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Research

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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 IPM programs (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, Wermelinger et al. 2008, Gariepy et al. 2014, Faúndez 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 (2*E*,4*E*,6*Z*)-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 (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol and (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen 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-folding sticky cards (23 × 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 × 10 × 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 × 3 mm^2).

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 (~250 cm^2) 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 to 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 χ^2-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

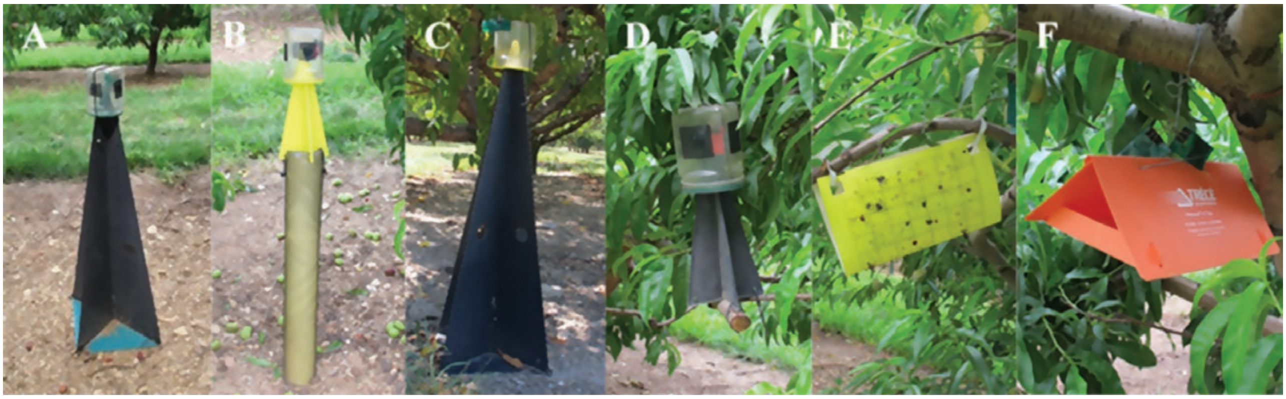

Fig. 1. Trap types used to capture adult and nymphal *H. halys* captures: A) standard black pyramid, B) pipe, C) modified pyramid, D) small hanging pyramid, E) yellow sticky, and F) orange delta trap.

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

Location (Co., State)	Year	Crop	Latitude	Longitude
Berkeley, WV	2015–2016	Peach and Apple	39°27′14.53″N	78°2′7.12″W
Berkeley, WV	2015–2016	Apple	39°23′38.38″N	78°4′47.99″W
Jefferson, WV	2015	Apple	39°22′25.59″N	77°51′57.07″W
Washington, MD	2015	Apple	39°40′25.20″N	77°32′25.80″W
Washington, MD	2015–2016	Peach	39°39′32.20″N	77°33′16.86″W
Frederick, VA	2016	Apple	39° 6′12.16″N	78°17′18.63″W
Cecil, MD	2015	Apple	39°40′29.38″N	75°49′28.44″W
Carroll, MD	2015	Peach	39°36′36.57″N	77°3′14.28″W

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 replaced every two weeks (Hercon Environmental, Emigsville, PA); 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 tags (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 and MDT lures. In 2014, three replicates of traps were deployed from 18 July through 3 October, along the edges of orchards and wood lines and spaced 50 m apart at the Appalachian Fruit Research Station in Kearneysville, WV. Treatment location was randomized each week. Traps were emptied each week and the number of live and dead *H. halys* adults and nymphs recorded. The effectiveness of each killing mechanism was compared using five separate repeated measure analysis of variance (ANOVA), with total *H. halys* captured, dead adults, live adults, dead nymphs, or live nymphs as the response variable. Dead nymphs and total *H. halys* captures were cube-root transformed to meet the normality assumption. Explanatory variables for each model included killing mechanism, replication, and week. Pairwise comparisons were analyzed using Tukey's HSD when ANOVA was significant.

We examined the efficacy of netting (Trimaco, Morrisville, NC) (see Trap Type for details) treated with the following pyrethroids to retain and kill *H. halys* in black pyramid traps (see Table 5 for details): 1) lambda-cyhalothrin (25% V/V; 2) zeta-cypermethrin and bifenthrin (10% V/V); 3) zeta-cypermethrin and bifenthrin (25% V/V); 4) pyrethrins (25% V/V); and 5) untreated control. 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. The locations of treatments were randomized each week. Traps were emptied each week and the number of live and dead *H. halys* nymphs and adults recorded. To compare the effectiveness of each insecticide-treated net, adult and nymphal captures were evaluated with four separate repeated measure ANOVA with dead adults, live adults, dead nymphs, or live nymphs as the response variable. Dead adults were cube-root transformed to meet the normality assumption. Explanatory variables for each model included insecticide, replication, and week. Pairwise comparisons were analyzed using Tukey's HSD when ANOVA was significant.

