Ecology and Behavior

Improved Trap Designs and Retention Mechanisms for *Halyomorpha halys* (Hemiptera: Pentatomidae)

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Abstract

Current monitoring systems for the invasive *Halyomorpha halys* (Stål) (Hemiptera; Pentatomidae) in orchard agroecosystems rely on ground-deployed tall black pyramid traps baited with the two-component *H. halys* aggregation pheromone and pheromone synergist. Pyramid traps are comparatively costly, require considerable time to deploy and service, and may not be best suited to grower needs. Therefore, we evaluated other traps for *H. halys*, including modified pyramid traps (lures deployed on the outside), a canopy-deployed small pyramid, a pipe trap, delta traps, and yellow sticky cards in 2015 and 2016 in commercial apple and peach orchards. We also compared various *H. halys* killing agents for use in standard pyramid trap collection jars, including VaporTape kill strips, cattle ear tags, and plastic netting treated with various pyrethroids. Finally, we evaluated the effect of positioning the lures inside versus outside the collection jar on standard pyramid traps on overall captures. Among trap types, modified pyramid and pipe traps were most effective, capturing more adults than all other trap designs. Adult captures in small canopy-deployed pyramid, delta, and yellow sticky traps were lower, but significantly correlated with the standard black pyramid. Placing lures on the outside of collection jars on pyramid traps resulted in significantly greater captures and insecticide-impregnated netting was as effective for retaining bugs as VaporTape strips. These studies demonstrate that trapping systems for *H. halys* can be simplified and improved by modifying the trap design, lure deployment location, and/or killing agent.

Keywords: BMSB, brown marmorated stink bug, monitoring, integrated pest management

Effective monitoring tools for insect pests are an essential component of integrated pest management (IPM). Efficient traps can support management decisions such as timing of insecticide applications based on captures, thereby reducing production costs, nontarget effects, and secondary pest outbreaks (Toscano et al. 1974, Ragsdale et al. 2007). Invasive insect species can severely disrupt established agroecosystems (Szczepaniec et al. 2011, Leskey et al. 2012b), and can be particularly difficult to monitor because of general lack of knowledge about their behavior and ecology in the invaded range (Elton 1958, Lockwood et al. 2013).

*Halyomorpha halys* (Stål) (Hemiptera; Pentatomidae) is an invasive herbivore originating from Asia that currently has established populations in the United States, Canada, Western and Eastern Europe, and South America (Hoebeke and Carter 2003, Wermeling et al. 2008, Gariepy et al. 2014, Faiúndez and Rider 2017, Leskey and Nielsen 2018). *H. halys* is a major agricultural pest of a wide range of commodities including fruits, vegetables, field crops, and ornamentals, and has caused severe economic injury (American Western Fruit Grower 2011, Rice et al. 2014, Leskey and Nielsen 2018). In response, growers have relied on weekly insecticide applications, leading to increased production costs and secondary pest outbreaks (Leskey et al. 2012b).

In Asia, stink bug monitoring programs suggested that *H. halys* were cross-attracted to the aggregation pheromone of the oriental stink bug *Plautia stali* Scott (Hemiptera; Pentatomidae), methyl (2E,4E,6Z)-2,4,6-decatrienoate (MDT) (Tada et al. 2001a,b; Lee et al. 2002). This was confirmed later with invasive *H. halys* populations in the United States (Aldrich et al. 2007, Khrimian et al. 2008). In 2014, the two-component aggregation pheromone of *H. halys* was identified as (3S,6S,7R,10S)-11-epoxy-1-bisabolene-3-ol and (3R,6S,7R,10S)-11-epoxy-1-bisabolene 3-ol (PHER) (Khrimian et al. 2014). When deployed with visually attractive black pyramid...
traps (Leskey et al. 2012a), PHER and MDT provided effective season-long monitoring of H. halys adults and nymphs (Weber et al. 2014, Leskey et al. 2015, Morrison et al. 2015). These pyramid traps have been used as a decision support tool in apple orchards (Short et al. 2017) but are large, expensive, require considerable labor to deploy and service, and can interfere with farm operations such as chemical applications and mowing. Additionally, its collection jar requires venting modifications (Leskey and Hogmire 2005) and a killing mechanism such as 2,2-dichlorovinyl dimethyl phosphate (DDVP) VaporTape strips to prevent H. halys escape, adding additional costs and labor. In Asia, yellow sticky traps baited with pheromone lures are used to monitor P. stali (Toyama et al. 2015), although this trap had not been evaluated for H. halys.

