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REVIEW

Review of the chemical control research on *Halyomorpha halys* in the USA

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Abstract The invasive brown marmorated stink bug *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) has become a serious economic pest in parts of the USA, and control tactics are often needed in order to avoid crop losses in tree fruit and other crops. Chemical control is usually the most effective and efficient tactic for preventing damage in crops. Researchers have tested a wide range of insecticides using laboratory and field experiments to determine the best options for *H. halys* control in the USA. This review summarizes that work and describes current practices with regard to insecticide options for *H. halys*.

Keywords *Halyomorpha halys* · Brown marmorated stink bug · Chemical control · Insecticides

Key message

- A number of pyrethroids, organophosphates, carbamates, organochlorines, and neonicotinoids provide effective control of *H. halys*.
- High variability of effectiveness can occur with insecticides, based on breakdown of the residue over time and recovery of insects after initial intoxication.
- Most of the insecticides available to growers for *H. halys* control are broad-spectrum in their activity and thus not compatible with most IPM systems.

Special Issue: The brown marmorated stink bug Halyomorpha halys an emerging pest of global concern.

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Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) was first detected in the USA in the late 1990s (Hoebeke and Carter 2003). This invasive species has become a serious agricultural pest in the mid-Atlantic region of the country where the bug feeds on tree fruit (Nielsen and Hamilton 2009; Leskey et al. 2012a), various vegetable crops (Kuhar et al. 2012g), soybean (Nielsen et al. 2011; Owens et al. 2013), and other crops (Basnet et al. 2014; Rice et al. 2014; Basnet et al. 2015). In 2010, high densities of *H. halys* caused as much as 100% crop loss in some apple and peach orchards in the Eastern USA. (Leskey et al. 2012b, c). In addition, insecticide spray programs that were recommended for native stink bugs failed to provide satisfactory control in some cases (Leskey et al. 2012b), which brought to light an immediate quest to better understand chemical control of this invasive pest in the interest of short-term mitigation.

Lee et al. (2013a) provide an excellent summary of the effectiveness of insecticides on *H. halys* based on laboratory and field experiments conducted in Asia. In that publication, 35 different insecticides, including chlorinated hydrocarbons, organophosphates, carbamates, pyrethroids, neonicotinoids, the phenylpyrazole fipronil, and combination products containing two of the aforementioned groups, were reported to provide excellent control of *H. halys* in laboratory assays where bugs were treated directly (Saito et al. 1964; Fujisawa 2001; Funayama 2002; Bae et al. 2008), or exposed to dry insecticide residue (Fujisawa 2001), or in semi-field experiments where bugs were caged on treated plants (Qin 1990; Chung et al. 1995; Fujisawa 2001). However, many of the insecticides are not registered for use on critical crops in the USA or also performed poorly in other experiments conducted in Asia (Lee et al. 2013a). Consequently, there has been great impetus for additional insecticide testing on *H. halys*. Over the past few years, researchers in the USA have evaluated a wide range of insecticides using laboratory and field experiments to determine the best options for *H. halys* control. Herein, we review this work.

Laboratory assays of insecticides

Residual impact of insecticides and the subsequent recovery of moribund insects is an important aspect of insecticide application IPM programs, especially for orchards with border spray or an alternate row spray program. Multiple laboratory studies have examined the residual effect of insecticides on *H. halys* by assessing mortality and mobility (Nielsen et al. 2008; Kuhar et al. 2012; Leskey et al. 2012a; Lee et al. 2013b). Nielsen et al. (2008) conducted one of the first insecticide efficacy experiments on *H. halys* in the USA using a treated scintillation glass-vial bioassay and showed that the pyrethroid insecticides bifenthrin, beta-cyfluthrin, lambda-cyhalothrin, cyfluthrin, and fenpropathrin had the highest toxicity (lowest LC_{50} levels) to *H. halys* followed by the neonicotinoids dinotefuran and thiamethoxam. Acetamiprid was less toxic than the other neonicotinoids, and the organophosphate phosmet was considerably less toxic than the other insecticides tested, having LC_{50} values up to 3.6-fold higher than bifenthrin, which was the most toxic insecticide to *H. halys* among those tested. These researchers also demonstrated that the toxicities of most of the insecticides were similar for adult males and females and that nymphs were typically more susceptible to insecticides than adults.

