Evaluation of Trap Designs and Deployment Strategies for Capturing *Halyomorpha halys* (Hemiptera: Pentatomidae)

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ABSTRACT *Halyomorpha halys* (Stål) is an invasive pest that attacks numerous crops. For growers to make informed management decisions against *H. halys*, an effective monitoring tool must be in place. We evaluated various trap designs baited with the two-component aggregation pheromone of *H. halys* and synergist and deployed in commercial apple orchards. We compared our current experimental standard trap, a black plywood pyramid trap 1.22 m in height deployed between border row apple trees with other trap designs for two growing seasons. These included a black lightweight coroplast pyramid trap of similar dimension, a smaller (29 cm) pyramid trap also ground deployed, a smaller limb-attached pyramid trap, a smaller pyramid trap hanging from a horizontal branch, and a semipyramid design known as the Rescue trap. We found that the coroplast pyramid was the most sensitive, capturing more adults than all other trap designs including our experimental standard. Smaller pyramid traps performed equally in adult captures to our experimental standard, though nymphal captures were statistically lower for the hanging traps. Experimental standard plywood and coroplast pyramid trap correlations were strong, suggesting that standard plywood pyramid traps could be replaced with lighter, cheaper coroplast pyramid traps. Strong correlations with small ground- and limb-deployed pyramid traps also suggest that these designs offer promise as well. Growers may be able to adopt alternative trap designs that are cheaper, lighter, and easier to deploy to monitor *H. halys* in orchards without a significant loss in sensitivity.

KEY WORDS captures, monitoring, integrated pest management, invasive species, brown marmorated stink bug

Effective trap design is necessary for monitoring pests and imperative for the implementation of many integrated pest management (IPM) programs. Many longstanding IPM programs rely on traps, which are often baited with a pheromone, kairomone, or other semiochemical. For example, native stink bugs, such as *Euschistus* spp. (Hemiptera: Pentatomidae), have commonly been monitored using yellow pyramid traps baited with (2*E*,4*Z*)-decadienoate (Leskey and Hogmire 2005), and with the identification of the attractive harlequin bug aggregation pheromone (two stereoisomers of the parent compound 10,11-epoxy-1-bisabolen-3-ol: Weber et al. 2014a), efficient trapping of *Murgantia histrionica* (Hemiptera: Pentatomidae) appears likely in the near future as well.

Monitoring for recently established invasive species is likewise important, especially when such species cause significant economic losses to the economy. One such damaging invasive species is the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), which was first detected in the United States in the early 2000s (Hoebeke and Carter2003). Since that point, populations have increased and *H. halys* has become a serious pest of row and specialty crops (Leskey et al. 2012a, b; Rice et al. 2014), causing US$37 million in damage in apple alone in 2010 in the mid-Atlantic (United States Apple Association [USAA] 2011). Growers were forced to increase insecticide applications by up to 4-fold in the aftermath of the outbreaks of *H. halys* in 2010 (Leskey et al. 2012b), which has resulted in the disruption of many long-standing IPM programs for specialty crops.

Effective insecticides to control *H. halys* populations in both conventional (Nielsen et al. 2008, Lee et al. 2013, Leskey et al. 2014) and organic systems (Lee et al. 2014) have been identified. These include, for example, bifenthrin, dinotefuran, thiamethoxam, clothianidin, fenpropathrin, and permethrin. However, a logical next step in re-establishing IPM programs is to integrate monitoring tools for *H. halys* to allow growers to establish the need for and timing of insecticide applications and ultimately reduce the reliance on these insecticides while maintaining control of *H. halys* populations. Thus, it is vital that growers have a trap for accurately assessing the presence and abundance of *H. halys* in the field.

Prior to 2012, the only available attractive semiochemical for baiting traps for *H. halys* was methyl

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(*E*,*E*,*Z*)-2,4,6-decatrienoate (MDT; e.g., Nielsen et al. 2011), which is the aggregation pheromone for *Plautia stali* Scott (Hemiptera: Pentatomidae) and is cross-attractive to *H. halys* (Khrimian et al. 2008). However, it is only effective in the late-season for adults. More recently, the 2-component male-produced aggregation pheromone has been identified for *H. halys*, consisting of (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-bisabolen-3-ol (major component) and (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisa bolen-3-ol (minor component; Khrimian et al. 2014). MDT has been shown to have a synergistic effect on the attraction of *H. halys* when combined with the *H. halys* aggregation pheromone (Weber et al. 2014b).

The best trap for landscape-scale detection and monitoring of the spread of *H. halys* has been blacklight traps (Nielsen et al. 2013). To date, the best trap design for farmscape-level monitoring has been using a 1.22 m black, upright wooden pyramid trap that is ground-deployed (Leskey et al. 2012c) and baited with both of the semiochemicals above (Leskey et al. 2015a). In studies in which pyramid traps were baited with MDT, there were greater captures of *H. halys* adults and nymphs in ground-deployed black pyramid traps than traps colored green, white, yellow or clear, or traps that were canopy-deployed, or bucket shaped (Leskey et al. 2012c). The black pyramid may be perceived as a trunk-mimicking stimulus by *H. halys* (Leskey et al. 2012c), as many of the hosts of *H. halys* are arboreal species (Lee et al. 2013) .

There are many considerations that must be accounted for in increasing the likelihood of adoption of a monitoring trap for *H. halys* by growers and to aid in the reestablishment of IPM programs. One of these is that a monitoring trap must not be overly expensive, bulky, or difficult for growers to install. Another consideration is that the monitoring trap should be effective at capturing adult and nymphal *H. halys* when they are present in the field during the growing season and reflect the relative size of or threat posed to susceptible crops.