The goals of this study were to refine H. halys trapping techniques to reduce costs and labor associated with trapping systems for H. halys. First, we evaluated H. halys captures in standard pyramid traps with five other trap designs that were either commercially available, less expensive, and/or potentially easier to deploy. We then evaluated five different H. halys killing mechanisms for use in collection jars atop the standard black pyramid traps, as well as the efficacy insecticide-treated netting. Finally, we compared the effect of lure positioning on captures in pyramid traps.

Methods
Trap Type
We evaluated H. halys adult and nymphal captures in the following traps (Fig. 1) deployed in commercial orchards: 1) standard black Coroplast pyramid traps (Dead-Inn Pyramid Trap, 1.2 m height, AgBio Inc., Westminster, CO); 2) experimental pipe traps (1.2 m height); 3) modified black Coroplast pyramid traps (Dead-Inn Pyramid Trap, 1.2 m height, AgBio Inc.); 4) smaller black pyramid traps (Dead-Inn Pyramid Trap, 0.29 m height, AgBio Inc.); 5) yellow back-foiling sticky cards (23 x 14 cm, Alpha Scents, West Linn, OR); and 6) orange delta traps (Pherocon VI Delta, Trece Inc, Adair, OK). Each trap was baited with a lure containing PHER (10 mg) and MDT (66 mg) (AgBio, Inc.). Lures were positioned above delta and sticky traps by attaching them to hanging wires with binder clips. Standard pyramid, small pyramid, and pipe traps had lures and 5 cm pieces of DDVP kill strips (Hercon VaporTape II, Hercon Environmental, Emigsville, PA) inside the vented collection jar (Joseph et al. 2013). Kill strips were replaced every other week. Standard pyramid traps consisted of Coroplast panels (1.07 m in height, 52 cm width at the base, 8.2 cm width at the top) topped with a clear plastic collection jar (16 x 10 x 10 cm H:L:W) with an inverted funnel cone lid (1.6 cm internal opening) (AgBio, Inc., Westminster, CO). Collection jars were vented on all four sides with 3 cm openings covered with vinyl-coated polyester screen (mesh size: 1 x 3 mm²).

The modified pyramid trap consisted of an unvented collection jar with lures attached to the outside top of the jar, and netting treated with 25% v/v lambda-cyhalothrin (a.i.22.8%) (Quest Outfitters, Sarasota, FL, No-See-Um-Mesh) attached to the inside funnel (~2.50 cm²) as a replacement for VaporTape kill strips. Mesh netting was soaked in insecticide solution for 1 h, and then air-dried for 24 h in a fume hood. Nets were cut to cover the entire surface area of the inside funnel of jar tops of pyramid traps and attached with glue. Pipe trap bases were constructed from 81 cm long PVC pipe (10 cm diameter), painted canary yellow (Rust-Oleum, Vernon Hills, IL) and wrapped with black charcoal fiberglass insect screen (18 threads/2.5 cm) (Saint-Gobain ADFORS, Malvern, PA) (Jasinski and Welty, personal communication).

Standard and modified pyramid traps were deployed on the ground between trees in the border row or at row ends. Pipe bases were placed over a 0.91 m fence post that was staked into the ground and also deployed between trees or at the row ends. Smaller pyramid (see Morrison et al. 2015), delta, and sticky traps were deployed on scaffold limbs in the tree canopy (see Morrison et al. 2015) while delta and sticky traps were hung from scaffold limbs in the tree canopy. In 2015, traps were deployed from 27 May through 28 September at five commercial apple orchards and from 20 April through 30 September at three commercial peach orchards (see Table 1 for locations). In 2016, traps were deployed from 3 May through 11 October at three commercial apple orchards and from 3 May through 13 September at two commercial peach orchards. Three replicates of each trap per site were positioned randomly at 50 m intervals along orchard edges adjacent to woods. Year and orchard type (apple or peach) were analyzed separately, because preliminary models showed significant differences in abundance of H. halys. Total season long captures of H. halys adult and nymphs were compared among trap types using a generalized linear model with repeated measures by time. The model used a quasi-poisson distribution to account for overdispersion in the data set and appropriately adjust standard error values (Aho 2014). Tests for significance employed log-likelihood ratio tests based on a χ²-distribution. Upon a significant result from the model, pairwise comparisons employed Tukey’s honest significant difference (HSD). Afterward, standard black pyramid trap captures were compared with other trap types.