Leskey et al. (2012b) investigated the efficacy of 37 insecticides against *H. halys*. Insecticides were applied at recommended spray tank concentrations and allowed to dry for 18 h on a glass Petri dish. Adult *H. halys* were exposed to an insecticide residue for 4.5 h and then monitored daily for survivorship over a 7-d period. Among all materials evaluated, the pyrethroids, bifenthrin, fenpropathrin, and permethrin, the organophosphates dimethoate, malathion, methidathion, chlorpyrifos, and acephate, the carbamate methomyl, and the organochlorine endosulfan, were the most efficacious (Table 1). These researchers also reported that *H. halys* adults recovered from a moribund state after exposure to acetamiprid and several of the pyrethroids over the 7-d period.

Krawczyk et al. (2011) evaluated the efficacy of high field rates of 41 insecticides using a topical application bioassay where each individual adult bug was treated dorsally with 2 µl of solution. A high mortality was achieved with bifenthrin, methomyl, endosulfan, and most of the neonicotinoids except thiacloprid (Table 1). Bifenthrin significantly outperformed the other pyrethroids. In addition, combination products that included a pyrethroid and neonicotinoid, or either of these with the diamide chlorantraniliprole, all resulted in very high mortality.

Kuhar et al. (2012a) tested field-rate concentrations of 22 insecticides using a green bean (*Phaseolus vulgaris* L.) dip bioassay. Mortality of *H. halys* nymphs and adults was assessed by recording the number of dead + moribund after 72-h exposure to the treated bean in a Petri dish. High mortality of nymphs was observed with most of the insecticides except esfenvalerate and flonicamid (Table 1). Adult mortality was lower than nymphal mortality for several of the insecticides including acephate, oxamyl, zeta-cypermethrin, fenpropathrin, lambda-cyhalothrin, and acetamiprid. These results support those of Nielsen et al. (2008) that *H. halys* adults are typically harder to kill than nymphs.

In general, after insects are exposed to treatments in bioassays, researchers typically consider insects to be alive if they are moving without uncoordinated activities, knocked down if they are uncoordinated but still respond to stimuli, and dead if insects show no response to stimuli. In order to assess the quick "knock-down" effect of insecticides, Lee et al. (2013b) evaluated 28 insecticides for their speed of activity and impact on locomotory behavior and mobility of adult *H. halys*. Horizontal distance and angular velocity were measured for individuals exposed to dry insecticide residue in glass arenas for 4.5 h. Eight out of nine pyrethroid insecticides caused uncoordinated and irregular movement within 10 min after exposure, and incapacitation after 1.5 h. Phosmet and diazinon exposure increased movement of the stink bug. Increased movement may foster dispersal to an untreated area and subsequent recovery of the pest. By contrast, there was no immediate effect when *H. halys* were exposed to organophosphate, carbamate, or neonicotinoid residues. Despite the lack of immediate neurotoxic effects of some of the insecticides, 100% mortality of *H. halys* adults was achieved in this study with many of the insecticides including: methomyl, acephate, chlorpyrifos, dimethoate, malathion, methidathion, bifenthrin, fenpropathrin, permethrin, dinotefuran, and endosulfan. In contrast, substantial recovery of the *H. halys* adults occurred over the 7-d period with six of the nine pyrethroids (beta-cyfluthrin, cyfluthrin, esfenvalerate, gamma-cyhalothrin, lambda-cyhalothrin, and zeta-cypermethrin). Nielsen et al. (2008) and Leskey et al. (2012b) also found that *H. halys* recovered from a moribund state after exposure to certain pyrethroids.

