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ORIGINAL PAPER

Efficacy of organically approved insecticides against brown marmorated stink bug, *Halyomorpha halys* and other stink bugs

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Abstract The brown marmorated stink bug, *Halyomorpha halys* (Stål), is a serious invasive pest in the USA. Organic growers have limited options to effectively manage this pest. Several organically approved insecticides including pyrethrins, azadirachtin, spinosad, potassium salts of fatty acids, sabadilla, extract from *Burkholderia* sp., and two combination products were evaluated for toxicity to *H. halys* nymphs and adults using laboratory bioassays and evaluated in field experiments on tomatoes and peppers using weekly applications of the highest labeled rates of the products. In submersion bioassays, high mortality (>70%) of *H. halys* nymphs was achieved with pyrethrins, azadirachtin, azadirachtin + pyrethrins, potassium salts + spinosad, and sabadilla alkaloids. Using the same bioassay for adult *H. halys*, only pyrethrins, azadirachtin + pyrethrins, and potassium salts resulted in high mortality. In bean dip bioassays, only pyrethrins resulted in moderate mortality of nymphs and high mortality of adults. In field experiments, which included weekly insecticide applications, none of the insecticides that were tested significantly reduced stink bug feeding injury (from all species) to tomatoes or peppers with the exception of one harvest date of peppers in 2014, where pyrethrins + azadirachtin had less injury than the control. Our results confirm that several organically approved insecticides may demonstrate a high level of activity on *H. halys* in laboratory bioassays, but when applied in the field, none of the products that we tested appear to be consistently effective at reducing stink bug injury to peppers or tomatoes.

Keywords Organic insecticides · Biopesticides · Chemical control · *Euschistus servus*

Key message

- *Halyomorpha halys* is an important agricultural pest in the USA and is particularly damaging to organic production systems, which lack effective tools for managing it.
- A number of organically approved insecticides such as pyrethrins, azadirachtin, azadirachtin + pyrethrins, potassium salts + spinosad, and sabadilla alkaloids show promise in laboratory bioassays causing high levels of mortality to *H. halys*.
- However, when sprayed weekly on fruiting peppers and tomatoes in field efficacy experiments, none of the tested products significantly reduced stink bug feeding injury compared to the untreated control.

Introduction

The brown marmorated stink bug, *H. halys* (Stål), is native to East Asia (Lee et al. 2013) and has recently become a serious invasive pest in North America and Europe (Leskey et al. 2012a; Haye et al. 2015). This highly polyphagous insect attacks a number of agricultural crops in the USA

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

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including, but not limited to tree fruit (Nielsen and Hamilton 2009; Leskey et al. 2012a, c), vegetables such as sweet corn, beans, peppers, tomatoes, eggplant, and okra (Kuhar et al. 2012a; Cissel et al. 2015), tree nuts (Hedstrom et al. 2014), grapes (Basnet et al. 2015), berries (Basnet et al. 2014; Wiman et al. 2015), and soybeans (Nielsen et al. 2011; Owens et al. 2013). Similar to other stink bugs, *H. halys* feeds by inserting its stylets into the fruit, stem, or leaves and secreting digestive enzymes into the plants, allowing it to feed on plant fluids (McPherson and McPherson 2000; Haye et al. 2014). For fruiting vegetables such as peppers and tomatoes, feeding by *H. halys* nymphs and adults on the developing and mature fruit results in conspicuous feeding injury (Kuhar et al. 2015a) and often significant economic loss to growers.

Control of this pest has been challenging since its arrival in the USA (Leskey et al. 2012c). Currently, chemical control remains the most effective and efficient strategy (Rice et al. 2014; Kuhar et al. 2015b). Although a number of insecticides including cyclodienes, pyrethroids, organophosphates, carbamates, and neonicotinoids have been shown to be efficacious against *H. halys* (Nielsen et al. 2008; Kuhar et al. 2012b, c; 2013a, b, c; Leskey et al. 2012b, 2013; Lee et al. 2013), all of these insecticides are broad spectrum toxicants that can also be harmful to beneficial organisms such as natural enemies and pollinators (Rock 1979; Hull and Starner 1983; Desneux et al. 2007). Moreover, many growers have greatly increased the number of sprays they apply per year just to deal with *H. halys*, as much as four times as many sprays (Leskey et al. 2012b). The increased frequency of insecticide applications suppresses natural enemy populations, which can lead to secondary pest outbreaks of aphids, scales, and mites in vegetables and tree fruit (Kuhar et al. 2013a; Leskey et al. 2012a).