![Fig. 1. Trap types used to capture adult and nymphal H. halys captures: A) standard black pyramid, B) pipe, C) modified pyramid, D) small hanging pyramid, E) yellow sticky, and F) orange delta trap.](https://academic.oup.com/jee/advance-article-abstract/doi/10.1093/jee/toy185/5048228)
using Pearson’s correlation to understand if the phenological information about captures in the other trap types was similar to that from standard black pyramid traps.

Killing Agents
We compared the efficacy of the following retention/killing mechanisms for *H. halys* adults and nymphs in standard black pyramid traps: 1) cattle ear tags (Python Magnum, Southern States, Richmond, VA); 2) insecticide netting (Quest Outfitters, Sarasota, FL, No-See-Um-Mesh) (a.i. 22.8% lambda-cyhalothrin soaked for 18 h); 3) insecticide netting (a.i. 22.8% lambda-cyhalothrin treatment soaked for 1 h); 4) VaporTape kill strips cut in half and ear tagged; and 5) VaporTape kill strips with no replacement; and 6) control (no killing mechanism). VaporTape kill strips (a.i. = dichlorovinyl) were cut in half and ear tagged (a.i. = zeta-cypermethrin) were cut to have equal surface area as kills strips, both of these were hung from the inside top of collection jars. All traps were baited with PHER (10 mg) and MDT (66 mg) and deployed along orchard and wood line edges at the Appalachian Fruit Research Station in Kearneysville, WV from 2 September through 22 October 2016. Each location contained three replicates, and traps were spaced 50 m apart along orchards and wood lines from 13 September through 27 September 2013. VaporTape kill strips were replaced every other week. Traps were emptied each week and the number of *H. halys* were compared using ANOVA. All statistical analyses were conducted using SAS (SAS 2004).

Lure Position
We compared *H. halys* captures in standard pyramid traps with lures deployed in the following positions: 1) hanging from inside the vented collection jar (standard position); 2) hanging from the outside middle of collection jar; and 3) hanging from the pyramid base, 30 cm below the bottom of collection jars. Traps were spaced 50 m apart along orchards and wood lines from 13 September through 27 September 2013. VaporTape kill strips were replaced every other week. Traps were emptied each week and the number of *H. halys* were compared using ANOVA. All statistical analyses were conducted using SAS (SAS 2004).

Results
Trap Type
Total *H. halys* captures in apple orchards in 2015 and 2016, respectively, were 1,991 nymphs and 3,298 adults, and 3,492 nymphs and 5,378 adults. In 2015, modified pyramid traps captured significantly more adult *H. halys* ($\chi^2 = 214.4; df = 5; P < 0.0001$) and pipe traps ($\chi^2 = 325.7; df = 5; P < 0.0001$) captured significantly more nymphs compared with standard pyramid, small pyramid, yellow sticky cards and delta traps (Fig. 2). In 2016, modified pyramid traps again captured more adults compared with all other traps except pipe traps ($\chi^2 = 384.3; df = 5; P < 0.0001$) and modified pyramid, pipe, small pyramid, and standard pyramids traps captured significantly greater numbers of nymphs compared with yellow sticky and delta traps ($\chi^2 = 174.0; df = 5; P < 0.0001$) (Fig. 2). In both years, adult captures in standard pyramid traps were significantly correlated with adult captures in all other trap types, and nymphal captures in standard pyramid traps were correlated with captures in all other traps except yellow sticky traps in 2015 and delta traps in 2016 (Table 2).

In peach orchards during 2015 and 2016, respectively, combined captures totaled 153 nymphs and 435 adults, and 829 nymphs and 1,080 adults. In 2015, modified pyramid and pipe traps captured significantly more adults than all other trap types ($\chi^2 = 241.8; df = 5; P < 0.0001$), and pipe traps captured significantly more nymphs compared with all traps except modified pyramids ($\chi^2 = 261.7; df = 5; P < 0.0001$). In 2016, modified pyramids captured greater numbers of adults ($\chi^2 = 188.6; df = 5; P < 0.000$) and nymphs ($\chi^2 = 120.2; df = 5; P < 0.0001$) compared with small pyramid, yellow sticky, and delta traps (Fig. 3). Adult captures in standard pyramid traps were correlated with all other trap types except for delta traps in 2016. For nymphs, captures in standard pyramid traps were correlated with small and modified pyramid traps in both years and with yellow sticky traps and pipe traps in 2015 and 2016, respectively (Table 3).