Thus, despite different methodologies and approaches, there were fairly similar and consistent results found across

Table 1 Performance of insecticides against *H. halys* in different types of laboratory bioassays conducted in the mid-Atlantic USA from 2011-2016

Insecticide (IRAC Classification[a])	Mortality (or lethality) based on a 1–4 scale, where 1 (<50%), 2 (50–69%), 3 (70–89), 4 (90–100%)				
	Adults exposed to dry pesticide residue on glass[b]	Topical application to the dorsum of adults[c]	Nymphs exposed to dipped green bean for 72 h[d]	Adults exposed to dipped green bean for 72 h[d]	Average
Organophosphate (1A)					
Dimethoate	4	–	–	–	4
Malathion	4	–	–	–	4
Methidathion	4	–	–	–	4
Chlorpyrifos	3	3	–	–	3
Methyl parathion	–	3	–	–	3
Acephate	3	1	4	2	2.5
Formetanate	2	2	–	–	2
Azinphos-methyl	–	1	–	–	1
Diazinon	1	1	–	–	1
Phosmet	1	1	–	–	1
Carbamate (1B)					
Methomyl	4	4	2	3	3.3
Oxamyl	1	3	3	1	2
Carbaryl	1	1	3	1	1.5
Chlorinated hydrocarbon (2)					
Endosulfan	4	4	4	4	4
Pyrethroid (3)					
Etofenprox	–	–	4	4	4
Bifenthrin	4	4	4	3	3.8
Permethrin	3	1	4	4	3
Fenpropathrin	3	3	4	1	2.8
Lambda-cyhalothrin	2	2	4	3	2.8
Cyfluthrin	1	–	3	4	2.7
Beta-cyfluthrin	2	1	4	3	2.5
Cypermethrin	–	–	4	1	2.5
Gamma-cyhalothrin	2	–	–	–	2
Zeta-cypermethrin	2	1	4	1	2
Esfenvalerate	1	–	1	1	1
Neonicotinoid (4A)					
Dinotefuran	2	4	4	3	3.3
Clothianidin	2	4	3	2	2.8
Thiamethoxam	2	4	2	3	2.8
Acetamiprid	1	3	4	1	2.3
Imidacloprid	1	3	1	1	1.5
Thiacloprid	1	2	1	2	1.5
Other insecticide classes					
Spinetoram (5)	–	1	–	–	1
Abamectin (6)	1	1	–	–	1
Pyriproxyfen (7)	–	1	–	–	1
Pyrifluquinazon (9)	1	–	–	–	1
Novaluron (15)	–	1	–	–	1
Tolfenpyrad (21)	1	–	–	–	1
Indoxacarb (22)	1	1	–	–	1
Spirotetramat (23)	1	–	–	–	1

Table 1 continued

Insecticide (IRAC Classification[a])	Mortality (or lethality) based on a 1–4 scale, where 1 (<50%), 2 (50–69%), 3 (70–89), 4 (90–100%)				
	Adults exposed to dry pesticide residue on glass[b]	Topical application to the dorsum of adults[c]	Nymphs exposed to dipped green bean for 72 h[d]	Adults exposed to dipped green bean for 72 h[d]	Average
Chlorantraniliprole (28)	–	1	–	–	1
Cyantraniliprole (28)	1	1	–	–	1
Flubendiamide (28)	–	–	1	1	1
Flonicamid (29)	1	–	–	–	1
Combinations					
Thiamethoxam (4A) + chlorantraniliprole (28)	–	4	–	–	4
Beta-cyfluthrin (3) + imidacloprid (4A)	–	4	4	3	3.7
Lambda-cyhalothrin (3) + thiamethoxam (4A)	–	4	3	4	3.7
Bifenthrin (3) + imidacloprid (4A)	–	–	3	3	3
Zeta-cypermethrin (3) + bifenthrin (3)	–	3	4	2	3
Lambda-cyhalothrin (3) + chlorantraniliprole (28)	–	1	–	–	1

[a] Insecticide mode of action classification number from IRAC (2016)

[b] Data adapted from Leskey et al. (2012b)

