops. Additionally, the proximity of peach and apple orchards at FOREC decreases the likelihood that differences in response are due to site-specific factors besides crop type.

At harvest, severity of stink bug feeding was measured by counting the number of feeding sites per fruit at harvest, with a maximum of 100 per fruit. Injury severity was measured in trees associated with the trap (i.e., trap placed 60 cm from trunk) and trees adjacent to the trap to identify the relationship between number of *H. halys* and spillover injury. Severity of injury did not meet assumptions of normality and was  $(x)^{1/2}$  transformed prior to all analyses. Effect of tree location (associated or adjacent trees) and lure treatment was analyzed using a two-way ANOVA with treatment, block, and location by treatment interaction [JMP 2016].

The relationship between injury severity and the explanatory variables within-field block, lure treatment, and stink bug counts was analyzed using multiple regression, separately for apple and peach. To determine which method to include for estimating bug density in the multiple regression (i.e., total capture in trap, total visual counts, or the sum of capture in trap and visual counts), simple linear regressions of injury severity and bug counts were performed for each estimation method, and  $R^2$  values were compared. The method for estimating stink bug numbers that resulted in the highest  $R^2$  was then incorporated into the full model: Severity ~ ‘within-field block’ + counts + treatment. For peach, the additional explanatory variable ‘field site’ (i.e., orchard) was included as a blocking factor. The full models for peach and apple were then simplified using stepwise comparisons of Akaike information criterion (AIC; RCoreTeam vers. 3.4.4). *P* values and *F* statistics are reported for the models with the lowest AIC values for apple and peach. Pairwise comparisons were made for both severity and percent injury responses using Tukey–Kramer HSD where applicable (RCoreTeam 2013, vers. 3.4.4).

## Results

### Seasonality of *H. halys* and Endemic Pentatomids in Peach and Apple.

*H. halys* and endemic pentatomid populations recorded in baited traps in peach differed during 2015 and 2016, with 2015 having low *H. halys* and higher endemic pentatomids, whereas 2016 had higher *H. halys* numbers and no observed endemic species. Similar trends in seasonality were found for *H. halys* adults and nymphs in both peach (Fig. 1) and apple (Fig. 2), although nymphs were captured ca. 1 mo earlier in peach than in apple. In 2015 peach, *H. halys* activities as measured by the pheromone traps were delayed compared with model predictions (Nielsen et al. 2016), likely due to the lower population pressure.

Adults were captured in traps beginning in the middle of season (July; Fig. 1A) in 2015. Similarly, nymphs were captured toward the end of the season in August (Fig. 1B). In 2016, adults were present in traps from early to mid-May peaking in early to mid-June after which the numbers declined until mid- to late July when numbers began to peak again in late July through early August (Fig. 1C). However, nymphs were captured in mid-June and peaked in July (Fig. 1D). Similar trends were observed in apple in 2016 except that the late peak was extended following the ripening period beginning in early September (Fig. 2A) and nymph capture in traps peaked during the ripening period (Fig. 2B). The average number of *H. halys* recorded per sampling date in apple was higher than peach, likely due to later fruit availability in apple coinciding with higher populations late season.

### Response of *H. halys* and Endemic Pentatomids to Lures in Peach

In 2015, the model was significant for the response of *H. halys* adults ( $F = 14.23$ ,  $df = 4, 31$ ,  $P = 0.0093$ ) to the treatments, but this was not significant for nymphs ( $F = 1.02$ ,  $df = 2, 6$ ,  $P = 0.4161$ ). Similarly, the response of adults was significant ( $F = 14.23$ ,  $df = 4, 31$ ,  $P = 0.0066$ ) but not for nymphs ( $F = 1.02$ ,  $df = 2, 6$ ,  $P = 0.4161$ ) observed on the trees associated with the traps. Both the Trécé and Xtra Combo baited traps captured significantly more *H. halys* adults than unbaited traps (Table 1). However, there was no difference among the lure treatments for *H. halys* nymphs. For endemic pentatomids, there was no significant difference among the treatments (Table 1). The traps recorded no endemic pentatomid nymphs. The number of endemic pentatomids