<table>
<thead>
<tr>
<th>Location (Co., State)</th>
<th>Year</th>
<th>Crop</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkeley, WV</td>
<td>2015–2016</td>
<td>Apple</td>
<td>39°23'38.38&quot;N</td>
<td>78°4'47.99&quot;W</td>
</tr>
<tr>
<td>Jefferson, WV</td>
<td>2015</td>
<td>Apple</td>
<td>39°22'25.59&quot;N</td>
<td>77°51'57.07&quot;W</td>
</tr>
<tr>
<td>Washington, MD</td>
<td>2015</td>
<td>Apple</td>
<td>39°40'25.20&quot;N</td>
<td>77°32'25.80&quot;W</td>
</tr>
<tr>
<td>Washington, MD</td>
<td>2015–2016</td>
<td>Peach</td>
<td>39°39'32.20&quot;N</td>
<td>77°33'16.86&quot;W</td>
</tr>
<tr>
<td>Frederick, VA</td>
<td>2016</td>
<td>Apple</td>
<td>39°6'12.16&quot;N</td>
<td>78°17'18.63&quot;W</td>
</tr>
<tr>
<td>Cecil, MD</td>
<td>2015</td>
<td>Apple</td>
<td>39°40'29.38&quot;N</td>
<td>75°49'28.44&quot;W</td>
</tr>
<tr>
<td>Carroll, MD</td>
<td>2015</td>
<td>Peach</td>
<td>39°36'36.57&quot;N</td>
<td>77°3'14.28&quot;W</td>
</tr>
</tbody>
</table>

Table 1. Location and GPS coordinates of field sites comparing *Halyomorpha halys* captures among different trap types
Killing Agent

Traps with ear tags yielded significantly greater total captures of *H. halys* compared with control traps and kill strip augmented traps that were not replaced following deployment (*F* = 3.44; df = 5, 206; *P* = 0.005). Traps containing insecticide netting (18 h treatment) and ear tags yielded greater numbers of dead adults compared with control traps (*F* = 4.13; df = 5, 206; *P* = 0.0014). However, traps with ear tags had similar numbers of live adults as control traps, whereas traps with insecticidal netting and kill strips that were replaced every...

Fig. 2. Mean weekly adult and nymphal *H. halys* captures by trap type in apple orchards in 2015 and 2016. Capitalized letters represent pairwise comparisons among adult captures, while lower case letters represent pairwise comparisons among nymphal captures. Bars with shared letters are not significantly different from each other (*α* = 0.05, Tukey’s HSD).

Fig. 3. Mean weekly adult and nymph *H. halys* captures by trap type in peach orchards in 2015 and 2016. Capitalized letters represented pairwise comparisons among adult captures, while lower case letters represent pairwise comparisons among nymphal captures. Bars with shared letters are not significantly different from each other (*α* = 0.05, Tukey’s HSD).

Table 2. Pearson correlation coefficient between captures of *H. halys* in standard black pyramid traps and other traps in apple orchards in 2015 and 2016

<table>
<thead>
<tr>
<th>Trap type</th>
<th>Adults</th>
<th>Nymphs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>r</em></td>
<td>df</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Sticky Card</td>
<td>0.732</td>
<td>132</td>
</tr>
<tr>
<td>Modified Pyramid</td>
<td>0.759</td>
<td>132</td>
</tr>
<tr>
<td>Pipe Trap</td>
<td>0.858</td>
<td>132</td>
</tr>
<tr>
<td>Small Pyramid</td>
<td>0.729</td>
<td>132</td>
</tr>
<tr>
<td>Delta Trap</td>
<td>0.266</td>
<td>132</td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Sticky Card</td>
<td>0.447</td>
<td>64</td>
</tr>
<tr>
<td>Modified Pyramid</td>
<td>0.626</td>
<td>64</td>
</tr>
<tr>
<td>Pipe Trap</td>
<td>0.411</td>
<td>64</td>
</tr>
<tr>
<td>Small Pyramid</td>
<td>0.477</td>
<td>64</td>
</tr>
<tr>
<td>Delta Trap</td>
<td>0.329</td>
<td>64</td>
</tr>
</tbody>
</table>

*ns* = not significant (*P* > 0.05), *P* < 0.05, **P* < 0.01, ***P* < 0.001.