Control of *H. halys* is an even greater challenge for organic growers, who rely heavily upon alternative methods such as biological control and cultural control to prevent damage to crops (Zehnder et al. 2007). One cultural control tactic that has shown promise for managing stink bugs in general is trap cropping, where highly attractive plants are grown to draw pest pressure from a protected crop (Tillman 2006; Mizell et al. 2008; Wallingford et al. 2013). Researchers have recently investigated this approach for managing *H. halys* and have demonstrated significant behavioral manipulation of *H. halys* in the field using border plots of sunflowers or sorghum millet (Soergel et al. 2015; Nielsen et al. 2016). However, the overall efficacy of this approach at reducing stink bug feeding injury to a cash crop such as bell pepper is lacking mostly because of "spillover" of the pest population after they are drawn to the trap crop. Integrating the use of organically approved insecticides into this management strategy may provide growers with an IPM approach that can significantly reduce crop damage by this invasive bug.

Some naturally derived insecticides that are organically certified in the USA include: azadirachtins, which are derived from the neem tree, *Azadirachta indica* (Meliaceae), and have a wide range of insect growth and behavioral effects on insects (Schmutterer 1990); pyrethrins, which are derived from chrysanthemum flowers, *Chrysanthemum* spp., and have neurotoxic effects on many insects (Casida 1980); sabadilla alkaloids, which are extracted from the seeds of *Schoenocaulon* sp., a South American lily plant, and which have a mode of action similar to pyrethrins; spinosyns, which are derived from the fermentation of the soil microbe *Saccharapolyspora spinosa*, and which act on the nicotinic receptor site of post-synaptic nerves (Horowitz and Ishaaya 2004); potassium salts of fatty acids (also known as insecticidal soap), which affect the insect cuticle; and a relatively new biological insecticide containing heat-killed cells and fermentation solids of the bacteria *Burkholderia* spp. that works by contact and ingestion to disrupt insect exoskeletons and interfere with molting (Asolkar et al. 2013).

Most of the aforementioned insecticides have demonstrated activity against pentatomids or related bugs in previous studies. For instance, azadiractins have been shown to impact nymphal development, oviposition, and feeding on cowpea by the southern green stink bug, *Nezara viridula* L. (Seymour et al. 1995; Abudulai et al. 2003; Durmusoglu et al. 2003; Riba et al. 2003). Pyrethrins and spinosad each demonstrated high toxicity to the green stink bug, *Chinavia hilaris* (Say) and brown stink bug, *Euschistus servus* (Say) in the laboratory (Kamminga et al. 2009). Sabadilla has been shown to be efficacious against milkweed bugs, *Oncopeltus fasciatus* (Dallas) (Allen et al. 1945) and squash bug, *Anasa tristis* (DeGeer) (Walton 1946). Potassium salts of fatty acids have been recommended by Trdan et al. (2006) as a control measure for cabbage stink bug, *Eurydema* sp. and shown by Durmusoglu et al. (2003) to control *N. viridula* when combined with azadirachtins. Lee et al. (2014) recently examined the efficacy of many of the aforementioned certified organic insecticides in treated glass surface (contact) bioassays against *H. halys* and showed significant mortality of nymphs and adults after a few days of exposure to pyrethrins, potassium salts of fatty acids, spinosad, and extracts of *Burkholderia* spp.

Herein, we further investigate the potential of several certified organic insecticides at controlling *H. halys* nymphs and adults in different types of bioassays as well as in the field for protecting tomatoes and peppers from feeding damage. This information will further help determine viable *H. halys* control options for organic growers.

Materials and methods

Insecticides

All insecticides used in the experiments were commercially formulated products that were supplied by their manufacturers (Table 1). All insecticides were diluted in 1 l of distilled water proportional to a typical tank mix concentration based on a spray application rate of 355 l/ha and the highest recommended field application rate listed on the label (Table 1). The sabadilla alkaloids (Veratran D®) required a special preparation of placing the ground seeds in a fine mesh bag that was allowed to seep for >2 h in water prior to use the bioassays or field application.