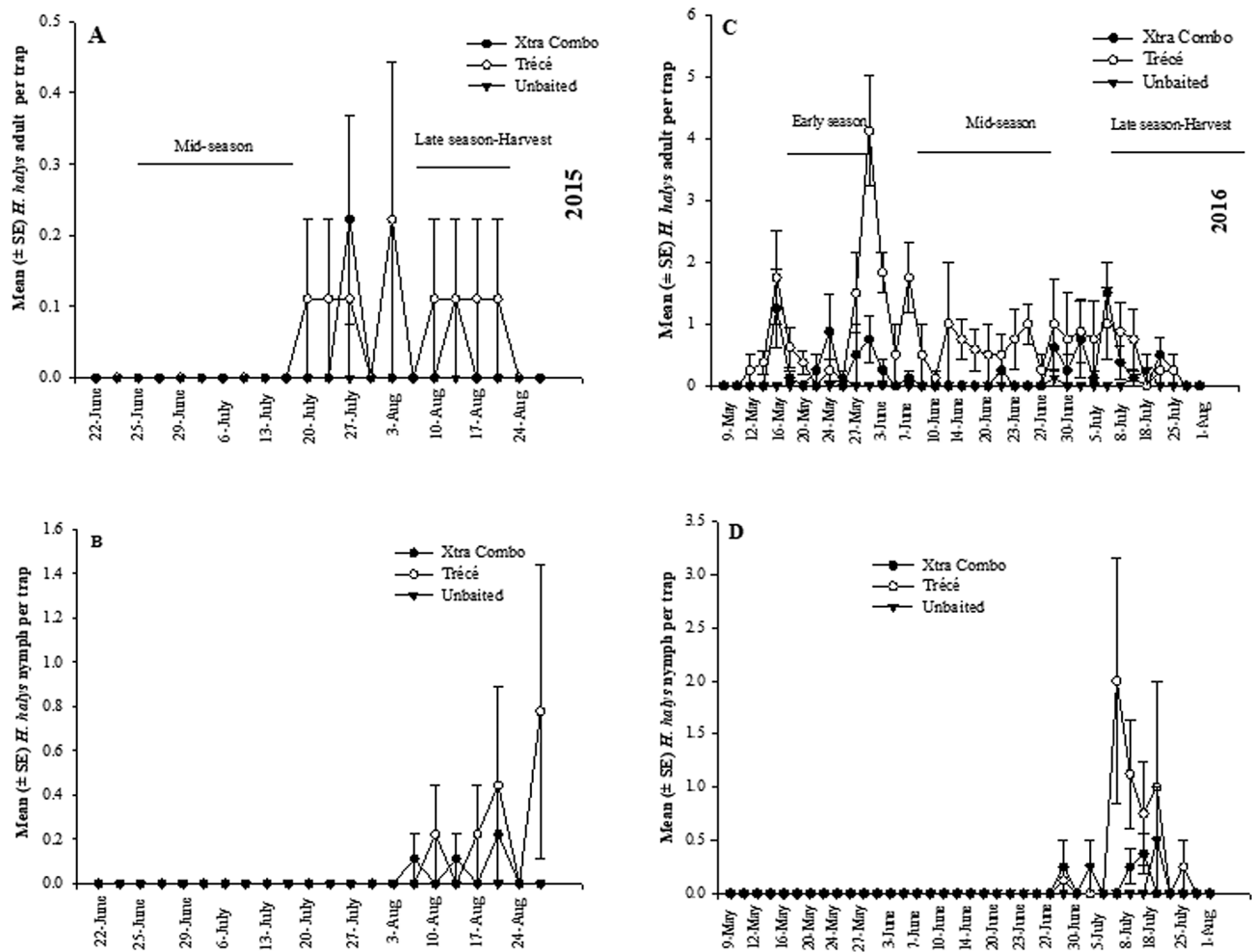


Fig. 1. Seasonality of *Halyomorpha halys* adults (A) and nymphs (B) in 2015 and adults (C) and nymphs (D) in 2016 in unbaited and traps baited with Xtra Combo and Trécé lures in peach blocks at RAREC.

observed on the associated trees followed the same trend with no significant treatment effect for adult and nymph *H. halys*. Although not significant, Xtra Combo baited trap and associated trees recorded numerically higher numbers of adult endemic pentatomids compared with Trécé and unbaited control traps and associated trees.

In 2016, the model was significant for the response of nymphs ( $F = 14.23$ ,  $df = 4, 31$ ,  $P < 0.0001$ ) and adults ( $F = 26.09$ ,  $df = 4, 31$ ,  $P < 0.0001$ ) to the lure type. Similarly, the response of nymphs ( $F = 11.84$ ,  $df = 4, 31$ ,  $P < 0.0001$ ) and adults ( $F = 33.05$ ,  $df = 4, 31$ ,  $P < 0.0001$ ) observed on the associated trees was significant among the lure types. Trécé baited traps captured significantly more adults and nymphs than Xtra Combo (Table 2). The spillover, as measured by the number of *H. halys* observed in associated trees, followed the same trend for adults but not for nymphs (Table 2).

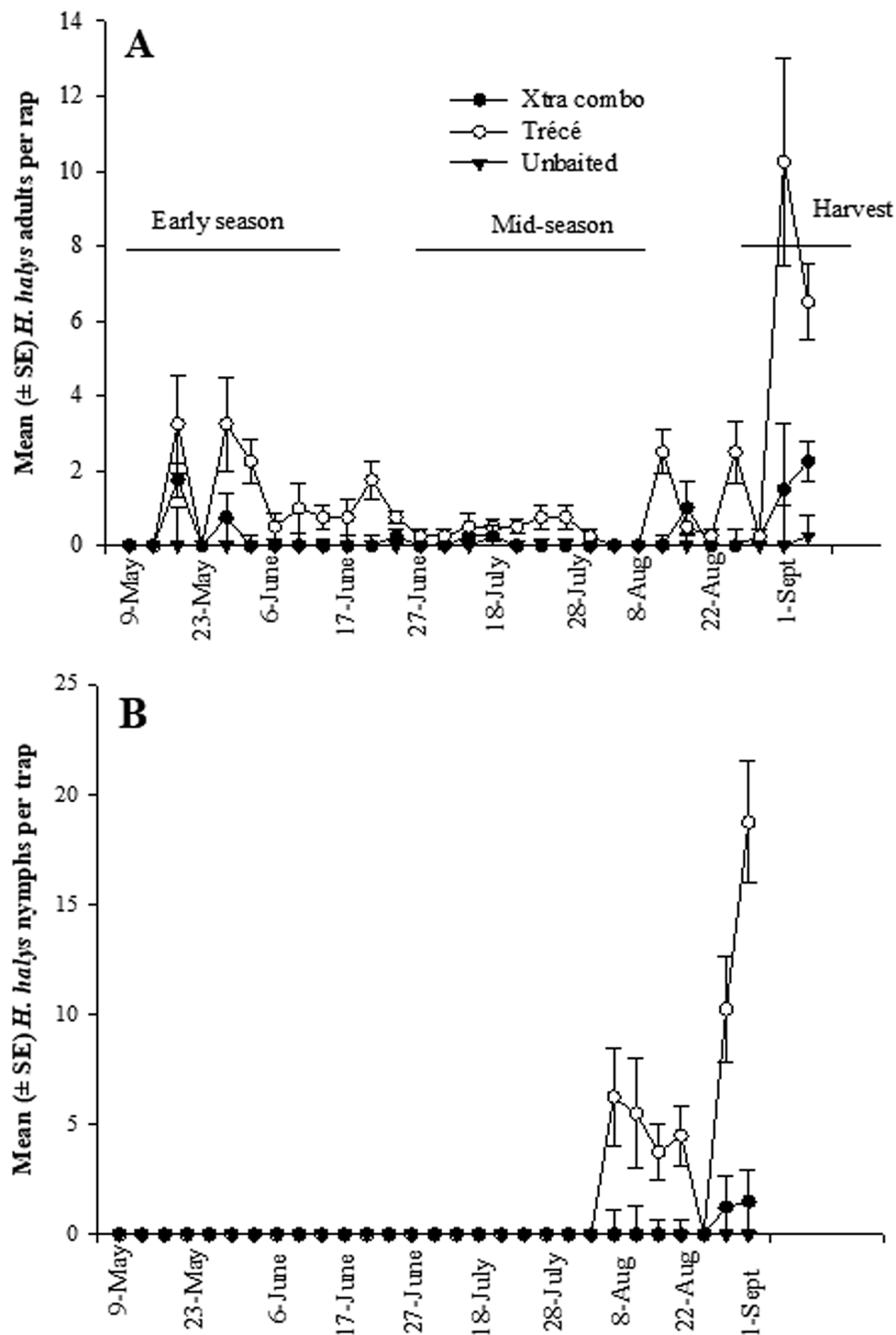
In 2015, the field response index, which measures the relative population response of *H. halys* due to the addition of the olfactory cue (aggregation baited pheromone traps relative to the unbaited traps), was not significant between lure treatments for any life stage of *H. halys* (nymph:  $\chi^2 = 0.00$ ,  $df = 1$ ,  $P = 1.000$ ; adult:  $\chi^2 = 0.00$ ,  $df = 1$ ,  $P = 1.000$ ; Fig. 3A). The mean response for Trécé lure and Xtra Combo was the same for nymphs (66.7%) and adults (100%; Fig. 3A) suggesting that at low population numbers, the recorded response to either lure was equal whether in the traps or on the associated trees. For endemic pentatomid species, there was no significant difference in the FRI between lure treatments for nymphs