Therefore, the aim of this current study was to compare season-long trap captures in our standard black plywood pyramid trap deployed on the ground between border row apple trees with other trap designs and deployment locations to better assess if alternative trap designs and deployment strategies provide reliable biological information as to the presence, abundance, and seasonal activity of *H. halys* in and near commercial apple orchards. These included similarly sized coroplast and smaller plastic pyramid traps also deployed on the ground, smaller pyramid traps hung from or deployed on horizontal limbs within the apple tree canopy, and the Rescue trap hung from horizontal limbs within the host tree canopies. All traps were baited with the two-component *H. halys* aggregation pheromone (Khrimian et al. 2014) and MDT synergist (Weber et al. 2014b).

Materials and Methods

Study Sites. Traps were deployed in two apple blocks in two different commercial orchards located in Smithsburg, MD (Orchard 1: 39° 40'21.62" N, 77° 32'29.99" W; Orchard 2: 39° 39'21.40" N, 77° 33'29.5" W), with each block bordered by mixed hardwood forests consisting primarily of *Quercus* spp., but also included *Carya* spp., *Prunus* spp., *Robinia* spp., and small patches of *Ailanthus altissima* Swingle. Apple varieties included Fuji, Golden Delicious, and Stamens. Both orchard locations were used in 2013 and 2014.

Trap Designs and Deployment. We evaluated different trap designs and deployment strategies. Treatments included four unique trap designs: large wooden black pyramid (1.22 m height, AgBio, Inc., Westminster, CO), large black coroplast pyramid (1.22 m height, AgBio, Inc.), small plastic wooden black pyramid (0.29 m height, AgBio, Inc.), and a modified pyramid consisting of a Rescue trap (Sterling International, Inc., Spokane, WA; Fig. 1). Each trap top except the Rescue brand trap was composed of plastic with ventilation holes on the sides, with 10.2 by 10.2 by 15.2 cm (W × L × H) dimensions, and each supplied with a funnel that had a 7.6-cm opening into the trap (Fig. 1; Leskey et al. 2012b). The large pyramid trap bases were 50.2 cm wide at the base and 3.8 cm at the top, while the small pyramids were 15.2 cm wide at the base and 3.8 cm at the top. For the small black pyramid, we varied the deployment location by placing them: on the ground (placed at the end of a tree row or between two trees on the edge of the block), attached to a scaffold limb (positioned midway between the base of the trunk and the top of the canopy), or hanging from a branch (and touching foliage). In total, there were six trap designs and deployment locations that were evaluated: large black wooden pyramid trap (ground deployed), large black coroplast pyramid trap (ground deployed), small black plastic pyramid (ground deployed), small black pyramid (deployed on a limb), small black plastic pyramid (hanging from a branch and touching foliage), and a Rescue trap (hanging from a branch and touching foliage). The spacing between each trap in the block was 50 m along the edge of an orchard in the border row.

Each type of trap had a single rubber septum (1-F SS 1888 GRY, West Pharmaceutical Services, Lititz, PA), which was loaded with 10.66 mg of the parent compound, 10,11-epoxy-1-bisabolen-3-ol, containing 2 mg of the SSRS aggregation pheromone component and 0.67 mg of the RSRS component (for formulation details, see Weber et al. 2014b). The rubber septa had an overall release rate of about 0.24 mg d^{-1} of total isomers at 20°C, and were changed every 2 wk. In addition, each trap contained a 66 mg MDT lure (4 by 4 cm, AgBio, Inc.) with a release rate of 0.6 mg d^{-1} at 20°C, and were changed on a monthly basis during the course of the experiment.

There were three replicates of each treatment in each orchard in 2013 and 2014, but due to space constraints at one of the orchard location, the Rescue and large coroplast trap were not included. The traps were deployed from 15 April to 3 October, 2013, except the large coroplast trap and Rescue trap, which were deployed from 2 July and 11 June, respectively. In 2014, all the traps were deployed from 13 April to

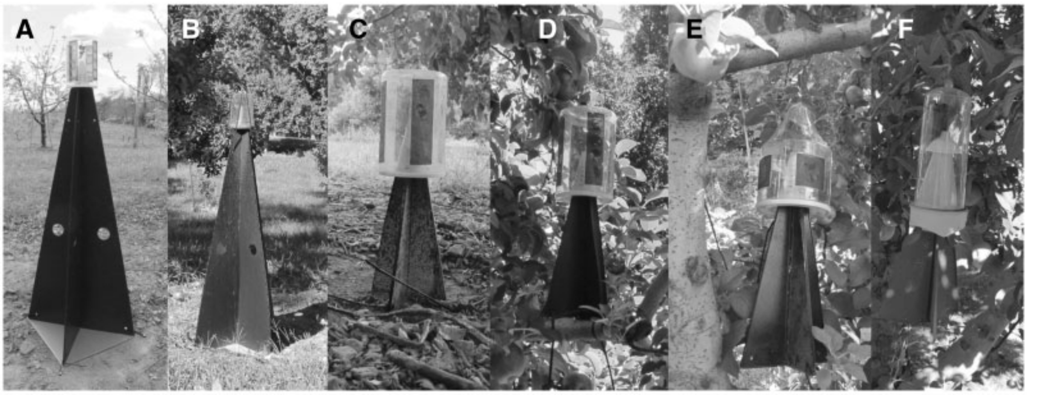

Fig. 1. Various *H. halys* trap types assessed for use in monitoring pest populations in 2013 and 2014 in Smithsburg, MD, at two commercial orchards, including (A) experimental standard large wooden pyramid, (B) large coroplast pyramid, (C) small, ground-deployed pyramid, (D) small, limb-attached pyramid, (E) small, hanging pyramid, and (F) commercial Rescue trap.