[c] Data adapted from Krawczyk et al. (2011)

[d] Data adapted from Kuhar et al. (2012a)

the previously discussed laboratory experiments conducted on *H. halys* in the USA (Table 1). These results also are quite consistent with those from previous work in Asia (Lee et al. 2013a) that report several insecticide classes, including various chlorinated hydrocarbons, organophosphates, carbamates, pyrethroids, neonicotinoids, and combinations of the aforementioned to be the most efficacious on *H. halys* nymphs and adults in laboratory bioassays. However, insecticides that perform well in laboratory studies do not always exhibit the same response in the field. Leskey et al. (2014) reported an average decrease of more than 35% in efficacy when comparing mortality that occurred during laboratory assays to those in the field.

Field efficacy

In the field, protecting the fruiting stage of the crop from stink bug feeding injury is typically the goal of most insecticide efficacy studies, and this may or may not correlate with laboratory bioassays that typically assess bug mortality. *Halyomorpha halys* can move quickly between hosts, either wild or cultivated, and this behavior allows them to disperse into and out of a crop from a bordering host (Lee and Leskey 2015), or among different crops such as vegetables (Zobel et al. 2015). Quick dispersal between crops allows them to escape insecticide applications and recover in an untreated area. In order to effectively protect a crop from *H. halys* feeding, the insect needs to come in contact with a lethal dose of insecticide (Morrison et al. 2016a).

Residual activity is thus, a critical factor for insecticide efficacy. By recording percent mortality of *H. halys* bagged on fruit at 0, 3, and 7 days after insecticide application, Leskey et al. (2014) showed that freshly applied insecticide is significantly more lethal to the insect than dry residue on apple foliage for many insecticides. Additionally, they reported that fenpropathrin and dinotefuran reduced feeding injury for mid-season insecticide applications; however, mortality was low for insects bagged on fruit 24 h after insecticide application. The authors suggested that the residue acted as an antifeedant thereby reducing fruit injury. For two field seasons, significantly higher mortality was reported for most insecticides tested during early season application than mid to late season. They repeatedly observed that overwintered *H. halys* appear to be more susceptible to all classes of insecticides than the successive generations.

Bergmann and Raupp (2014) showed that while high mortality of *H. halys* adults occurred after exposure to fresh topical sprays of ready-to-use household carbaryl, acetamiprid, and permethrin, that only the dry residue of permethrin and carbaryl remained efficacious (>80% mortality) against nymphs after 48-h exposure to residue. Further, Mooneyham et al. (2016) evaluated nine different commercial insecticides registered for use on urban buildings (structural insect control). Insecticides were applied to window screens that were sewn into a bag in which adult *H. halys* were placed at various intervals after application. Most insecticides caused significant mortality of bugs on the first day of treatment; however, after 10 days in the field, only half of the insecticide treatments, lambda-cyhalothrin, lambda-cyhalothrin + thiamethoxam, beta-cyfluthrin, or beta-cyfluthrin + imidacloprid, provided effective control (mortality > 80%) of *H. halys*. Interestingly, the latter three insecticides continued to provide the same level of control after 22 d in the field.

Numerous field efficacy evaluations of insecticides have been conducted on tree fruit, vegetables, and soybeans in the mid-Atlantic USA since 2011. Although these field experiments vary based on cropping system, application method, timing of sprays, number of sprays, intervals between sprays, pest pressure, etc., when taken collectively, they provide a good indication of which chemicals provide significant control of *H. halys* in the field.

Results of experiments that had a significant treatment effect on stink bug damage are summarized in Table 2. In general, many of the same insecticides (and classes) that were effective in laboratory bioassays also performed well in the field. Active ingredients that have been most effective and consistent include several pyrethroids (beta-cyfluthrin, bifenthrin, permethrin, fenpropathrin, lambda-cyhalothrin, zeta-cypermethrin), neonicotinoids (dinotefuran, clothianidin, and thiamethoxam), carbamates (methomyl and oxamyl), the organophosphate acephate, and the organochlorine endosulfan.