Table 3. Pearson correlation coefficient between captures of *H. halys* in standard black pyramid traps and the following traps in peach orchards in 2015 and 2016

<table>
<thead>
<tr>
<th>Trap type</th>
<th>Adults</th>
<th>Nymphs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>r</em></td>
<td>df</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Sticky Card</td>
<td>0.745</td>
<td>60</td>
</tr>
<tr>
<td>Modified Pyramid</td>
<td>0.881</td>
<td>60</td>
</tr>
<tr>
<td>Pipe Trap</td>
<td>0.950</td>
<td>60</td>
</tr>
<tr>
<td>Small Pyramid</td>
<td>0.722</td>
<td>60</td>
</tr>
<tr>
<td>Delta Trap</td>
<td>0.040</td>
<td>60</td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow Sticky Card</td>
<td>0.556</td>
<td>40</td>
</tr>
<tr>
<td>Modified Pyramid</td>
<td>0.587</td>
<td>40</td>
</tr>
<tr>
<td>Pipe Trap</td>
<td>0.992</td>
<td>40</td>
</tr>
<tr>
<td>Small Pyramid</td>
<td>0.591</td>
<td>40</td>
</tr>
<tr>
<td>Delta Trap</td>
<td>0.316</td>
<td>40</td>
</tr>
</tbody>
</table>

*ns* = not significant (*P* > 0.05), *P* < 0.05, **P* < 0.01, ***P* < 0.001.

*Test not possible because of no captures of nymphs in the delta traps during the season.*
two weeks yielded significantly fewer live adults compared with control 
traps ($F = 11.93; \text{df} = 5, 206; P < 0.0001$) (Table 4). Traps with 
insecticidal netting (both 18 h and 1 h treatments) contained 
significantly greater numbers of dead nymphs compared with control 
traps ($F = 5.77; \text{df} = 5, 206; P < 0.0001$). The overall number of live 
nymphs in traps was low (190 individuals), therefore statistical 
analysis was not conducted.

Traps containing netting treated with lambda-cyhalothrin yielded 
significantly greater numbers of dead H. halys adults compared with 
control traps ($F = 3.1; \text{df} = 4, 120; P = 0.016$), and those with netting 
treated with lambda-cyhalothrin, or zeta-cypermethrin and bifenthrin 
(both 10 and 25% V/V) had fewer live adults compared with traps 
containing pyrethrin-treated nets or controls ($F = 6.22; \text{df} = 4, 120; P = 0.0002$) (Table 5). No statistical difference was observed 
among insecticide treated nets for live nymphs. Only two dead 
nymphs were recorded across all treatments; therefore, no statistical 
analyses were performed on dead nymphs.

Lure Position
Greater numbers of bugs were captured when lures were placed 
on the outside of jar tops compared with lures placed inside of 
jar tops ($F = 5.14; \text{df} = 2, 24; P = 0.015$), and captures for lures 
placed high and low on outside of traps were not statistically dif-
ferent (Fig. 4).

Discussion
We have demonstrated varying effectiveness of different styles of 
monitoring traps for H. halys. Although several monitoring and 
detection devices have been developed for H. halys (Leskey et al. 
2012a,b; Nielsen et al. 2013; Rice et al. 2015), ground-deployed 
standard black pyramid traps are considered the most sensitive, 
providing season-long captures of adults and nymphs (Joseph et al. 
2013, Morrison et al. 2015), but are more costly than other 
commercially available traps. Replacing pyramid traps with simpler, less 
expensive traps may increase adoption of H. halys monitoring, thus 
potentially reducing nontarget effects and secondary pest outbreaks 
associated with calendar-based insecticide applications (Rice et al. 
2015). Although sticky traps deployed in trees captured significantly 
fewer H. halys compared with ground-deployed modified pyramid 
and pipe traps, adult captures in both years and nymphal captures 
in 2016 were correlated with standard pyramid traps in both apple 
and peach orchards, suggesting these traps may adequately predict 
relative H. halys presence, abundance, and seasonal activity, while 
requiring less effort to enumerate individuals on traps. Moreover, 
a recent study by Morrison et al. (2017a) used clear sticky traps 
deployed on wooden posts and baited with PHER + MDT to moni-
tor H. halys populations in the eastern United States and in multiple 
European countries, although how these captures relate to those of 
standard pyramid traps is unknown. Deploying sticky traps attached 
atop wooden posts on the ground might reduce the number of struc-
tures by which foraging H. halys become arrested on, compared 
to the numerous and complex branching structures found within 
tree canopies (as we report here) (Leskey and Nielsen 2018). Thus, 
ground-deployed trap designs could be most sensitive for H. halys 
mobile life stages due to fewer options for foraging individuals 
to become arrested by pheromonal stimuli. Captures in ground-
deployed pyramid traps baited with PHER + MDT combination 
were used as decision support tools for H. halys in apple orchards, 
with insecticides applied only when a predetermined cumulative 
adult captures in traps were reached (Short et al. 2017). Thus, to 
move to simpler designs, further studies that compare alternate trap 
designs with the widely used standard pyramid trap, under varying 
population densities, must be conducted.