23 September. The season was split up into three sampling periods: early (15 April to 14 June), mid (15 June to 14 August), and late (15 August to 14 October).

Statistical Analysis. All analyses were performed with JMP Genomics v5.0 (SAS Institute, Inc.). To compare the effectiveness of each trap type and deployment location, adult and nymphal captures (response variables) were evaluated with two repeated-measure ANOVAs of the same form. Explanatory variables for each model included sampling year (2013 or 2014), trap type (wooden pyramid, coroplast pyramid, small hanging, small ground, small limb-attached, or Rescue traps), and sampling period (early, mid, or late). Repeated measures was run on each trap located at each site in a given year, and the variance–covariance matrix was modeled on a first-order autoregressive structure between sampling points. Because initial runs of the model revealed that the sampling year was not significant, data were pooled for the final analysis. Residuals did not conform to the expectations of a normal distribution, and were log-transformed for both adults and nymphs. Pairwise comparisons were performed after a significant result from the ANOVA, using Tukey's HSD for adults and for nymphs. For this analysis and all subsequent ones, we set $\alpha = 0.05$.

In order to evaluate if the biological information generated by alternative traps corresponded to that of our experimental standard, correlations were performed on the number of *H. halys* nymphs and adults captured per date between the experimental standard (wooden black pyramid) and each of the other trap types. Spearman rank correlations were performed, because the data were not normally distributed.

Because coroplast pyramid traps captured the greatest number of *H. halys* nymphs and adults (see below), correlations were performed between this trap design and all others to determine if seasonal captures in other trap designs reflected those of the most sensitive trap design (coroplast pyramid). Spearman rank correlations were performed because the data were not normally distributed.

Results

Season-Long Trap Captures. Overall, all the traps caught a combined total of 1,172 *H. halys* adults and 807 nymphs in 2013 and 1,140 adults and 629 nymphs in 2014. The patterns of trap captures in the two years were not significantly different from one another (repeated-measures ANOVA: $F = 0$; df = 1,180; $P = 1.0$), and as a result, the data were combined for the years for the rest of the analysis. Overall, trap design significantly affected trap captures of both *H. halys* adults ($F = 54.7$; df = 5, 180; $P < 0.0001$) and nymphs ($F = 69.6$; df = 5, 180; $P < 0.0001$; Fig. 2). Statistically, the greatest number of adults was captured in the coroplast pyramid trap compared with all other trap designs. This was followed by the standard plywood pyramid trap which had statistically equivalent captures to small pyramid traps deployed on the ground or hung from or attached to horizontal scaffold branches within the tree canopy. The Rescue trap, by contrast, had significantly lower adult captures compared with all other trap designs (Fig. 2).

For nymphal captures, the coroplast pyramid trap captured significantly more nymphs than all other trap designs except the standard wooden pyramid trap. Conversely, the Rescue trap captured significantly fewer nymphs than all other trap designs except the pyramid trap hung from a horizontal scaffold limb within the tree canopy (Fig. 2).

Early, Mid-, and Late-Season Captures. There were significant differences in the captures of adults ($F = 242.9$; df = 2, 180; $P < 0.0001$) and nymphs ($F = 100.0$; df = 2, 180; $P < 0.0001$; Table 1; Figs. 3 and 4) during different periods of the season. On average, traps caught almost five times more adults in the late season than the early and mid-season, while many more nymphs were caught in the mid- and late-season when compared with the early season when none were captured (Table 1; Fig. 3). The coroplast trap generally had the highest captures of adults regardless of the sampling period, which had on the order of 3- to 21-fold

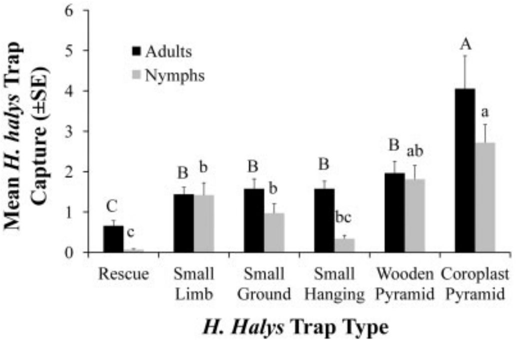

Fig. 2. Mean (± SE) effectiveness of traps for nymphal (gray bars) or adult (black bars) *H. halys* for April to October in 2013–2014 in Washington Co., MD. The coroplast traps were only deployed in one site starting from 2 July in 2013, and for the whole growing season in 2014 at the same site. Bars with shared letters are not significantly different from each other (Tukey's HSD, $\alpha = 0.05$), with the letter case representing pairwise comparisons within a particular life stage.

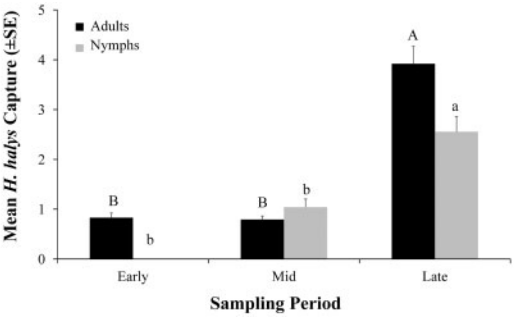

Fig. 3. Abundance of adult (black) or nymphal (gray) *H. halys* captured across trap types and aggregated for 2013 and 2014 in the early-, mid-, or late-season from Washington Co., MD. Bars with shared upper (within adult comparison) or lower case letters (within nymph comparison) are not significantly different from each other (Tukey's HSD, $\alpha = 0.05$).