Adjuvants

Various adjuvants can be added to a pesticide tank mix to enhance performance by improving deposition, spreading, penetration, and rain fastness among other functions (MeisterPro 2014). Leskey et al. (2014) evaluated the residual efficacy of several insecticides applied with and without two popular adjuvants, one a nonionic blend of fatty acids designed to enhance spray deposition and resist wash-off, and another a surface-active agent film-free sticker that improves penetration and reduce wash-off of the pesticide. They assessed mortality of *H. halys* bagged on apple trees at various times after spray application and found that the adjuvants generally did not increase the activity of most pyrethroid, neonicotinoid, or carbamate insecticides. In two instances, one with endosulfan and another with a mixture containing lambda-cyhalothrin + thiamethoxam, mortality of *H. halys* was higher with the addition of an adjuvant. However, these same authors also showed that the addition of adjuvants significantly reduced *H. halys* mortality rates for lambda-cyhalothrin, clothianidin, and acetamiprid. For most insecticides, however, there was no significant difference in *H. halys* mortality observed from the addition of an adjuvant.

Chemical control future outlook

Although there are many insecticides that have been shown to be effective on *H. halys*, not all of the insecticides are registered or available for use on all crops. Endosulfan, as well as other chlorinated hydrocarbons, is no longer registered for use in the USA and other countries. Moreover, relatively few organophosphates or carbamates are still registered on food crops, and these likely may face regulatory action in the coming years. Neonicotinoids have also faced regulatory action that has banned their use in some locations, or limited their use due to pollinator protection concerns (Goulson 2013; Stokstad 2013). Thus, pyrethroids, given their availability, effectiveness, and relatively low cost, have been the most widely used insecticides for *H. halys* control. However, pyrethroids are also quite toxic to natural enemy populations and often disruptive to integrated pest management strategies (Hull and Starner 1983). Moreover, their proliferated use can lead to outbreaks of secondary pests such as aphids, scales, and mites (Rock 1979; Roush and Hoy 1978; Gerson and Ephraim 1987; Kuhar et al. 2012d; Leskey et al. 2012a; Rice et al. 2014).

Heavy reliance on one class of insecticides such as pyrethroids could also potentially result in resistance development in *H. halys* populations. However, to our knowledge, there are no documented cases of insecticide resistance development in *H. halys*. Because of its very broad host range and movement from crop to crop and to wild vegetation within a landscape (Lee and Leskey 2015; Zobel et al. 2015), the selective pressures for resistance development in *H. halys* are relatively low compared with monophagous and less mobile crop pests.

IPM-compatible chemical control

The use of selective or narrow-spectrum insecticides for *H. halys* control is one approach to IPM compatibility. Insecticides such as spinosyns (spinosad and spinetoram), avermectins (abamectin and emamectin benzoate), anthranilic diamides (chlorantraniliprole, flubendiamide, and cyantraniliprole), insect growth regulators, and those that

Table 2 Insecticides that provided a significant reduction in *H. halys* densities or feeding damage to fruit relative to an untreated control in field efficacy experiments conducted on various crops in the USA from 2011 to 2016