( $\chi^2 = 0.00$ ,  $df = 1$ ,  $P = 1.00$ ; Fig. 3B), but field response for adults was significant ( $\chi^2 = 3.87$ ,  $df = 1$ ,  $P = 0.05$ ; Fig. 3B). Similar to the numeric response, there was a higher mean value of the FRI for Xtra Combo baited traps ( $39.9 \pm 10.3$ ) than for Trécé baited traps ( $0.7 \pm 10.3$ ). In 2016, under higher population pressure, the FRI showed a marginal effect for the adults ( $\chi^2 = 3.3$ ,  $df = 1$ ,  $P = 0.07$ ) but no significant difference between lure treatments for nymphs ( $\chi^2 = 2.6$ ,  $df = 1$ ,  $P = 0.11$ ; Fig. 4A).

Injury to peach fruit at harvest was assessed in 2015 and 2016. There was no significant effect of year ( $F = 1.26$ ,  $df = 3$ ,  $P = 0.3001$ ) or year by treatment interaction ( $F = 1.0$ ,  $df = 6$ ,  $P = 0.42$ ), so the data was pooled. The model was significant for the percent injury among treatments (L-R  $\chi^2 = 24.51$ ,  $df = 2$ ,  $P < 0.0001$ ). However, there was no significant effect of orchard blocks (L-R  $\chi^2 = 5.38$ ,  $df = 4$ ,  $P = 0.2509$ ) nor block by treatment interaction (L-R  $\chi^2 = 10.10$ ,  $df = 8$ ,  $P = 0.2579$ ). The mean percent fruit injury was significantly higher on trees associated with Trécé lure baited traps ( $52.2 \pm 5.0\%$ ) than Xtra Combo and unbaited traps (Xtra Combo:  $35.2 \pm 4.5\%$ ; unbaited:  $22.2 \pm 3.5\%$ ; Fig. 5A).

### Response of *H. halys* to Lures in Apple

In 2016, the model was significant for the response of nymphs ( $F = 45.64$ ,  $df = 2, 9$ ,  $P < 0.0001$ ) and adults ( $F = 35.35$ ,  $df = 2, 31$ ,  $P < 0.0001$ ) to the lure type. Similarly, the response of adults was significant ( $F = 24.02$ ,  $df = 2, 9$ ,  $P < 0.0001$ ) but not for nymphs



**Fig. 2.** Seasonality of *Halyomorpha halys* adults (A) and nymphs (B) in unbaited traps and traps baited with Xtra Combo and Trécé lures in an apple block at FOREC in 2016. No data was taken in apple in 2015.

( $F = 2.89$ ,  $df = 2, 9$ ,  $P = 0.1072$ ) observed on the associated trees. Trécé baited traps captured significantly more adults and nymphs than Xtra Combo (Table 2). The spillover, as measured by the number of *H. halys* observed in associated trees, followed the same trend for adults but not for nymphs (Table 2).

In apple, both nymphs and adults demonstrated no significant difference in the field response between the lure treatments (nymphs:  $\chi^2 = 1.75$ ,  $df = 1$ ,  $P = 0.19$ ; adults:  $\chi^2 = 3.41$ ,  $df = 1$ ,  $P = 0.07$ ; Fig. 4B).

There was a significant difference between the treatments for injury in apple ( $F = 62.37$ ,  $df = 2, 6$ ,  $P < 0.0001$ ). Fruit injury in

trees associated with Trécé lure baited traps ( $93.0 \pm 3.8\%$ ) and Xtra Combo ( $74.1 \pm 5.1\%$ ) was significantly different from fruit in trees associated with the unbaited trap ( $19.0\% \pm 2.7$ ; Fig. 5B).

#### Comparison of *H. halys* Response to Lures in Peach and Apple

In 2016, feeding injury severity was compared in a paired block of peach and apple at FOREC between lure treatments. There was significant model effect ( $F = 82.60$ ,  $df = 5, 900$ ,  $P < 0.0001$ ) with a significant crop type by treatment interaction ( $F = 24.59$ ,  $df = 2$ ,

**Table 1.** Seasonal mean ( $\pm$ SE) total number of *Halyomorpha halys* and endemic pentatomids captured in black pyramid traps and observed during 3-min visual count on associated tree per sampling date in peach in 2015