Table 1. Summary of trap capture of nymphal and adult *H. halys* depending on trap configuration and per date within each sampling period across years in commercially managed orchards in Washington Co., MD

Trap type	Nymphs Mean ± SE	Adults Mean ± SE
Early[a]		
Coroplast Pyramid	0 ± 0a[b]	2.2 ± 0.8ABCD[c]
Wooden Pyramid	0 ± 0a	0.7 ± 0.1CD
Small Ground	0 ± 0a	0.3 ± 0.1BC
Small Hanging	0 ± 0a	0.9 ± 0.2B
Small Limb	0 ± 0a	1.0 ± 0.2D
Rescue	0 ± 0a	1.6 ± 0.4A
Mid		
Coroplast Pyramid	3.1 ± 0.8a	1.5 ± 0.4A
Wooden Pyramid	2.2 ± 0.6a	1.0 ± 0.2AB
Small Ground	0.4 ± 0.1bc	0.5 ± 0.1B
Small Hanging	0.2 ± 0.1c	1.0 ± 0.2AB
Small Limb	1.0 ± 0.3b	0.6 ± 0.1B
Rescue	0.1 ± 0.0c	0.4 ± 0.2B
Late		
Coroplast Pyramid	2.5 ± 0.5a	5.6 ± 1.2A
Wooden Pyramid	3.4 ± 0.8a	4.6 ± 0.9AB
Small Ground	2.8 ± 0.7a	4.5 ± 0.7AB
Small Hanging	0.9 ± 0.3b	3.2 ± 0.5BC
Small Limb	3.7 ± 0.9a	3.1 ± 0.5BC
Rescue	0.1 ± 0.0c	0.4 ± 0.1C

[a] Trapping started later for the Rescue (11 June) and coroplast pyramid trap (2 July) in 2013 than the other treatments (23 April).

[b] Tukey's HSD overall between the sampling periods and within a life stage; periods with shared letters are not significantly different from one another.

[c] Tukey's HSD between the trap types within a period and life stage; trap types with shared letters are not significantly different from one another.

greater captures of adults than the lowest performing trap. In terms of nymphal captures, the wooden and coroplast traps performed equally well in the mid-season, while all the traps performed equally well in the late-season, with the exception of Rescue and the small hanging trap (Fig. 3; Tukey's HSD).

Correlation Among the Experimental Standard Trap and Other Trap Designs. There were strong significant correlations among adult captures in the experimental standard pyramid traps and those found in the small ground (Spearman rank correlation: $\rho = 0.802$; $P < 0.0001$; Fig. 5B), small hanging ($\rho = 0.817$; $P < 0.0001$; Fig. 5C), and small limb traps ($\rho = 0.732$; $P < 0.0001$; Fig. 5D). However, adult captures were not significantly correlated between the experimental standard and the Rescue trap ($\rho = -0.186$; $P = 0.293$; Fig. 5A).

In contrast, there were strong significant correlations for nymphal captures among the experimental standard pyramids and all the other trap types, including the Rescue ($\rho = 0.668$; $P < 0.0001$; Fig. 6A), small ground ($\rho = 0.786$; $P < 0.0001$), small hanging ($\rho = 0.846$; $P < 0.0001$), and small limb trap ($\rho = 0.828$; $P < 0.0001$).

Correlation Among the Coroplast Pyramid Traps and Other Trap Designs. There was a strong significant correlation of adult captures in the standard plywood pyramid traps and coroplast pyramid traps (Spearman rank correlation: $\rho = 0.735$; $P < 0.0001$; Fig. 7A). Among the other traps, adult captures in coroplast pyramid traps were best correlated with the captures in the small ground traps ($\rho = 0.740$; $P < 0.0001$), and were not correlated at all with adult captures in the Rescue traps ($\rho = 0.04$; $P = 0.813$; Fig. 7B and C). The captures of adults in the coroplast pyramid traps were also well correlated with those found in the small hanging pyramid traps ($\rho = 0.587$; $P < 0.0001$; Fig. 7D), and the small limb trap ($\rho = 0.608$; $P < 0.0001$; Fig. 7E).

Moreover, the number of nymphs captured between coroplast and plywood pyramids were also strongly correlated ($\rho = 0.90$; $P < 0.0001$; Fig. 8A). In addition, all of the nymphal captures in the other trap designs were significantly correlated to those found in the coroplast pyramid traps (Fig. 8B–E). The trap that correlated the