Insects

Adults, nymphs, and egg masses of *H. halys* were collected from trees in near Blacksburg, Virginia (USA), from May to September in 2014 and 2015 in order to start a laboratory colony at Virginia Tech. Insects were maintained in 0.028 m^3 screened cages in a temperature chamber (Percival Scientific Inc., Perry, IA, USA) set at 28 ± 2 °C, a 16:8 h L:D photoperiod, and a 50% relative humidity. Adults and nymphs were provided a water wick and snap beans, *Phaseolus vulgaris* L. (Fabales: Fabaceae); carrots, *Daucus carota* L. (Apiales: Apiaceae); and raw unshelled peanuts, *Arachis hypogaea* L. (Fabales: Fabaceae). Nymphs and adults were held in separate 56 × 56 × 56 cm fine mesh insect rearing and observation cages with vinyl windows (BioQuip Products, Rancho Dominguez, CA, USA) and were supplemented regularly with field-collected insects when found. Fresh egg masses were isolated from the cages and held in small Petri dishes until 2nd instars appeared, at which time they were returned to the cages. Isolating eggs and 1st instars from the rest of the colony minimized cannibalism. Nymphs and adults were starved for 24 h prior to use in bioassays. When possible, only 3rd instars were used for the nymph bioassays. However, because of mortality in the *H. halys* colony presumably from humidity dropping below 50%, not enough healthy 3rd instars were always available at the time of the bioassays and consequently one or two 2nd or 4th instars per treatment were sometimes included in the bioassay to keep the numbers tested at 20 per replicate. When this occurred, the same number of 2nd or 4th instars was partitioned for each of the treatments to keep uniformity. Data were not separated by instar, but rather lumped together for a single nymphal mortality assessment.

Submersion (dipped mesh bag) bioassay

The aim of this bioassay was to assess the toxicity of each of the insecticides when applied directly to the insects. For each treatment and replication of the bioassay, we placed 20 adult *H. halys* and 20 nymphs (mostly 3rd instars) each in a fine mesh polyethylene bag and submerged it in 500 ml of treatment solution for 3–5 s and then allowed it to air dry at (room temperature). The bugs were provided with a fresh green bean pod for food and hydration in the dry treated bag. Percent mortality was recorded at 24 and 48 h. Mortality was counted as dead plus moribund, upside

Table 1 Insecticide treatments used in our bioassays and field experiments for control of *H. halys*

Active ingredient (a.i.)	Product (% a.i.)	Manufacturer	Recommended field rate: (g a.i./ha[a])
Azadirachtin	AzaDirect® (1.2%)	Gowan Company LLC, Yuma, Arizona (USA)	28.0
Azadirachtin + pyrethrins	Azera® (1.2% azadirachtins + 1.4% pyrethrins)	MGK, Minneapolis, Minnesota (USA)	28.0 30.0
Spinosad	Entrust® (22.5%)	Dow AgroSciences LLC, Indianapolis, Indiana (USA)	131.4
Potassium salts of fatty acids	M-Pede® SL (49.0%)	Gowan Company LLC, Yuma, Arizona (USA)	183.0
Potassium salts of fatty acids + spinosad	Neudorff 1138 (47% potassium salts, 0.1% spinosad)	Neudorff North America Brentwood Bay, BC (Canada)	175.6 0.3
Pyrethrins	Pyganic® (5.0%)	MGK, Minneapolis, Minnesota (USA)	65.4
Burkholderia sp.	Venerate® (94.4%)	Marrone Bio Innovations Inc., Davis, California (USA)	17,667.0
Sabadilla alkaloids	Veratran D® (0.2%)	MGK, Minneapolis, Minnesota (USA)	33.6

[a] Recommended field rates are based on control of stink bug on fruiting vegetables when included on the product label. If not stink bug is not included, then the highest rate for another pest or on another vegetable crop was used

down and unable to right themselves, or unable to walk. Three replicates ($n = 3$) were conducted for each insecticide treatment over time. We were not able to test every insecticide treatment at the same time in a given bioassay due to lack of bugs; however, all treatments were compared to a water control within a replicate. If control mortality exceeded 20% (>4 dead out of the 20 individuals tested), then the bioassay replicate was not used. If control mortality was between 5 and 20%, then Abbott's formula (Abbott 1925) was used to correct for control mortality for the treatments used in that particular replicate (Finney 1971).