Insecticide (IRAC Classification)	Apple	Peach	Pepper or tomato	Bean (soy and snap bean)
Organophosphate (1A)				
Acephate	–	–	–	9
Phosmet	–	26	–	–
Carbamate (1B)				
Methomyl	3,10	**4**,5,6,**22**,25	17,18	9,12
Oxamyl	–	5,6,22	**17**	9
Chlorinated hydrocarbon (2)				
Endosulfan	2	–	–	–
Pyrethroid (3)				
Beta-cyfluthrin	1,**2**	19,22	–	–
Bifenthrin	–	–	**11**,18	9,12
Esfenvalerate	–	5	17	–
Etofenprox	–	24	16	–
Fenpropathrin	1,**2**,10	20,**23**,24	16	–
Gamma-cyhalothrin	1,2	–	–	–
Lambda-cyhalothrin	–	25	–	9,12
Permethrin	**2**	25	–	–
Zeta-cypermethrin	–	–	18	12,14
Bifenthrin + zeta-cypermethrin	–	–	13,15,18	14
Neonicotinoid (4A)				
Clothianidin	1,**2**	20,23	16	–
Dinotefuran	1,**2**	20,24	16	–
Thiamethoxam	–	26	16	–
Other insecticide classes				
Flupyridafurone (4D)	–	–	–	12
Diflubenzuron (15)	–	–	–	9
Indoxacarb (22)	–	21	–	–
Chlorantraniliprole (28)	3	8	–	–
Cyclaniliprole (28)	–	–	–	12
Flonicamid (29)	–	–	18	–
Combinations				
Beta-cyfluthrin (3) + imidacloprid (4A)	1,**2**	22	–	–
Beta-cyfluthrin (3) + spinetoram (5)	7	–	–	–
Bifenthrin (3) + abamectin (6)	–	–	13,15,18	–
Bifenthrin (3) + chlorantraniliprole (28)	–	5	–	–
Bifenthrin (3) + imidacloprid (4A)	–	–	13	14
Lambda-cyhalothrin (3) + chlorantraniliprole (28)	–	–	–	12
Lambda-cyhalothrin (3) + thiamethoxam (4A)	–	**4**,21,25,26	–	–
Fenpropathrin (3) + Clothianidin (4A)	–	–	16	–
Methomyl (1B) + phosmet (1A)	–	8	–	–
Methomyl (1B) + zeta-cypermethrin (3)	–	–	15,18	–
Thiamethoxam (4A) + chlorantraniliprole (28)	–	21,26	–	–
Zeta-cypermethrin (3) + abamectin (6)	–	–	18	–

Table 2 continued

Insecticide (IRAC Classification)	Apple	Peach	Pepper or tomato	Bean (soy and snap bean)
Zeta-cypermethrin (3) + bifenthrin (3) + imidacloprid (4A)	–	–	18	–

Numbers refer to citations in the footnote. Bold face indicates that the insecticide also provided ≥80% reduction in stink bug injury to fruit or pods at harvest

1. Bergh (2013a); 2. Bergh (2013b); 3. Biggs and Park (2012a); 4. Biggs and Park (2012b); 5. Biggs and Park (2012c); 6. Frank (2014); 7. Frank and Biggs (2013); 8. Frank and Biggs (2014); 9. Herbert et al. (2013); 10. Hull (2012); 11. Kuhar and Doughty (2016b); 12. Kuhar et al. (2015); 13. Kuhar et al. (2012b); 14. Kuhar et al. (2012c); 15. Kuhar et al. (2012d); 16. Kuhar et al. (2012e); 17. Kuhar et al. (2012f); 18. Kuhar et al. (2014); 19. Nielsen and Rucker (2013a); 20. Nielsen and Rucker (2013b); 21. Nielsen and Rucker (2013c); 22. Rucker and Hamilton (2012a); 23. Rucker and Hamilton (2012b); 24. Rucker and Hamilton (2012c); 25. Rucker and Hamilton (2012d); 26. Walgenbach and Schoof (2015)

target soft-bodied hemipterans such as pymetrozine, flonicamid, spirotetramat, flupyridafurone, and sulfoxaflor have filled that role for selective control of many important pests of horticultural crops. However, most of these insecticides have not provided acceptable control of *H. halys* (Table 1; Krawczyk et al. 2011; Kuhar et al. 2012a; Leskey et al. 2012b; Bergmann and Raupp 2014; Morehead and Kuhar 2017).

A few selective insecticides, however, have shown some promise for *H. halys* control and are worth discussing. Kamminga et al. (2012) tested the efficacy of the chitin biosynthesis inhibitors (IRAC 2016, Class 15) novaluron and diflubenzuron on *H. halys* adult mortality, nymphal growth, adult fecundity, and egg hatch. They demonstrated that treatments of novaluron at 362.2 g ai/ha or diflubenzuron at 280.2 g ai/ha effectively controlled *H. halys* nymphs, but had very little effect on adults or eggs. In addition, Herbert et al. (2013) reported significant reductions in total *H. halys* and other stink bug numbers in soybeans after diflubenzuron at 35.4 and 70.8 g ai/ha application.