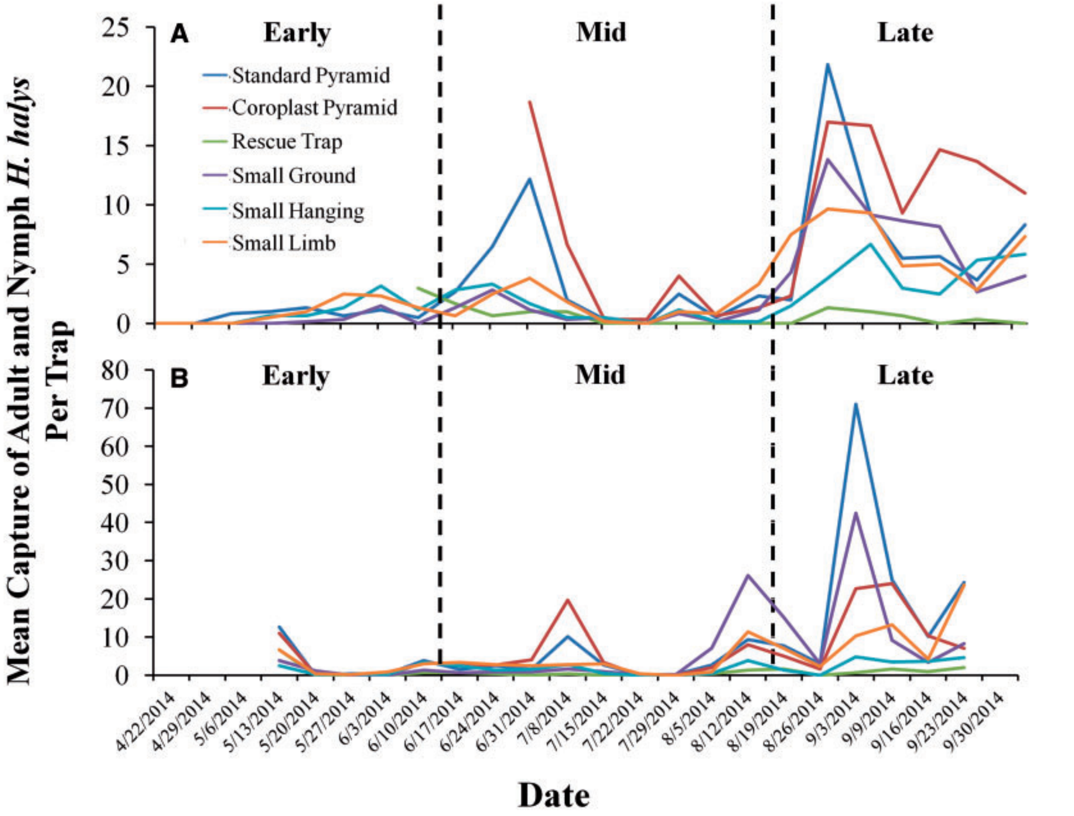

Fig. 4 Mean combined captures of adult and nymphal *H. halys* per trap through the course of the season for (A) 2013 and (B) 2014 at two sites, each with three replicates, in Washington Co., MD. Trapping started later in 2013 for the large coroplast pyramid (2 July) and the Rescue semi-pyramid trap (11 June) than the other traps (23 April). Traps were established throughout the entire year in 2014 for all treatments. For the sake of simplicity, the standard errors have been left off the lines. For interpretation of the lines, please refer to the online version of the article.

best with the nymphal captures in the coroplast trap was the small pyramid trap deployed on a horizontal limb ($\rho = 0.848$; $P < 0.0001$; Fig. 8E).

Discussion

Sampling for native stink bugs has had a long history in the United States, including California where common techniques include beat tray samples, visual inspection of broadleaf weedy hosts, and incidence of fruit injury (Ohlendorf 1999). In the eastern United States, monitoring native stink bugs in orchards has been best accomplished using large yellow pyramid traps in a similar style to the upright plywood pyramids used in this study for *H. halys* (Leskey and Hogmire 2005), with the major difference being the color of the trap (black instead of yellow for *H. halys*) and the attractant. The attractant found to be most effective for native stink bugs in previous studies was methyl 2,4,6-decadienoate (*Euschistus* spp. pheromone: Aldrich et al. 1991, 2007; Leskey and Hogmire 2005).

However, in the case of *H. halys*, methyl decatrienoate has been found to be an effective synergist on attraction when combined with the *H. halys* aggregation pheromone (Weber et al. 2014b). The standard experimental trap for *H. halys* has consisted of an upright, plywood black pyramid trap (Leskey et al. 2012c) baited with the aggregation pheromone and MDT synergist. This experimental standard trap has exhibited season-long attraction throughout the United States (Leskey et al. 2015a), but we have demonstrated here that several other traps have potential for effectively capturing *H. halys* through the course of the season. Moreover, we are obtaining similar biological information from these new trap designs and deployment locations in comparison with our standard pyramid trap.

We have established that there are good correlations between the captures in the wooden experimental standard pyramid compared with other trap designs for both adults and nymphs; these included the larger coroplast pyramid trap and small pyramid traps deployed on the ground or attached to the top of or hung from a scaffold limb. This signifies that the other trap designs may be able to supplant the experimental standard, while yielding the same biological information of relative seasonal dynamics of *H. halys* adults and nymphs in the field.