Green bean dip assay

The aim of this bioassay was to assess the toxicity of each of the insecticides via a combination of dermal and oral exposure. Following Kuhar et al. (2007, 2013a), green bean dip assays were conducted on nymphs (2nd–4th instars) and adults. For each bioassay, four green bean pods were dipped in each selected treatment and allowed to dry for 30 min under a fume hood, then one treated bean pod, a filter paper disk, and five insects of the selected stage were placed in a 9-cm-diameter Petri dish. Four dishes (20 insects total) were set up per treatment per replicate. Percent mortality was recorded 48 h after treatment, and data were handled as described above.

Field efficacy experiments

Small plot field experiments were conducted at Virginia Tech's Kentland Farm near Blacksburg, VA, in 2014 and 2015. In 2014, experiments were conducted on "Baby Cake" tomatoes (*Solanum lycopersicum* L.) and in 2015, on the same tomato variety as well as "Aristotle" bell peppers (*Capsicum* spp.). Both crops were planted the first week of June in both years following standard commercial production practices, including raised beds covered with black polyethylene mulch and with drip irrigation. Pepper and tomato plants were spaced 0.3 and 0.5 m, respectively, within rows. Plots were one row by 6 m long. Each experiment was set up in a randomized complete block design with four replicates. Crops were grown and maintained without any insecticide applications until fruit began appearing on plants at which time the treatment applications were initiated.

All insecticide treatments were applied as foliar sprays with a CO_2 backpack sprayer at 276 kPa delivering 356 l/Ha through a three-nozzle drop down boom that provided excellent coverage over the plant. Insecticides were applied four times in 2014: 19, 25 August and 3, 9 September. In 2015 peppers were treated five times: 27 July; 3, 10, 17, 18, 24 August; and tomatoes were also treated five times: 28 July; 4, 11, 18, 25 August.

One week prior to each of the August insecticide applications, we inspected the untreated control plots to confirm stink bug and other pest populations. Sampling involved five separate 2 min visual samples of the plots recording all stink bug species observed on both pepper and tomato. Peppers were harvested twice in 2014: 29 August and 17 September, and twice in 2015: 13 and 26 August. Tomatoes were harvested three times in 2014: 29 August, 8, and 12 September; and two times in 2015: 20 and 31 August. At each harvest, a subsample of 20 or 25 fruit per plot depending on availability were inspected for stink bug feeding injury, which appeared as characteristic marks on the fruit (Kuhar et al. 2015a). A single fruit was classified as "injured" only if it had visibly clear and distinct stink bug feeding marks. Proportion fruit injury was calculated as the number of injured fruit divided the number of fruit harvested per plot.

Data analysis

All data were initially tested for normality using the NORMAL TEST (Shapiro–Wilk test), and when necessary, the proportion mortality data from the laboratory bioassays or the proportion fruit injury data from the field experiments were transformed using an arcsine square root transformation to normalize the variances (Sokal and Rohlf 1995), and then analyzed using ANOVA, JMP version 10.0 (SAS 2007, SAS Institute, Cary, NC, USA). Bioassay mortality data were analyzed using one-way ANOVA with insecticide being the only treatment factor. Fruit injury data from the field experiments were analyzed using a two-way ANOVA for randomized complete block designs where both treatment and block were factors. Means were separated using Fisher's protected LSD at the $P < 0.05$ level of significance. Data are presented as original means.