The pyridinecarboxamide flonicamid was introduced in 2005. It has a novel mode of action as a chordotonal organ modulator (IRAC 2016, Class 29) acting as a feeding inhibitor for control of thysanoptera and some hemipterans like aphids, whiteflies, plant bugs (*Lygus* spp.), and scales. Mixed results have been shown with this insecticide. Flonicamid did not perform well in the lethality index bioassays conducted by Leskey et al. (2012a) and did not reduce stink bug damage to pepper in a recent field experiment (Kuhar and Doughty 2016b); however, it did reduce stink bug damage compared to the untreated control in an experiment conducted on peppers (Kuhar et al. 2014).

Sulfoxaflor is a relatively new sulfoximine insecticide introduced in 2013. It has a similar mode of action (IRAC 2016, Class 4C) as neonicotinoids (IRAC 2016, Class 4A). It has demonstrated toxicity against several hemipteran pests including *Lygus* bugs (Kerns et al. 2011), harlequin bugs, *Murgantia histrionica* (Hahn), and kudzu bug, *Megacopta cribraria* (Fabricius) (Wilson et al. 2015). In a recent field experiment, sulfoxaflor applications reduced *H. halys* damage to pepper by 76%, which was comparable to the pyrethroid standard, bifenthrin (Kuhar and Doughty 2016b).

Cyclaniliprole is a new diamide (IRAC 2016, Class 28) insecticide that is scheduled for registration in 2018. Unlike other diamides, it has demonstrated activity against stink bugs including *H. halys* (Aigner et al. 2015a). In recent field experiments, cyclaniliprole applications reduced stink bug damage about 50% in snap bean (Kuhar and Doughty 2016a) and pepper (Kuhar and Doughty 2016b). As such, very little data have been published about its efficacy.

Further testing should be done with the aforementioned insecticides perhaps in combination or rotation with other insecticides. Their reduced impact on natural enemies and pollinators makes them worthy of further examination as potential tools for *H. halys* control. Development and evaluation of novel insecticides that target stink bugs with less impact on beneficial insects would significantly advance grower capabilities of combating *H. halys*, and fit better into integrated pest management programs.

Another approach for making *H. halys* chemical control more IPM-compatible is more targeted insecticide applications combining efficient use of insecticides with a better understanding of the pest's biology and behavior. Aigner et al. (2015b) showed that soil drench applications of the neonicotinoids clothianidin, dinotefuran, imidacloprid, and thiamethoxam were toxic to *H. halys* and significantly reduced stink bug damage to pepper and tomato. Similar field experiments conducted on tomatoes in North Carolina revealed a similar reduction in stink bug damage with a single drip chemigation application of either dinotefuran or imidacloprid (Aigner et al. 2015b). This application strategy minimizes the use of foliar-applied insecticides and does not flare pyrethroid-resistant aphid populations (Kuhar et al. 2012d).

Field border sprays or attract-and-kill strategies are currently being researched in the mid-Atlantic USA and show tremendous promise for effective management of *H. halys* with minimal insecticide inputs. *Halyomorpha halys* is a border-driven field edge pest (Rice et al. 2014). In soybeans, *H. halys* populations do not move far from field edges (Aigner et al. 2017) and a single field edge-only insecticide treatment (one spray boom width) can be highly effective at controlling *H. halys* if timed correctly (Cissel et al. 2015). This strategy also reduces the amount of insecticides applied and provides a reservoir for natural enemies in the center of the field. A similar strategy has also worked in peaches in the mid-Atlantic USA (Blaauw et al. 2014).