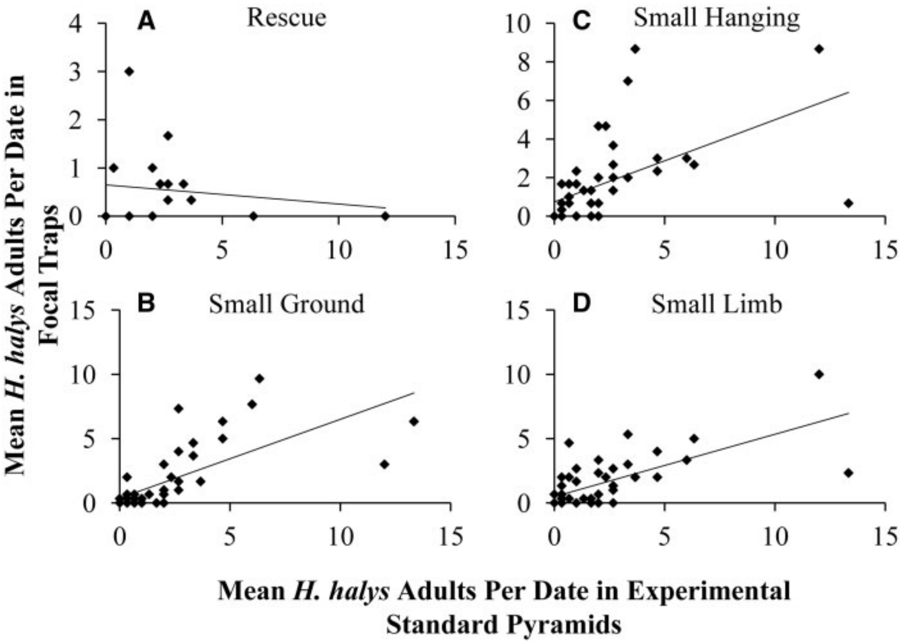

Fig. 5. Correlation between the mean trap capture of adult *H. halys* in a (A) Rescue, (B) small ground, (C) small hanging, or (D) small limb-based trap and the experimental standard pyramid traps on a given date over three replicates from April 2013 to October 2013 and April 2014 to October 2014 in Smithsburg, MD, at two orchards. The calculated best fit lines are as follows for each of the traps: small ground (y = 0.612 x + 0.372), small hanging (y = 0.426 x + 0.740), and small limb (y = 0.485 x + 0.484).

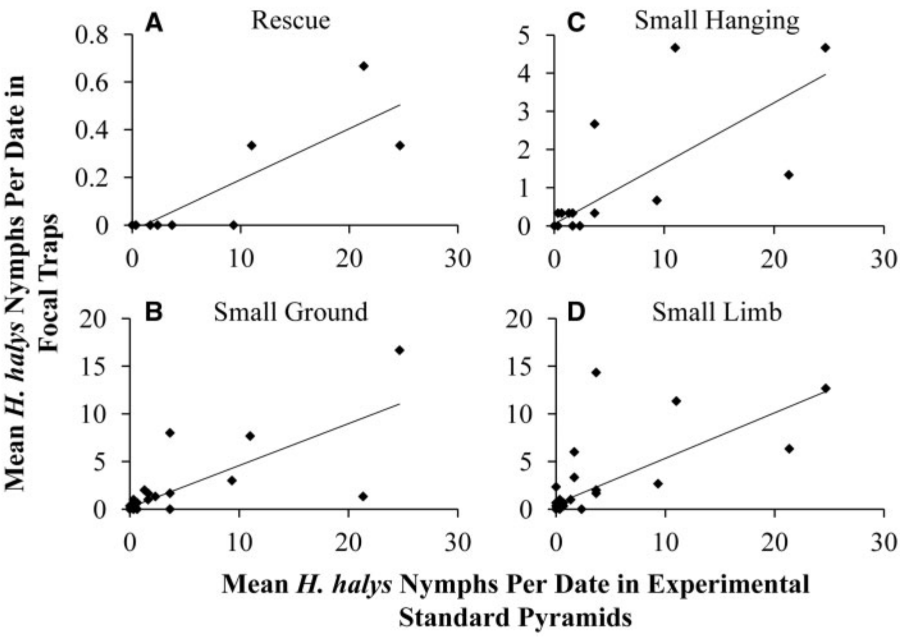

Fig. 6. Correlation between the mean trap capture of nymphal *H. halys* in a (A) Rescue, (B) small ground, (C) small hanging, or (D) small limb-based trap and the experimental standard pyramid traps on a given date over three replicates from April 2013 to October 2013 and April 2014 to October 2014 in Smithsburg, MD, at two orchards. The calculated best fit lines are as follows for each of the traps: Rescue (y = 0.021 x + 0.023), small ground (y = 0.440 x + 0.175), small hanging (y = 0.159 x + 0.053), and small limb (y = 0.478 x + 0.551).