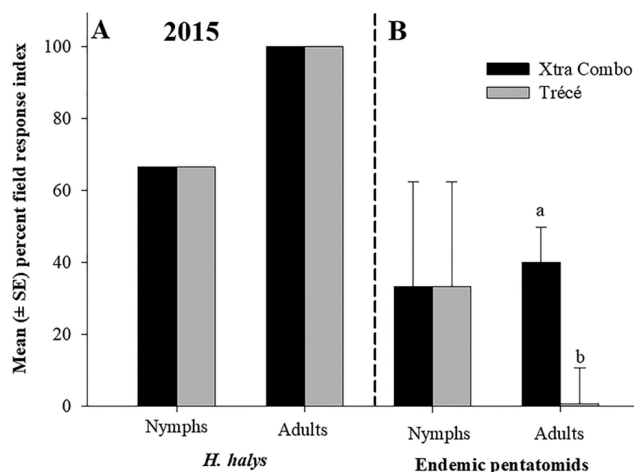
Method	Treatment	<i>H. halys</i>		Endemic pentatomids	
		Adult	Nymph	Adult	Nymph
Trap	Xtra Combo	1.00 $\pm$ 0.57a	1.33 $\pm$ 1.33a	5.33 $\pm$ 2.60a	0.00 $\pm$ 0.00a
	Trécé	3.00 $\pm$ 0.57a	5.00 $\pm$ 4.51a	2.67 $\pm$ 1.76a	0.00 $\pm$ 0.00a
	Unbaited	0.00 $\pm$ 0.00b	0.00 $\pm$ 0.00a	0.33 $\pm$ 0.33a	0.00 $\pm$ 0.00a
	<i>F</i>	11.26	1.02	2.37	0.00
	<i>P</i>	0.0093	0.4161	0.1741	1.0000
	<i>df</i>	2, 6	2, 6	2, 6	2, 6
Visual	Xtra Combo	2.00 $\pm$ 1.00a	0.67 $\pm$ 0.33a	3.33 $\pm$ 0.33a	8.33 $\pm$ 8.33a
	Trécé	3.00 $\pm$ 0.57a	1.00 $\pm$ 0.00a	1.67 $\pm$ 0.67a	8.33 $\pm$ 8.33a
	Unbaited	0.00 $\pm$ 0.00b	0.33 $\pm$ 0.33a	1.33 $\pm$ 0.88a	0.00 $\pm$ 0.00a
	<i>F</i>	13.00	1.50	2.12	0.50
	<i>P</i>	0.0066	0.2963	0.2008	0.6297
	<i>df</i>	2, 6	2, 6	2, 6	2, 6

Endemic pentatomid species were primarily *Euschistus servus*. Means in the same column having the same letter for each method are not significantly different from each other using Tukey's HSD method ( $P = 0.05$ ).

**Table 2.** Seasonal mean ( $\pm$ SE) total number of *Halyomorpha halys* captured in aggregation pheromone-baited traps and observed during 3-min visual count on associated trees for peach and apple in 2016 per sampling date

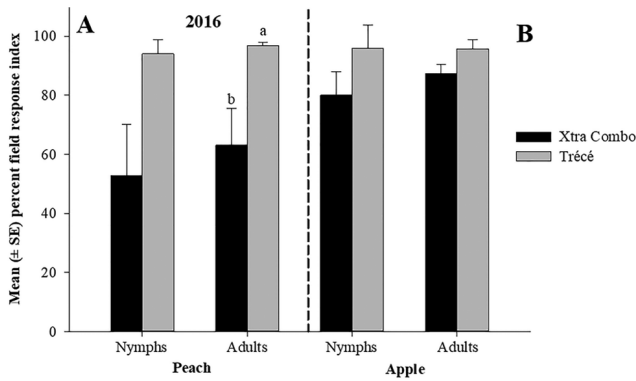
Method	Treatment	Peach		Apple	
		Adult	Nymph	Adult	Nymph
Trap	Xtra Combo	4.33 $\pm$ 1.36b	1.75 $\pm$ 0.65b	8.00 $\pm$ 1.08b	2.75 $\pm$ 1.55b
	Trécé	16.67 $\pm$ 2.07a	6.42 $\pm$ 1.41a	40.75 $\pm$ 14.34a	49.75 $\pm$ 9.91a
	Unbaited	0.33 $\pm$ 0.34c	0.17 $\pm$ 0.51c	0.50 $\pm$ 0.29c	0.00 $\pm$ 0.00b
	<i>F</i>	51.73	25.55	35.35	45.64
	<i>P</i>	<0.0001	<0.0001	<0.0001	<0.0001
	<i>df</i>	2, 31	2, 31	2, 9	2, 9
Visual	Xtra Combo	1.17 $\pm$ 0.53b	3.50 $\pm$ 2.22a	0.50 $\pm$ 0.29b	1.00 $\pm$ 0.71a
	Trécé	6.83 $\pm$ 0.84a	4.50 $\pm$ 1.90a	9.25 $\pm$ 2.53a	5.75 $\pm$ 2.39a
	Unbaited	0.08 $\pm$ 0.08c	0.25 $\pm$ 0.18b	0.25 $\pm$ 0.25b	0.50 $\pm$ 0.50a
	<i>F</i>	63.13	9.95	24.02	2.89
	<i>P</i>	<0.0001	0.0005	0.0002	0.1072
	<i>df</i>	2, 31	2, 31	2, 9	2, 9

Endemic pentatomids were found at too low of densities for analysis in 2016. Means in same column having the same letter for each method are not significantly different from each other using Tukey's HSD method ( $P = 0.05$ ). The degree of freedom for the tests for peach was 2, 31 and apple 2, 9.

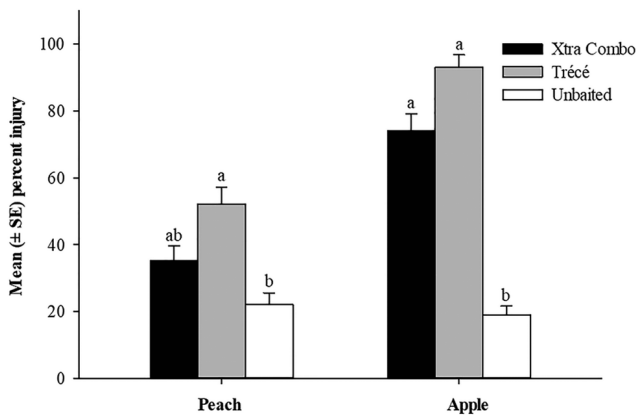
**Fig. 3.** Mean ( $\pm$ SE) percent field response index for (A) *Halyomorpha halys* and (B) endemic pentatomids in peach at RAREC in 2015. For each lure, bars connected with no letters are not significantly different according to chi-square approximation for one-way test ( $P = 0.05$ ).

$P < 0.0001$ ) with injury in apple associated with Trécé lure being higher overall but the unbaited peaches had significantly higher injury than unbaited apples but further analysis was not conducted due to possible pseudoreplication (Fig. 6). Treatment and location of fruit (associated or adjacent tree) also impacted damage severity for peach and apple at FOREC (Fig. 6). In apple, there was a significant model effect ( $F = 93.80$ ,  $df = 5, 559$ ,  $P < 0.0001$ ) with fruit location ( $F = 46.74$ ,  $df = 1$ ,  $P < 0.0001$ ), treatment ( $F = 206.57$ ,  $df = 2$ ,  $P < 0.0001$ ; Fig. 6), and their interaction effects ( $F = 9.59$ ,  $df = 2$ ,  $P < 0.0001$ ) being significant. In peach, there was a significant model effect ( $F = 10.94$ ,  $df = 5, 335$ ,  $P < 0.0001$ ) but only due to lure treatment effect. There was no significant difference in damage severity between associated or adjacent trees in peaches ( $F = 1.48$ ,  $df = 1$ ,  $P = 0.224$ ) suggesting more evenly distributed injury around the lure.