A killing agent is necessary for successful trapping of H. halys 
using pyramid traps with collection jars, as Leskey et al. (2012a) 
found a 250-fold increase in trap captures when a killing agent was 
added. This is quite different than native stink bugs such as Euschistus 
servus Say (Hemiptera; Pentatomidae), which can be contained within 
collection jars in the absence of a killing agent by simple mechanical 
modifications to the collection jar (Hogmire and Leskey 2006). The 
strong mobility of both adult and nymphal H. halys (Lee et al. 
2014, Lee and Leskey 2015) may account for these differences. In our 
studies, insecticide netting outperformed all other insecticide-based killing 
mechanisms including DDVP strips and cattle ear tags, having 
the greatest number of dead bugs and lowest number of live bugs

Table 4. Comparison of H. halys kill mechanisms in standard black pyramid traps

<table>
<thead>
<tr>
<th>Kill mechanism</th>
<th>Active ingredient</th>
<th>Total capture</th>
<th>Dead adults</th>
<th>Live adults</th>
<th>Dead nymphs</th>
<th>Live nymphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ear Tag</td>
<td>Zeta-cypermethrin</td>
<td>95.8 ± 18.6 A</td>
<td>63.5 ± 15.3 A</td>
<td>12.5 ± 3.5 AB</td>
<td>17.5 ± 5.2 AB</td>
<td>2.2 ± 0.7 AB</td>
</tr>
<tr>
<td>Net (18 h)</td>
<td>Lambda-cyhalothrin</td>
<td>73.4 ± 12.8 AB</td>
<td>51.8 ± 10.3 AB</td>
<td>0.06 ± 0.1 B</td>
<td>21.5 ± 5.8 AB</td>
<td>0.0 ± 0.0 C</td>
</tr>
<tr>
<td>Net (1 h)</td>
<td>Lambda-cyhalothrin</td>
<td>83.0 ± 17.5 AB</td>
<td>51.5 ± 12.8 ABC</td>
<td>0.1 ± 0.1 B</td>
<td>31.4 ± 9.8 A</td>
<td>0.0 ± 0.0 C</td>
</tr>
<tr>
<td>Kill Strip (replaced)</td>
<td>Dichlorvos</td>
<td>54.8 ± 10.0 AB</td>
<td>38.7 ± 8.0 ABC</td>
<td>0.1 ± 0.2 B</td>
<td>15.9 ± 4.3 ABC</td>
<td>0.1 ± 0.1 C</td>
</tr>
<tr>
<td>Kill Strip</td>
<td>Dichlorvos</td>
<td>34.3 ± 7.7 B</td>
<td>22.3 ± 5.5 BC</td>
<td>4.9 ± 1.3 B</td>
<td>6.3 ± 1.8 BC</td>
<td>0.8 ± 0.3 BC</td>
</tr>
<tr>
<td>Control</td>
<td>------</td>
<td>31.3 ± 6.4 B</td>
<td>9.9 ± 2.9 C</td>
<td>14.8 ± 14.8 A</td>
<td>4.1 ± 1.2 C</td>
<td>2.5 ± 0.6 A</td>
</tr>
</tbody>
</table>

Different letters within the same column indicate significant difference ($\alpha = 0.05$), Tukey’s HSD.