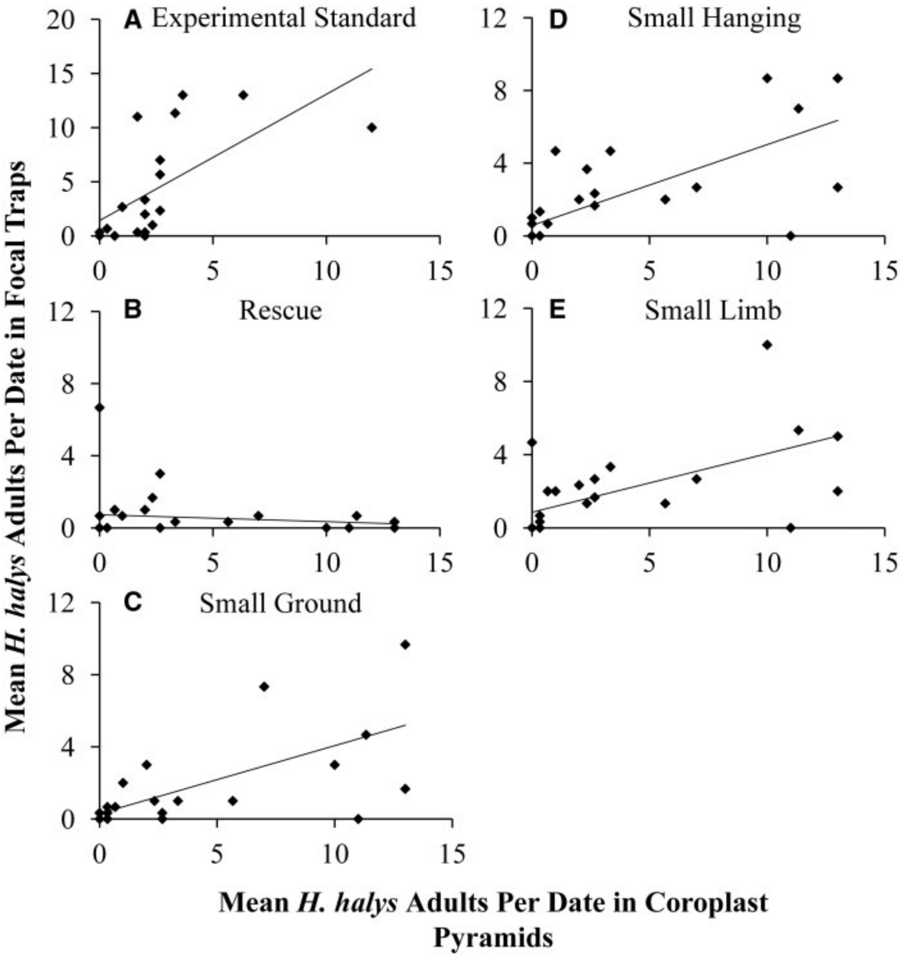

Fig. 7. Correlation between the mean trap capture of adult *H. halys* in a (A) experimental standard plywood pyramid, (B) Rescue, (C) small ground, (D) small hanging, or (E) small limb-based trap and the coroplast pyramid traps on a given date over three replicates from July 2013 to October 2013 and April 2014 to October 2014 in Edgemont, MD. The calculated best fit lines are as follows for each of the traps: experimental standard ($y = 1.167x + 1.412$), small ground ($y = 0.376x + 0.299$), small hanging ($y = 0.445x + 0.575$), and small limb ($y = 0.321x + 0.850$).

Notably, the much lighter coroplast trap, though similar in shape and color to the wooden pyramid trap, performed with equal or increased sensitivity for capturing adults and nymphs throughout the season. Moreover, the trap captures in the coroplast traps were strongly correlated with the numbers found in the wooden traps, indicating that information gleaned from the wooden traps may be transferable to interpretation of data from the coroplast traps. Coroplast pyramid traps can be purchased relatively inexpensively at US$31.50 (AgBio, Inc.) compared with wooden traps at US$45 apiece, an additional 25–50% cost in shipping, and the difficulty in their manufacture (J. Meneley, personal communication).

We found that reducing the size of pyramid trap also did not impair their effectiveness in capturing both *H. halys* adults and nymphs when compared to the most sensitive trap type. In fact, regardless of trap deployment location, the adult captures between the small limb, small ground, and small hanging plastic pyramids were statistically indistinguishable. The same was also true for captures of nymphs. The Rescue trap had fewer adult and nymphal captures compared with other trap types. Practically, this means that growers may be able to deploy the smaller and lighter traps in locations that will not interfere with normal orchard management practices such as mowing, while still gaining valuable biological information regarding the population dynamics of *H. halys*. Thus, the smaller traps deployed off the ground may be a better fit with other complimentary horticultural tactics in the orchard.

The use of economic thresholds in decision-making within the context of IPM programs is prevalent for pests in many agricultural systems. For example, economic thresholds are widely used in US cotton production for whitefly (Naranjo and Luttrell 2009), where roughly half the national acreage of cotton is scouted more than once per week (Williams 2007). One of the

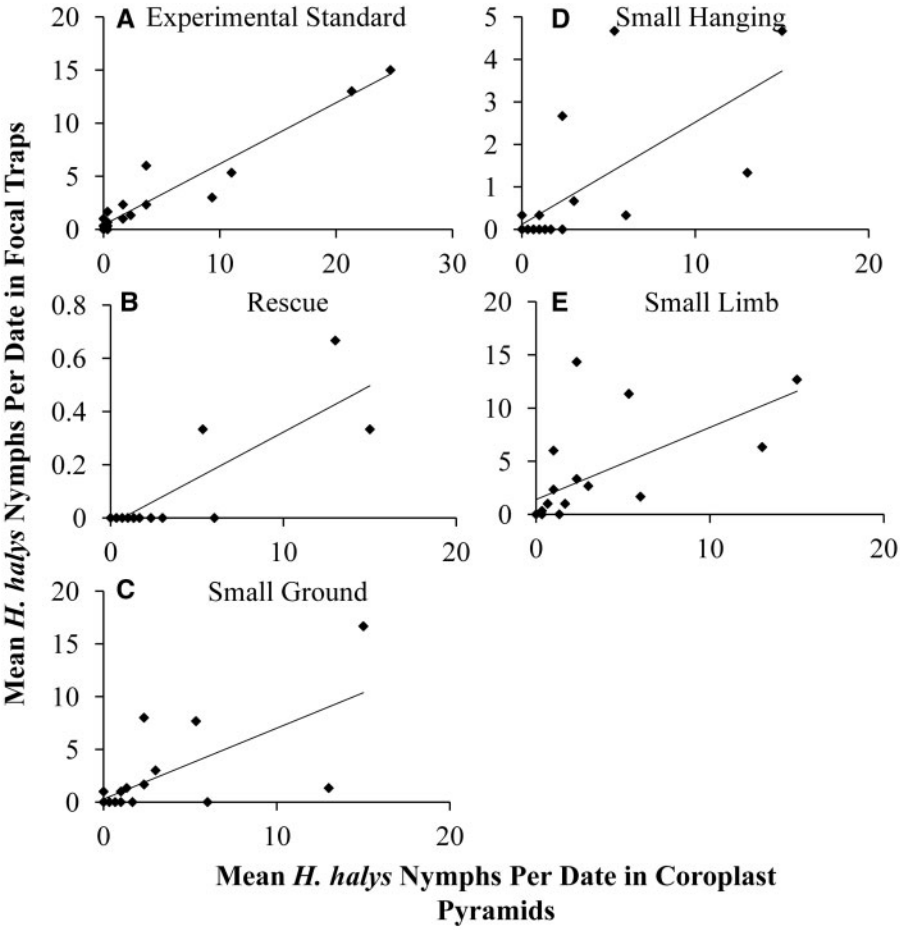

Fig. 8. Correlation between the mean trap capture of nymphal *H. halys* in a (A) experimental standard plywood pyramid, (B) Rescue, (C) small ground, (D) small hanging, or (E) small limb-based trap and the coroplast pyramid traps on a given date over three replicates from July 2013 to October 2013 and April 2014 to October 2014 in Edgemont, MD. The calculated best fit lines are as follows for each of the traps: experimental standard ($y = 0.575\,x + 0.419$), Rescue ($y = 0.0347\,x - 0.0242$), small ground ($y = 0.672\,x + 0.287$), small hanging ($y = 0.241\,x + 0.118$), and small limb ($y = 0.679\,x + 1.40$).