The monitoring method (visual, trap, visual + trap) that explained the most variation for damage severity was total capture in trap ( $R^2 = 0.60$  and  $0.2821$  in apple and peach, respectively). While the positive correlation between captures in trap and damage severity was significant in both apple and peach (apple:  $F = 17.52$ ,  $df = 1, 10$ ,  $P = 0.0019$ ; peach:  $F = 13.36$ ,  $df = 1, 34$ ,  $P = 0.0009$ ), AIC-based



**Fig. 4.** Mean ( $\pm$ SE) percent field response index for *Halyomorpha halys* in peach (A) and apple (B) in 2016. For each treatment type, bars connected with no letters are not significantly different according to chi-square approximation for one-way test ( $P = 0.05$ ).



**Fig. 5.** Mean ( $\pm$ SE) percent field injury of all stink bug species in peach (2015 and 2016) and apples (2016). For each treatment type, bars connected with different letters are significantly different using Tukey–Kramer HSD ( $P < 0.05$ ).

stepwise model simplification found that the best model (lowest AIC value) included only lure treatment as the single explanatory variable (Table 3). This held for both apple (AIC = 7.90,  $F = 29.97$ ,  $df = 2, 9$ ,  $P = 0.0001$ ) and peach (AIC = 27.90,  $F = 15.78$ ,  $df = 2, 33$ ,  $P < 0.0001$ ). Tukey-corrected pairwise comparisons indicated that significantly higher injury severity occurred on trees associated with Xtra Combo than controls ( $P = 0.013$ ) and more injury occurred on trees associated with Trécé lure than Xtra Combo lure ( $P = 0.006$ ) or controls ( $P < 0.0001$ ).

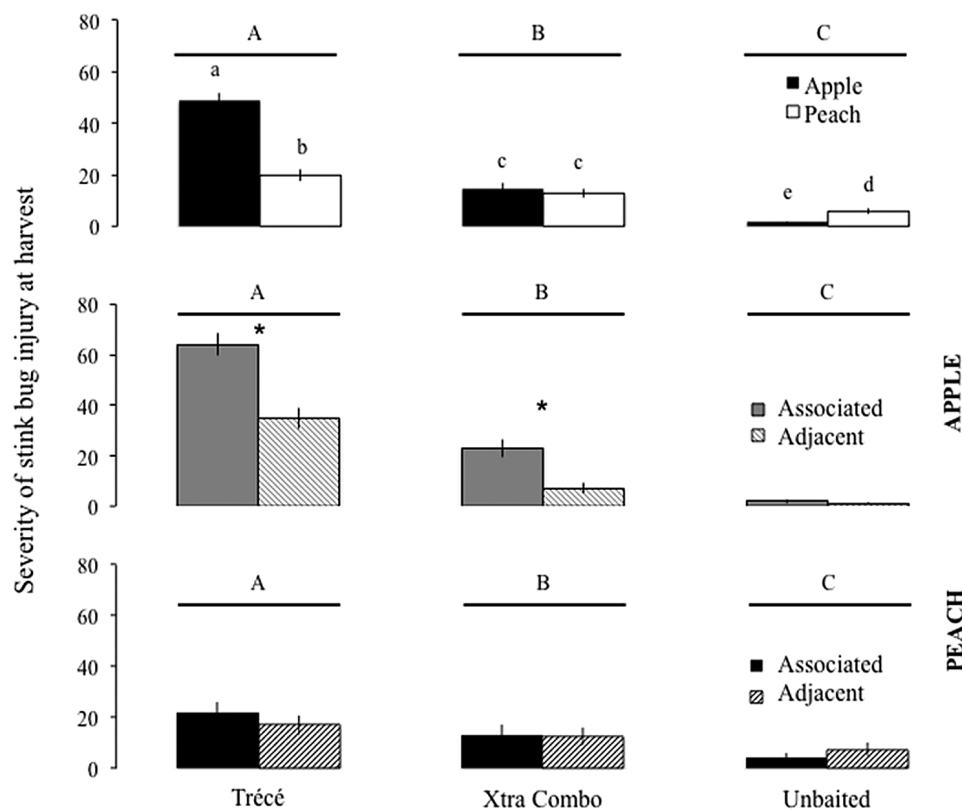
## Discussion

In this study, we have quantified *H. halys* adult and nymphal responses to two commercial aggregation pheromone lures in tree fruit and the injury caused by responding populations. We have demonstrated in peach and apple orchards that *H. halys* adults and nymphs are attracted to black pyramid traps baited with either Trécé or Xtra Combo lures, with a stronger response to Trécé lure baited traps. The difference in response to lures was consistent throughout the season and was most evident under higher population pressure. Corresponding to differences in the numbers of *H. halys* responding, higher injury occurred in peach and apple trees associated with traps baited with the Trécé lure than Xtra Combo or unbaited trees. Endemic pentatomids, particularly *Euschistus servus*, also responded to traps baited with the Xtra Combo lure in 2015 which

is somewhat expected as it contains the *Euschistus* spp. pheromone and some of the injury at harvest may be attributable to *E. servus*.

For any trap-based monitoring approach, it is important that numbers in the traps are consistently representative of the background population densities, at both high and low densities. Baited traps are often used in addition to other parameters such as thresholds or in conjunction with crop phenology to determine timing of management treatments (Prasad and Prabhakar 2012). However, Miller et al. (2015) note that insect numbers in pheromone-baited traps have not always translated into accurate estimates of absolute pest densities, which may reduce the utility of baited traps to predict pest populations and injury. We applied a field response index to quantify the behavioral response of the insect due to the attractiveness of the olfactory stimulus (modified from Akotsen-Mensah et al. [2010]). A similar approach was used to compare stimuli in paired laboratory studies where the absolute population was known (Phillips et al. 1993, Leskey and Prokopy 2000, Leskey et al. 2001). We identified that *H. halys* nymphs and adults showed equal response to Trécé and Xtra Combo lures when the *H. halys* population was low (2015). However, when the *H. halys* population was higher (2016), the difference in field response to Trécé lure was statistically higher for adults in peach and numerically higher to the Trécé lure in apple. It is not clear whether the increased overall response to the Trécé lures provides useful increased sensitivity to the true *H. halys* field abundance; however, in some contexts, Trécé may provide enhanced information about *H. halys* pressure that would balance a potential trade-off with increased spillover.