Utilizing the highly attractive aggregation pheromone lures of *H. halys*, identified as (3*S*,6*S*,7*R*, 10*S*)-10,11 epoxy-1-bisabolen-3-ol and (3*S*,6*S*,7*R*,10*R*)-10,11-epoxy-1-bisabolen-3-ol (Khrimian et al. 2014) along with 2,4,6, *E*,*E*,*Z* methyl decatrienoate the aggregation pheromone released by another pentatomid species, *Plautia stali* Scott, which synergizes the attractive response (Weber et al. 2014), researchers are now able to draw large numbers *H. halys* adults and nymphs to a specific location such as a single tree. This capability has opened the door to attract-and-kill strategies for *H. halys*, which are currently being investigated in the mid-Atlantic USA (Morrison et al. 2016b). Pyrethroid insecticide applications to attract-and-kill trees have resulted in tremendous numbers of dead *H. halys,* while only treating specific plants or rows with insecticide, thus substantially reducing the overall amount of insecticide applied in the environment.

Chemical control in organic agriculture

While most organic growers rely heavily on cultural and biological methods for pest management; naturally derived insecticides also play a rescue role in some instances, often to save a crop from destruction. *Halyomorpha halys* has caused serious crop losses for organic producers in the mid-Atlantic USA. Organic growers have fewer chemical options that are effective on stink bugs compared with conventional insecticides (Kamminga et al. 2009). In their evaluations of ready-to-use household insecticides, Bergmann and Raupp (2014) achieved only minimal mortality of *H. halys* adults with applications of spinosad, horticultural oil, essential oils, potassium salts of fatty acids (insecticidal soap), and capsaicin. Lee et al. (2014) examined the efficacy of several certified-organic insecticides in treated glass surface (contact) bioassays against *H. halys* and demonstrated significant mortality of nymphs and adults after a few days of exposure to pyrethrins, potassium salts of fatty acids, spinosad, and an extract made from heat-killed cells and fermentation solids of the bacteria *Burkholderia* spp. Morehead and Kuhar (2017) also recently evaluated several organically approved insecticides using bug submersion and bean-dip bioassays. High mortality (>70%) of *H. halys* nymphs and adults was achieved with pyrethrins, azadirachtin + pyrethrins, and potassium salts. However, in bean-dip bioassays, only pyrethrins resulted in significant mortality of nymphs and adults. Unfortunately, in field tests where insecticide treatments were applied weekly, none of the certified-organic insecticides that were tested including pyrethrins, spinosad, azadirachtin, azadirachtin + pyrethrins, potassium salts, potassium salts + spinosad, extract of *Burkholderia*, or sabadilla provided a significant reduction in stink bug damage to pepper or tomato in replicated trials over two seasons (Morehead and Kuhar 2017). However, some of the aforementioned organic insecticides could perhaps be useful tool for attract-and-kill or trap crop strategies (Nielsen et al. 2016). This work warrants further investigation.

In summary

Through field and laboratory studies, researchers in the USA have been exploring options to manage and control *H. halys* since its establishment in the mid-Atlantic region of the country over a decade ago (Hoebeke and Carter 2003; Rice et al. 2014). Building on previous work conducted in Asia (Funayama 2012; Lee et al. 2013a), researchers in the USA have conducted numerous laboratory bioassays and field efficacy evaluations of various insecticides for control of *H. halys*. Insecticides that have been most effective include pyrethroids such as beta-cyfluthrin, bifenthrin, permethrin, fenpropathrin, lambda-cyhalothrin, zeta-cypermethrin, along with neonicotinoids such as dinotefuran, clothianidin, and thiamethoxam, and carbamates such as methomyl and oxamyl, organophosphates, and the organochlorine endosulfan. Most of these chemicals are broad-spectrum insecticides that are also potentially disruptive to natural enemies and/or pollinators. Selective insecticides that target primarily stink bugs are badly needed to help move or return agricultural pest management in tree fruit, vegetables, and field crops, to a more sustainable system that fully utilizes integrated pest management. In the meantime, strategies that utilize more targeted insecticide applications such as attract-and-kill and border sprays have shown great promise for control of this pest.

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Compliance of ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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