most widespread uses of insect pheromones in IPM is for monitoring to evaluate when a threshold has been reached (Baker 2009). For instance, before the introduction and outbreak of *H. halys*, economic thresholds for codling moth, oriental fruit moth, and apple maggot fly were regularly evaluated with traps containing species-specific blends of attractants, and these thresholds were the primary drivers for insecticide sprays in commercial apple in the northeastern United States (Prokopy and Mason 1996, MacHardy 2000). Ongoing work is developing new provisional economic thresholds for controlling *H. halys* in apples again (B.D. Short and T.C.L., unpublished data). The use of the formulas for the best fit lines between the trap types will aid in the translation of these provisional thresholds developed with the coroplast traps to meaningful numbers for these new trap types with the understanding that there will be some level of error around the newly calibrated thresholds. Nevertheless, it may be worth further investigation to validate the new thresholds before widespread adoption of new threshold numbers for when to spray for *H. halys* in apple.

Traps were effective throughout the growing season. However, the smaller traps were generally less effective at capturing nymphs compared with the coroplast and wooden pyramid traps, likely owing in part due to their smaller surface area. Importantly, the small hanging pyramid and Rescue traps yielded even lower captures of nymphs relative to the other traps, which is probably the result of their deployment strategy. Both traps are hung with a wire or string from a branch, resulting in a very narrow surface area from which nymphs walk down and gain access to the traps from the canopy. Moreover, *H. halys* nymphs have a natural tendency to climb up (not down) vertical surfaces, showing negative gravitaxis in behavioral trials (Acebes-Doria et al. unpublished data). Effectively, this means that these two trap types are less sensitive in accurately determining nymphal pressure in orchard blocks. Indeed, previous research has suggested that deployment strategy and location may be key in trapping the appropriate life stage of an insect (Drummond et al. 1984, Knight and Light 2005).

There are other factors that may influence the effectiveness of these traps that were beyond the scope of this paper. One of these is the use of differently formulated baits (Stelinski and Rogers 2008), which will become an issue as more manufacturers develop their unique patented blends of semiochemicals for baits targeting *H. halys*. However, because we used the same lure type in all traps, we can demonstrate the general efficacy of each trap design. The use of different baits will change provisional thresholds once again, and these will have to be recalibrated.

Another issue that remains unstudied is the distance from which each trap is attracting or sampling the *H. halys* population and the optimal spacing of traps for monitoring purposes. Morrison et al. (2015) has shown that adults will stay at a pheromone source for 24 h or more, and that they remain arrested around pheromone traps within a 2.5 m radius, but the area from which adults are being pulled is not known. As a result, captures in these traps are relative measures of *H. halys* population abundance.

From the current data, there is no single best trap design, as each has its associated advantages and disadvantages. Coroplast pyramids that were ground-deployed captured the greatest number of adults and nymphs, and season-long captures were strongly correlated with our experimental standard trap, indicating that this design was likely the most sensitive of those evaluated. Black pyramid traps have been shown to reliably capture adults and nymphs throughout the United States season long (Leskey et al. 2015a). The smaller ground-deployed and limb-attached pyramid traps also performed well in terms of captures of adults and nymphs and with strong correlations in season-long captures with both the experimental standard and coroplast pyramid. On the other hand, the hanging pyramid and Rescue traps caught fewer nymphs than other trap designs and there was no significant correlation in adult captures between coroplast or experimental standard pyramid trap and the Rescue traps; these trap designs and deployment strategies may not provide as sensitive biological information relative to other trap types.

It is important to note that these traps were deployed in apple orchards, and the results for these traps may differ depending on the crops in which they are employed. For example, plant species can affect the attractiveness of a trap through synergistic plant odors emitted (Krupke et al. 2001). However, plant architecture can also impact trap efficiency, as in the case of ground beetles and pitfall traps (Koivula et al. 2003). Indeed, certain types of plant architecture may increase or decrease the trapping efficiency by increasing or decreasing the visibility of the trap relative to the host plant. Taller, thicker host plants with complex canopies (e.g., asparagus: Morrison and Szendrei 2013) may obscure the visual signal provided by a trap, whereas a smaller, simpler host plant structure (e.g., cabbage: Bryant et al. 2013) may not depending on the deployment strategy. As a consequence, the trapping results of this study should be corroborated in other cropping systems with different host plants.

Effective monitoring is a vital tool for use in almost any integrated pest management program. Overall, we have shown that that smaller trap designs have the capacity to effectively capture nymphs and adults throughout the season, and that their information is biologically relevant to that collected prior using larger pyramid traps. This will make deploying traps easier for adoption by growers by decreasing the size of the trap and increasing the ease with which they can be set up and monitored. In combination with the fact that recent research has shown that less purified mixtures of stereoisomers in lures do not inhibit attraction of *H. halys* (Leskey et al. 2015b), a useful, reliable, and cheap monitoring tool seems to be forthcoming in the near future for growers. Future steps in refining the trap design for *H. halys* include testing the new semiochemical products being developed for *H. halys*, and further recalibration of provisional thresholds for spraying.

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