Table 5. Comparison of dead and alive H. halys adults and nymphs with different insecticidal nettings in standard black pyramid traps

<table>
<thead>
<tr>
<th>Active ingredient (%)</th>
<th>Trade name (v/v)</th>
<th>Dead adults</th>
<th>Live adults</th>
<th>Live nymphs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda-Cyhalothrin (22.8)</td>
<td>Warrior II (25%)</td>
<td>31.3 ± 10.3 A</td>
<td>0.8 ± 0.4 A</td>
<td>0.6 ± 0.4 ns</td>
</tr>
<tr>
<td>Zeta-cypermethrin (3.75) + Bifenthrin (11.25)</td>
<td>Hero (25%)</td>
<td>20.9 ± 5.6 AB</td>
<td>0.2 ± 0.1 A</td>
<td>0.3 ± 0.1 ns</td>
</tr>
<tr>
<td>Zeta-cypermethrin (3.75) + Bifenthrin (11.25)</td>
<td>Hero (10%)</td>
<td>22.3 ± 7.8 AB</td>
<td>0.9 ± 0.6 A</td>
<td>0.13 ± 0.1 ns</td>
</tr>
<tr>
<td>Pyrethrins (1.40)</td>
<td>Pyganic (25%)</td>
<td>11.1 ± 4.5 AB</td>
<td>10.1 ± 2.7 B</td>
<td>0.09 ± 0.06 ns</td>
</tr>
<tr>
<td>Control</td>
<td>------</td>
<td>9.5 ± 2.5 B</td>
<td>11.5 ± 4.1 B</td>
<td>0.8 ± 0.6 ns</td>
</tr>
</tbody>
</table>

Different letters within the same column indicate significant difference ($\alpha = 0.05$), Tukey’s HSD. Dead nymphs were not analyzed due to low captures.
in traps. Recent research has used deltamethrin-impregnated netting successfully as a kill mechanism to capture over 1,000 H. halys adults during the overwintering and early spring period in pheromone-baited traps in heated buildings and in areas surrounding buildings (Morrison et al. 2017b). Comparisons among pyrethroid-impregnated netting showed that lambda-cyhalothrin was the only netting that killed more adult H. halys than control traps. Current killing mechanisms such as vapor tape need to be replaced several times throughout the growing season (Morrison et al. 2015), whereas insecticide impregnated netting effectively kills stink bugs (Kuhar et al. 2017), and remains effective throughout the season (Martin et al. 2007). However, all of these insecticide kill mechanisms (ear tags, vapor tape, insecticide netting) require insecticide registrations for their use. On the other hand, sticky traps do not require new registrations, and have been widely adopted to monitor for pest species in diverse systems including greenhouses (Heinz et al. 1992), stored products (Hagstrum et al. 1994), vegetable crops (Cho et al. 1995), and orchard crops (Boivin et al. 1982, Hoddle et al. 2002).

Lure position on traps affected H. halys captures in our studies. Lures deployed on the outside of standard pyramid traps resulted in greater captures of H. halys compared to traps with lures inside collection jars in our studies. Lures positioned on the outside of traps likely increase the diffusion and plume reach of attractive semiochemicals as they are not confined in the small collection container with minimal air flow. Similar trends were observed in mosquito traps, with lures positioned on the outside of traps having greater captures than traps with lures on the inside (Ritchie et al. 2013). However, the optimal trap spacing or density is not known, but potentially could be resolved by quantifying the maximum dispersive distance of H. halys and plume reach of current lures, based on the methods developed by Miller et al. (2015). In preliminary trials using this methodology, traps baited with lures suggested that the trapping area of a single trap unit within a 12-h period was approximately 4.83 ha (Acebes-Doria, Rice and Leskey, unpublished data).

Overall, our results suggest that H. halys monitoring traps can be further improved to reduce cost and labor associated with deployment and maintenance. Although PHER + MDT have been proven to be attractive and reliable season-long stimuli for lures used in association with traps (Leskey et al. 2015), recent studies have identified ethyl (2E,4E,6Z)-decatrienoate (EDT) as an additional attractant for H. halys that enhanced trap captures (Rice et al. 2018). Combining EDT with MDT and PHER may further increase trap captures and overall sensitivity of monitoring systems. Moreover, pyramid traps also augmented with light sources could further enhance trap captures (Rice et al. 2017). Future studies should focus on direct comparisons of standard pyramid traps with some of these simpler alternative trap designs under a range of H. halys densities and across a larger geographical area to determine whether they can provide reliable and less expensive tools for monitoring this invasive species.

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