Results

Submersion bioassays

The mortality of *H. halys* nymphs was significantly different among treatments ($f = 11.67$; $df = 7$; $P < 0.001$). Pyrethrins, azadirachtin + pyrethrins, and potassium salts + spinosad each resulted in the highest mortality (>90%), which was significantly higher than that of *Burkholderia* sp., spinosad, and potassium salts alone ($P < 0.05$; Table 2). There also was a significant treatment effect on mortality of adults ($f = 5.68$; $df = 7$; $P < 0.002$), with pyrethrins and azadirachtin + pyrethrins causing the highest mortality (>95%), which was greater than most of

Table 2 Mean (±SE)% mortality of *H. halys* nymphs and adults 48 h after submersion in field rate concentrations of various organic insecticides

Treatment	Concentration (g a.i./l)	Mean ± SE % mortality at 48 h	
		Nymphs ($n = 20$)	Adults ($n = 20$)
Azadirachtin	3.0	78.5 ± 22.3 ab	55.0 ± 49.2 b
Azadirachtin + pyrethrins	3.0 + 3.2	95.5 ± 7.9 a	95.0 ± 8.7 a
Spinosad	14.1	19.4 ± 20.0 cd	40.0 ± 36.1 bc
Potassium salts	19.6	18.2 ± 31.5 d	73.3 ± 12.6 ab
Potassium salts + spinosad	18.8 + 0.1	96.4 ± 3.1 a	36.1 ± 3.4 bc
Pyrethrins	7.0	100.0 ± 0.0 a	100.0 ± 0.0 a
Burkholderia sp.	1891.6	0.0 ± 0.0 d	8.3 ± 14.4 c
Sabadilla alkaloids	3.6	55.1 ± 39.5 bc	26.7 ± 12.6 bc

Data are corrected for control mortality between 5 and 20% with Abbott's formula, and corrected values are shown. Bioassays were replicated three times for each treatment

Means within a column with a letter in common are not significantly different according to Fisher's protected LSD ($P > 0.05$)

the other treatments (Table 2). The *Burkholderia* sp. treatment caused little to no mortality of *H. halys* after 48 h in this bioassay.

Bean dip bioassays

Compared to the submersion bioassay, the overall mortality of *H. halys* nymphs was relatively low (<50%) in the bean dip bioassays; however, there was a significant treatment effect ($f = 3.17$; $df = 7$; $P < 0.026$). Sabadilla, pyrethrins, and azadirachtin + pyrethrins resulted in the highest mortality of nymphs (38–41%), which was significantly higher than that of *Burkholderia* sp. and potassium salts alone, which caused 0.0 and 3.3% mortality, respectively (Table 3). Overall adult mortality was numerically higher than nymphal mortality and there was a significant treatment effect ($f = 2.62$; $df = 7$; $P < 0.05$). Pyrethrins, once again, caused the highest mortality (80%), which was significantly higher than azadirachtins, potassium salts with and without spinosad, and *Burkholderia* sp. (Table 3).

Field experiments

Stink bug pest pressure was generally higher in tomatoes (Table 4) than peppers (Table 5) and higher in 2015 than 2014. In both years, *H. halys* was the only stink bug species found in peppers. However, in tomatoes, *E. servus* was the dominant species in both years comprising about 75% of the stink bug species found with *H. halys* comprising the remaining species.

In the untreated control plots in 2014, an average of 31 and 39% of tomato fruit, in the first and second harvest, respectively, had stink bug injury. In 2015, the untreated control plots had an average of 28, 65, and 65% stink bug injured fruit in three harvests, respectively (Table 4). There was no significant effect of treatment on stink bug

Table 3 Mean (±SE) % mortality of *H. halys* nymphs and adults 48 h after exposure to a bean pod that was dipped in field rate concentrations of various organic insecticides

Treatment	Concentration (g a.i./l)	Mean ± SD% mortality at 48 h	
		Nymphs	Adults
Azadirachtin	3.0	7.3 ± 6.4 abc	1.8 ± 3.0 c
Azadirachtin + pyrethrins	3.0 + 3.2	38.3 ± 17.6 a	55.2 ± 39.4 ab
Spinosad	14.1	24.0 ± 11.5 ab	44.6 ± 29.3 abc
Potassium salts	19.6	3.3 ± 5.8 bc	13.3 ± 12.6 bc
Potassium salts + spinosad	18.8 + 0.1	20.0 ± 21.8 abc	20.0 ± 5.0 bc
Pyrethrins	7.0	40.0 ± 26.5 a	80.0 ± 18.0 a
Burkholderia sp.	1891.6	0.0 ± 0.0 c	15.0 ± 21.8 bc
Sabadilla alkaloids	3.6	41.0 ± 44.0 a	40.0 ± 52.2 abc