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* (χ^2 = 214.4; df = 5; P < 0.0001) and pipe traps (χ^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 (χ^2 = 384.3; df = 5; P < 0.0001); modified pyramid, pipe, small pyramid, and standard pyramids traps captured significantly greater numbers of nymphs compared with yellow sticky and delta traps (χ^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 (χ^2 = 241.8; df = 5; P < 0.0001), and pipe traps captured significantly more nymphs compared with all traps except modified pyramids (χ^2 = 261.7; df = 5; P < 0.0001). In 2016, modified pyramids captured greater numbers of adults (χ^2 = 188.6; df = 5; P < 0.000) and nymphs (χ^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).

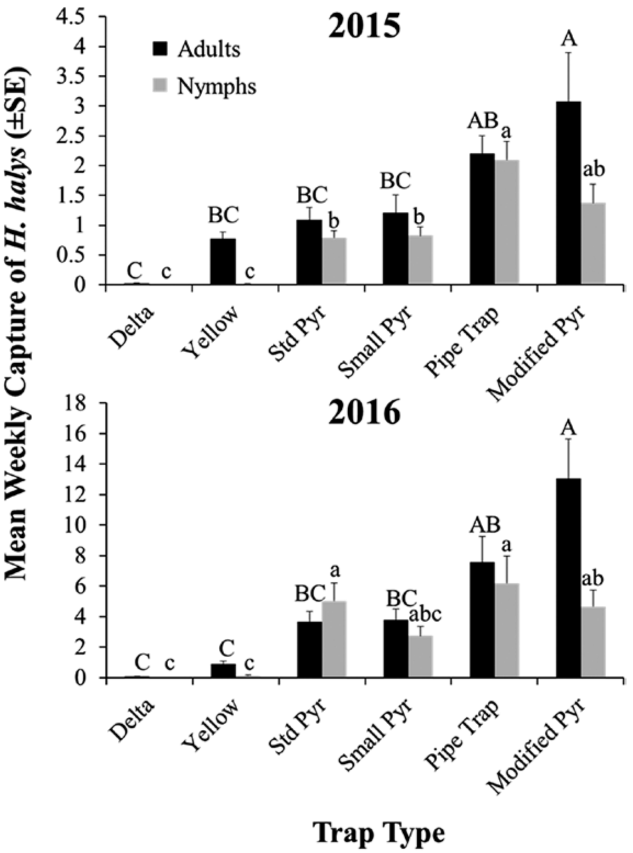

Fig. 2. Mean weekly adult and nymphal *H. halys* captures by trap type in apple orchards in 2015 and 2016. Capitalized letters represent pairwise comparisons among adult captures, while lower case letters represent pairwise comparisons among nymphal captures. Bars with shared letters are not significantly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

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

	Adults				Nymphs		
Trap type	*r*	df	*t*	*P*	*R*	*t*	*P*
2015							
Yellow Sticky Card	0.732	132	12.4	***	0.054	0.6	ns
Modified Pyramid	0.759	132	13.4	***	0.586	8.3	***
Pipe Trap	0.858	132	19.2	***	0.813	16.0	***
Small Pyramid	0.729	132	12.2	***	0.670	10.4	***
Delta Trap	0.266	132	3.2	**	0.440	5.6	***
2016							
Yellow Sticky Card	0.447	64	4.0	***	0.463	4.2	***
Modified Pyramid	0.626	64	6.4	***	0.857	13.3	***
Pipe Trap	0.411	64	3.6	**	0.582	5.7	***
Small Pyramid	0.477	64	4.3	***	0.852	13.0	***
Delta Trap	0.329	64	2.8	**	0.160	1.3	ns