We found a positive correlation between the severity of injury and cumulative numbers of *H. halys* in peach and apple. Correlations relating trap numbers and injury have been identified for some lepidopteran pest species (Grantham et al. 2002, Hillier et al. 2004) although this relationship is more difficult for aggregation pheromone-baited traps (Landolt 1997, Morrison et al. 2018) due to trap spillover in insect numbers and injury. However, the relationship we identified here was consistent with the treatment effects found by other measures in our study, with Trécé lure having both the largest numerical response by *H. halys* and subsequent injury. Increase in spillover injury associated with the use of the aggregation pheromone should be considered along with monitoring objectives. Several fundamental differences exist between the use of aggregation pheromones and sex pheromones for monitoring programs. First, sex pheromones usually only attract adults of a single sex (Carde and Baker 1984), while aggregation pheromones often attract adults of both sexes, and in the case of *H. halys*, nymphal stages as well (Leskey et al. 2015b). Second, response to sex pheromones is considered more of a point source, meaning the insect will be attracted to and make contact with the source emitting the pheromone stimuli (Roelofs and Cardé 1977). For aggregation pheromones, the insects are attracted to and arrive near the point of pheromone emission, but do not always enter the trap (Prokopy et al. 2004, Sargent et al. 2014) leading to what is termed ‘trap spillover’. The magnitude of the spillover effect from the baited traps in our study showed higher injury on trees associated with Trécé lure than Xtra Combo lure in apple. In peach however, the injury was not significantly different between trees associated with the trap and adjacent trees, which may be due to higher attractiveness or suitability of the peach itself (Funayama 2004, Acebes-Doria et al. 2016b). Because of the value of fresh market peaches (USDA 2017), growers may not be willing to tolerate injury to fruit due to trap spillover. Thus, a better understanding of how *H. halys* respond behaviorally to baited pheromone traps in different crop contexts is warranted.



**Fig. 6.** Mean ( $\pm$ SE) severity of stink bug injury in apple and peach on associated trees and adjacent trees by lure. Asterisk indicates significant difference between tree locations by lure treatment by Tukey's HSD ( $P < 0.05$ ).

**Table 3.** Correlation between stink bug counts and injury severity in 2016, and AIC-based model simplification, in apple and peach

Model	$R^2$	AIC	$F$	df	$P$ value
<b>Apple</b>					
Severity ~ Trap + Visual count	0.588	18.56	16.68	1, 10	0.0022
Severity ~ Visual	0.534	21.18	11.45	1, 10	0.0070
Severity ~ Trap	<b>0.600</b>	18.18	17.52	1, 10	0.0019
Severity ~ Treatment + Trap	0.879	9.97	19.40	3, 8	0.0005
Severity ~ Treatment	0.869	7.90	29.97	2, 9	0.0001
<b>Peach</b>					
Severity ~ Trap + Visual	0.277	38.38	13.04	1, 34	0.0010
Severity ~ Visual	0.147	44.33	5.87	1, 34	0.0209
Severity ~ Trap	<b>0.282</b>	38.13	13.36	1, 34	0.0009
Severity ~ Block + Trap + Treat	0.532	30.74	6.82	5, 30	0.0002
Severity ~ Trap + Treatment	0.505	28.74	10.89	3, 32	<0.0001
Severity ~ Treatment	0.489	<b>27.90</b>	15.78	2, 33	<0.0001

Severity is the square-root transformed response variable of fruit injury severity; Trap + Visual is the explanatory variable of trap counts of *H. halys* plus visual counts in the associated tree; Visual is the counts in the associated tree only; Trap is the trap counts only; Treatment is the lure treatment factor (i.e., Xtra Combo, Trécé, or unbaited); Block is the peach orchard field site location as a blocking factor. Bolded  $R^2$  values represent the highest value in apple and peach among bug count methods (i.e., visual tree counts, trap counts, or trap + visual counts), and bolded AIC values represent the lowest value in stepwise model selection for apple and peach.

When combined with our existing knowledge about *H. halys* seasonality and behavior in tree fruit systems, we propose that the trap deployment strategy should be different between the two crops. Research has shown that there is a strong edge effect on *H. halys* dispersal in peach (Blaauw et al. 2016), and of resultant injury in both peach and apple (Joseph et al. 2014). Due to the strong edge effect, and spillover seen in peach, and the high crop value, deployment of baited traps outside of the orchard edge may be preferable in peach. A comparison of seasonal trap captures in border areas

outside peach orchards and those within the border row itself would be a logical next step toward addressing these issues and establishing if captures outside the orchard reflect the insect pressure in the orchard itself.

Moreover, research by Morrison et al. (2016) indicated that retention of *H. halys* in apple trees was increased by the presence of the aggregation pheromone, though the presence of apple volatiles in pheromone-baited traps did not increase captures over captures of pheromone-baited traps alone. This same pattern was observed



for peach volatiles and pheromone-baited traps, with the presence of pheromone volatiles leading to increased retention on peach trees (Morrison et al. 2018), though retention was not as long as observed in apple (Morrison and Leskey, unpublished data). Because peach is a more suitable developmental host than apple for *H. halys* and second instar nymphs show less dispersion on peaches than apples (Acebes-Doria et al. 2016b; Acebes-Doria et al., unpublished data), we postulate that *H. halys* may not feed as long on apple and therefore does not remain as long on apple trees and forages over a greater area. If true, this would lead to a higher injury closest to the aggregation pheromone lure in an inferior host because of reduced retention. In a superior host, like peach, *H. halys* could arrest long-distance foraging behavior in response to the aggregation pheromone because of the high host quality of peach leading to a larger spillover area. We observed this where there was similar injury severity between associated and adjacent trees in peaches only. Although the response to pheromone traps by *H. halys* was not enhanced through the incorporation of host plant volatile compounds to date (Morrison et al. 2018), as has been shown for some coleopteran and lepidopteran species (Landolt and Phillips 1997, Reddy and Guerrero 2004), perhaps other volatiles could be identified that enhance attraction to baited traps.