Data are corrected for control mortality between 5 and 20% with Abbott's formula and corrected values are shown

Means within a column with a letter in common are not significantly different according to Fisher's protected LSD ($P > 0.05$)

Table 4 Field evaluation of organic insecticides for the control of stink bugs in tomatoes, Kentland Research Farm, Whitethorne, VA, in summer 2014 and 2015

Treatment	Rate (g a.i./ha)	Mean ± SD% of harvested fruit with stink bug injury				
		2014			2015	
		29 August	8 September	12 September	20 August	31 August
Water control	0	31.3 ± 7.6	39.0 ± 15.3	28.0 ± 19.8	65.0 ± 16.2	65.0 ± 12.4
Azadirachtin	28.0	23.8 ± 8.6	40.0 ± 13.8	26.0 ± 11.1	58.0 ± 7.2	44.0 ± 8.7
Azadirachtin/pyrethrins	28.0 + 30.0	22.5 ± 6.4	26.0 ± 23.9	24.0 ± 9.2	60.0 ± 5.0	49.0 ± 18.0
Spinosad	131.4	42.5 ± 18.4	33.0 ± 16.2	16.0 ± 15.2	35.0 ± 5.7	46.0 ± 23.4
Potassium salts	183.0	23.8 ± 14.4	32.0 ± 15.8	8.0 ± 7.8	59.0 ± 19.9	70.0 ± 14.0
Potassium salts/spinosad	175.6 + 0.3	25.0 ± 4.0	25.0 ± 17.1	20.0 ± 11.6	62.0 ± 11.1	55.0 ± 9.6
Pyrethrins	65.4	20.0 ± 0.0	37.0 ± 8.6	35.0 ± 20.3	56.0 ± 21.5	57.0 ± 10.6
Burkholderia sp.	17,667.0	25.0 ± 9.2	21.0 ± 6.5	21.0 ± 5.0	59.0 ± 14.1	58.0 ± 13.1
Sabadilla alkaloids	33.6	30.0 ± 17.4	21.0 ± 3.8	20.0 ± 19.6	61.0 ± 16.8	59.0 ± 28.0

The effect of treatment was not significant on any harvest date for either crop ($P > 0.05$)

Insecticides were applied four times (19, 25 August; 3 and 9 September) in 2014 and five times (28 July; 4, 11, 18, 25 August) in 2015

Means within a column with a letter in common are not significantly different according to Fisher's protected LSD ($P > 0.05$)

Table 5 Field evaluation of organic insecticides for the control of stink bugs in bell peppers, Kentland Research Farm, Whitethorne, VA, in 2014 and 2015

Treatment	Rate (g a.i./ha)	Mean ± SD% of harvested fruit with stink bug injury			
		2014		2015	
		29 August	17 September	13 August	26 August
Water control	0	10.0 ± 9.2	17.1 ± 7.0 a	47.0 ± 23.4	47.0 ± 19.7
Azadirachtin	48.4	13.8 ± 14.8	3.8 ± 5.2 ab	22.0 ± 13.8	46.0 ± 3.2
Azadirachtin/pyrethrins	49.0 + 53.9	15.0 ± 15.8	0.0 ± 2.3 b	19.0 ± 23.5	33.0 ± 20.9
Spinosad	175.1	6.3 ± 6.2	5.0 ± 7.7 ab	31.0 ± 19.4	62.0 ± 24.5
Potassium salts	2861.7	15.0 ± 17.8	2.5 ± 2.8 ab	19.0 ± 5.2	51.0 ± 10.8
Potassium salts/spinosad	2721.1 + 6.8	17.5 ± 10.4	1.3 ± 3.9 ab	32.0 ± 12.1	56.0 ± 10.9
Pyrethrins	58.1	5.0 ± 7.0	2.5 ± 4.7 ab	26.0 ± 21.0	40.0 ± 5.2
Burkholderia sp.	14,230.3	26.3 ± 24.0	3.8 ± 8.4 ab	41.0 ± 26.2	56.0 ± 19.8
Sabadilla alkaloids	33.6	7.5 ± 8.6	1.3 ± 4.1 ab	20.0 ± 12.0	34.0 ± 26.9