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

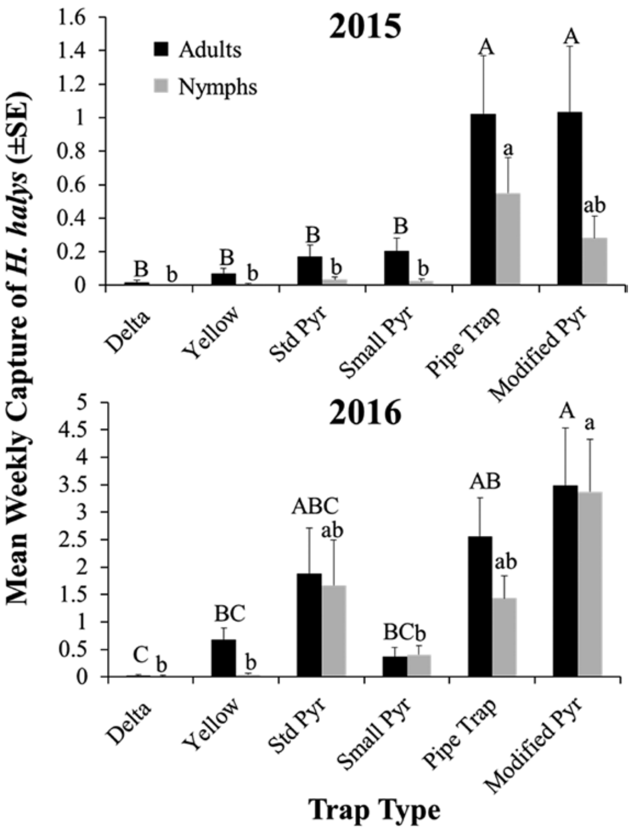

Fig. 3. Mean weekly adult and nymph *H. halys* captures by trap type in peach orchards in 2015 and 2016. Capitalized letters represented pairwise comparisons among adult captures, while lower case letters represent pairwise comparisons among nymphal captures. Bars with shared letters are not significantly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

Table 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

	Adults				Nymphs		
Trap type	*r*	df	*t*	*P*	*R*	*t*	*P*
2015							
Yellow Sticky Card	0.745	60	8.7	***	0.333	2.7	**
Modified Pyramid	0.881	60	14.4	***	0.363	3.0	**
Pipe Trap	0.950	60	23.6	***	0.157	1.2	ns
Small Pyramid	0.722	60	8.1	***	0.424	3.6	**
Delta Trap	0.040	60	0.3	ns	[a]-	-	-
2016							
Yellow Sticky Card	0.556	40	4.2	**	0.295	2.0	ns
Modified Pyramid	0.587	40	4.6	***	0.753	7.2	***
Pipe Trap	0.929	40	15.9	***	0.850	10.2	***
Small Pyramid	0.591	40	4.6	***	0.587	4.6	***
Delta Trap	0.316	40	2.1	*	0.028	0.2	ns

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

[a] Test not possible because of no captures of nymphs in the delta traps during the season.

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 two weeks yielded significantly fewer live adults compared with control traps ($F = 11.93$; 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 ($F = 5.77$; 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 ($F = 3.1$; 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 ($F = 6.22$; 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 ($F = 5.14$; df = 2, 24; $P = 0.015$), and captures for lures placed high and low on outside of traps were not statistically different (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 monitor *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 structures 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

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

Different letters within the same column indicate significant difference (α = 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

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

Different letters within the same column indicate significant difference (α = 0.05), Tukey's HSD. Dead nymphs were not analyzed due to low captures.

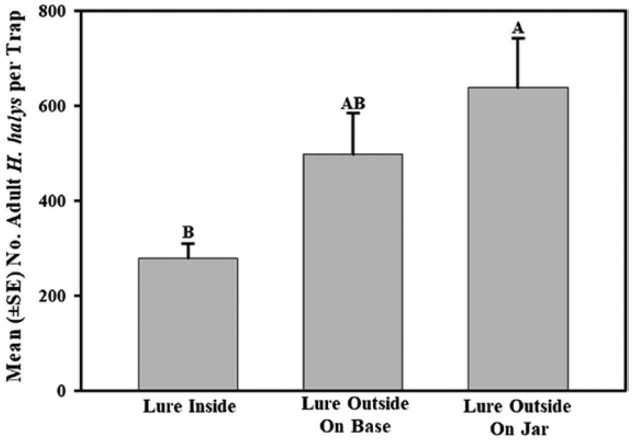

Fig. 4. Comparison of total *H. halys* mean captures in standard black pyramid traps with lures placed inside jar tops, outside on top of jar tops, and at the base of the pyramid. Bars with shared letters are not significantly different from each other (α = 0.05, Tukey's HSD).

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 (2*E*,4*E*,6*Z*)-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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