The trapping area of a pheromone-baited trap is determined by the size of the pheromone plume and the dispersal behavior of the target insect (Miller et al. 2015). Therefore, insect foraging behavior, which likely varies by crop and developmental status of the insect, is critical in determining how trap captures relate to absolute insect densities and at what spatial scale estimates may be reliable. The level of response that is most desirable will depend on crop-specific monitoring goals, noting that although the Trécé lure had a significantly higher response, there was higher associated damage as well, and it does not contain pheromone for endemic species, which can also be pests in tree fruit production. Our principal aim in this study was to determine a relationship between the numbers of *H. halys* responding to a specific pheromone lure and fruit injury in tree fruit. Although a positive relationship was identified, temporal variation within the growing season and differences between lures did not allow us to make an estimate on what numbers in traps mean for population pressure and resulting injury. Future research should focus on interpreting catches in traps for management decisions, which may be clarified through studies on placement of traps in fruit orchards and comparisons on the behavioral response of *H. halys* to peaches and apples.

## Acknowledgments

We are grateful to Ann Rucker, Brett Blaauw, Adam Morehead, William Woodroffe, and Meghin Rollins for their assistance in the field work. We also want to acknowledge the contributions made by all the staff and workers of RAREC. AgBio Inc. and Trécé Inc. did not provide materials for this study. This research was mainly supported by United States Department of Agriculture-National Institute of Food and Agriculture, Specialty Crop Research Initiative (USDA NIFA SCRI) 2011-51181-30397 and USDA-NIFA SCRI 2016-51181-25409 grants but also in part by New Jersey Agricultural Experiment State projects NJ08225 and NJ08131.

## References Cited

JMP® Pro 13. 2016. SAS Institute Inc., Cary, NC.

Acebes-Doria, A. L., T. C. Leskey, and J. C. Bergh. 2016a. 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.

Acebes-Doria, A. L., T. C. Leskey, and J. C. Bergh. 2016b. Host plant effects on *Halyomorpha halys* (Hemiptera: Pentatomidae) nymphal development and survivorship. *Environ. Entomol.* 45: 663–670.

Akotsen-Mensah, C., R. Boozer, and H. Y. Fadamiro. 2010. Field evaluation of traps and lures for monitoring plum curculio (Coleoptera: Curculionidae) in Alabama peaches. *J. Econ. Entomol.* 103: 744–753.

Bergh, J. C., W. R. Morrison, S. V. Joseph, and T. C. Leskey. 2017. Characterizing spring emergence of adult *Halyomorpha halys* using experimental overwintering shelters and commercial pheromone traps. *Entomol. Exp. Appl.* 162: 336–345.

Bergmann, E. J., P. D. Venugopal, H. M. Martinson, M. J. Raupp, and P. M. Shrewsbury. 2016. Host plant use by the invasive *Halyomorpha halys* (Stål) on woody ornamental trees and shrubs. *PLoS One.* 11: e0149975.

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.

Cambridge, J. 2016. Behavioral patterns of the brown marmorated stink bug and their implications for monitoring programs. Ph.D. dissertation, Rutgers University Graduate School, New Brunswick.

Carde, R. T., and T. C. Baker. 1984. Sexual communication with pheromones, pp. 355–383. *In* W. J. Bell and R. T. Carde (eds.), *Chemical ecology of insects*. Chapman and Hall Ltd, Sunderland, MA.

Cira, T. M., R. C. Venette, J. Aigner, T. Kuhar, D. E. Mullins, S. E. Gabbert, and W. D. Hutchison. 2016. Cold tolerance of *Halyomorpha halys* (Hemiptera: Pentatomidae) across geographic and temporal scales. *Environ. Entomol.* 45: 484–491.

Funayama, K. 2004. Importance of apple fruits as food for the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae). *Appl. Entomol. Zool.* 39: 617–623.

Grantham, R. A., P. G. Mulder, G. W. Cuperus, and J. D. Carlson. 2002. Evaluation of pecan nut casebearer *Acrobasis nuxvorella* (Lepidoptera: Pyralidae) prediction models using pheromone trapping. *Environ. Entomol.* 31: 1062.

Haye, T., T. Garipey, K. Hoelmer, J.-P. Rossi, J.-C. Streito, X. Tassus, and N. Desneux. 2015. Range expansion of the invasive brown marmorated stinkbug, *Halyomorpha halys*: an increasing threat to field, fruit and vegetable crops worldwide. *J. Pest Sci.* 88: 665–673.

Hillier, N. K., P. L. Dixon, and D. J. Larson. 2004. Trap captures of male *Grapholita libertina* (Lepidoptera: Tortricidae) moths: relationship to larval numbers and damage in wild lingonberry. *Environ. Entomol.* 33: 405–417.

Hoebeke, E. R., and M. E. Carter. 2003. *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae): a polyphagous plant pest from Asia newly detected in North America. *Proc. Entomol. Soc. Wash.* 105: 225–237.

Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Mono.* 54: 187–211.

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.

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.

Khrimian, A., A. Zhang, D. C. Weber, H. Y. Ho, J. R. Aldrich, K. E. Vermillion, M. A. Siegler, S. Shirali, F. Guzman, and T. C. Leskey. 2014. Discovery of the aggregation pheromone of the brown marmorated stink bug (*Halyomorpha halys*) through the creation of stereoisomeric libraries of 1-bisabolen-3-ols. *J. Nat. Prod.* 77: 1708–1717.

Kriticos, D. J., J. M. Kean, C. B. Phillips, S. D. Senay, H. Acosta, and T. Haye. 2017. The potential global distribution of the brown marmorated stink bug, *Halyomorpha halys*, a critical threat to plant biosecurity. *J. Pest Sci.* 90: 1033–1043.

Krupke, C. H., J. F. Brunner, M. D. Doerr, and A. D. Kahn. 2001. Field attraction of the stink bug *Euschistus conspersus* (Hemiptera: Pentatomidae) to synthetic pheromone-baited host plants. *J. Econ. Entomol.* 94: 1500–1505.

Landolt, P. J. 1997. Sex attractant and aggregation pheromones of male polyphagous insects. *Am. Entomol.* 43: 12–22.

- Landolt, P. J., and T. W. Phillips. 1997. Host plant influences on sex pheromone behavior of phytophagous insects. *Annu. Rev. Entomol.* 42: 371–391.
- Lee, D. H., and T. C. Leskey. 2015. Flight behavior of foraging and overwintering brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). *Bull. Entomol. Res.* 105: 566–573.
- 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., and R. J. Prokopy. 2000. Sources of apple odor attractive to adult plum curculios. *J. Chem. Ecol.* 26: 639–653.
- Leskey, T. C., R. J. Prokopy, S. E. Wright, P. L. Phelan, and L. W. Haynes. 2001. Evaluation of individual components of plum odor as potential attractants for adult plum curculios. *J. Chem. Ecol.* 27: 1–17.
- Leskey, T. C., B. D. Short, B. R. Butler, and S. E. Wright. 2012a. 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*. 2012: 1–14.
- Leskey, T. C., S. E. Wright, B. D. Short, and A. Khimian. 2012b. Development of behaviorally-based monitoring tools for the brown marmorated stink bug (Heteroptera: Pentatomidae) in commercial tree fruit orchards. *J. Entomol. Sci.* 47: 76–85.
- Leskey, T. C., G. C. Hamilton, A. L. Nielsen, D. F. Polk, C. Rodriguez-Saona, J. C. Bergh, D. A. Herbert, T. P. Kuhar, D. G. Pfeiffer, G. P. Dively, et al. 2012c. Pest status of the brown marmorated stink bug, *Halyomorpha halys* in the USA. *Outlooks Pest Manag.* 23: 218–226.
- Leskey, T. C., A. Khimian, D. C. Weber, J. C. Aldrich, B. D. Short, D. H. Lee, and W. R. Morrison. 3rd. 2015a. Behavioral responses of the invasive *Halyomorpha halys* (Stål) to traps baited with stereoisomeric mixtures of 10,11-epoxy-1-bisabolene-3-OL. *J. Chem. Ecol.* 41: 418–429.
- Leskey, T. C., A. Agnello, J. C. Bergh, G. P. Dively, G. C. Hamilton, P. Jentsch, A. Khimian, G. Krawczyk, T. P. Kuhar, D. H. Lee, et al. 2015b. Attraction of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) to traps baited with semiochemical stimuli across the United States. *Environ. Entomol.* 44: 746–756.
- Miller, J. R., C. G. Adams, P. A. Weston, and J. H. Schenker. 2015. Trapping small animals moving randomly, Springer International Publishing, XVIII, 114 pp.
- Morrison, W. R., 3rd, 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. Khimian, 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.* 89: 81–96.
- Morrison, W. R., M. Allen, and T. C. Leskey. 2018. Behavioural response of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) to host plant stimuli augmented with semiochemicals in the field. *Agric. For. Entomol.* 20: 62–72.
- Nielsen, A. L., and G. C. Hamilton. 2009. Seasonal occurrence and impact of *Halyomorpha halys* (Hemiptera: Pentatomidae) in tree fruit. *J. Econ. Entomol.* 102: 1133–1140.
- Nielsen, A. L., S. Chen, and S. J. Fleischer. 2016. Coupling developmental physiology, photoperiod, and temperature to model phenology and dynamics of an invasive heteropteran, *Halyomorpha halys*. *Front. Physiol.* 7: 165.
- Phillips, T. W., X. L. Jiang, W. E. Burkholder, J. K. Phillips, and H. Q. Tran. 1993. Behavioral responses to food volatiles by two species of stored-product coleoptera, *Sitophilus oryzae* (curculionidae) and *Tribolium castaneum* (tenebrionidae). *J. Chem. Ecol.* 19: 723–734.
- Prasad, Y. G., and M. Prabhakar. 2012. Pest monitoring and forecasting, pp. 41–57. In D. P. Arbol and U. Shankar (eds.), *Integrated pest management: principles and practice*. CABI Publishing, Cambridge, MA.
- Prokopy, R. J., I. Jacome, E. Gray, G. Trujillo, M. Ricci, and J. C. Piñero. 2004. 3 using odor-baited trap trees as sentinels to monitor plum curculio (Coleoptera: Curculionidae) in apple orchards. *J. Econ. Entomol.* 97: 511–517.
- R CoreTeam. 2013. R: a language and environment for statistical computing computer program, version v.3.3.0. RCoreTeam, Vienna, Austria.]
- Reddy, G. V., and A. Guerrero. 2004. Interactions of insect pheromones and plant semiochemicals. *Trends Plant Sci.* 9: 253–261.
- Rice, K. B., C. J. Bergh, E. J. Bergmann, D. J. Biddinger, C. Dieckhoff, G. Dively, H. Fraser, T. Garipey, G. Hamilton, T. Haye, et al. 2014. Biology, ecology, and management of brown marmorated stink bug (Hemiptera: Pentatomidae). *J. Integ. Pest Manag.* 5: A1–A13.
- Roelofs, W., and R. Cardé. 1977. Responses of Lepidoptera to synthetic sex pheromone chemicals and their analogues. *Annu. Rev. Entomol.* 22: 377–405.
- Rutgers. 2016. New Jersey commercial tree fruit production guide. Rutgers Cooperative Extension E002.
- Sargent, C., H. M. Martinson, and M. J. Raupp. 2014. Traps and trap placement may affect location of brown marmorated stink bug (Hemiptera: Pentatomidae) and increase injury to tomato fruits in home gardens. *Environ. Entomol.* 43: 432–438.
- Short, B. D., A. Khimian, 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.
- USDA, National Statistical Service. 2017. New Jersey 2016 annual report and agricultural statistics. [www.nass.usda.gov/Statistic\\_by\\_State/New\\_Jersey](http://www.nass.usda.gov/Statistic_by_State/New_Jersey). Accessed 20 April 2018.
- Weber, D. C., T. C. Leskey, G. C. Walsh, and A. Khimian. 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., W. R. Morrison, A. Khimian, K. B. Rice, T. C. Leskey, C. Rodriguez-Saona, A. L. Nielsen, and B. R. Blaauw. 2017. Chemical ecology of *Halyomorpha halys*: discoveries and applications. *J. Pest Sci.* 90: 989–1008.
- Wiman, N. G., V. M. Walton, P. W. Shearer, S. I. Rondon, and J. C. Lee. 2014. Factors affecting flight capacity of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). *J. Pest Sci.* 88: 37–47.
- Zhu, G., W. Bu, Y. Gao, and G. Liu. 2012. Potential geographic distribution of brown marmorated stink bug invasion (*Halyomorpha halys*). *PLoS One.* 7: e31246.