The effect of treatment was not significant on any harvest date for either crop ($P > 0.05$)

Insecticides were applied four times (19, 25 August; 3 and 9 September) in 2014 and five times (27 July; 3, 10, 17, 24 August) in 2015

Means within a column with a letter in common are not significantly different according to Fisher's protected LSD ($P > 0.05$)

injury to tomato fruit on any harvest date in either year ($P > 0.05$). Stink bug injury to pepper fruit averaged from 10 to 18% in the untreated control plots in 2014 and 47% in 2015 (Table 5). There was no significant effect of treatment on stink bug injury to pepper fruit on any harvest date ($P > 0.05$) except on 17 September 2014 ($f = 2.42$; $df = 8, 24$; $P < 0.045$), when peppers treated with azadirachtin + pyrethrins had less injury than the control.

Discussion

An effective insecticide for control of *H. hays* in certified organic agricultural systems is badly needed. In our experiments, several insecticides including pyrethrins, azadirachtins, sabadilla, spinosad, and potassium salts of fatty acids demonstrated at least some toxicity to *H. halys* nymphs and adults in submersion and bean dip laboratory bioassays. In both types of bioassays, pyrethrins resulted in the highest percent mortality at 48 h after treatment. It is not surprising that pyrethrins performed well in these bioassays as they are fast acting contact insecticides (Isman 2006), whereas most of the other products that affect insect growth and development may have required additional time to exhibit their full toxicity. Using a treated glass surface bioassay, Lee et al. (2014) demonstrated significant *H. halys* nymphal and adult mortality after 4–5 d of exposure to either pyrethrins, spinosad, potassium salts, or *Burkholderia* sp.

Field evaluations of insecticide efficacy are essential as some of the insecticides may be more effective in the field when repellency and antifeedancy responses to the chemicals also may occur in addition to direct toxicity. For instance, stink bugs may be repelled by pyrethrins or other insecticides at certain concentrations (Kamminga et al. 2009). Azadirachtins also have a number of behavioral effects on insects including antifeedancy (Seymour et al. 1995; Abudulai et al. 2003), ovipositional deterrence as well as growth regulation (Durmusoglu et al. 2003; Riba et al. 2003). In the laboratory, Kamminga et al. (2009) observed significantly fewer stylet sheaths from either *E. servus* or *C. hilaris*, on azadirachtin-treated tomato fruit compared to water-treated fruit, illustrating the efficacy of this insecticide as an antifeedant. Efficacy of insecticides also may be substantially reduced in the field due to photodegradation or treatment wash off or dilution following precipitation events (Schmutterer 1990; Zehnder et al. 2007).

In our field experiments, which included four or five weekly applications of the products during the fruiting stage of peppers and tomatoes, none of the insecticides significantly reduced stink bug feeding injury with the exception of one harvest date of peppers in 2014, where the pyrethrins + azadirachtin combination product (Azera®) had less injury than the control. These results are consistent with others who have evaluated the field efficacy of some of these insecticides against stink bugs. Kamminga et al. (2009) did not observe differences in stink bug injury to tomatoes in the field from applications of pyrethrins, spinosad, azadirachtin, or combinations of the aforementioned insecticides. Carson et al. (2014) also found that foliar applications of *Burkholderia* sp. did not reduce stink bug and other heteropteran feeding injury to tomatoes in California.

In conclusion, several natural insecticides appear to have toxic activity on *H. halys* based on their performance in laboratory bioassays. However, in the field, we were not able to significantly reduce stink bug injury to fruiting vegetables with any of the natural insecticide treatments. There may still be useful applications for some of these products in *H. halys* management programs. For instance, pyrethrins have been shown to be effective at removing *H. halys* adults from wine grape clusters at harvest to prevent them from being crushed with the clusters (Pfeiffer et al. 2010). Also, Trope (2016) reported that applications of pyrethrins + azadirachtin were effective for killing *H. halys* in sorghum and sunflower trap crops. It is important that we keep exploring biorational and certified organic insecticide options for stink bugs in agricultural crop systems as this is a serious pest management concern with little to no effective control solutions currently (Lee et al. 2014; Rice et al. 2014).

Author contributions

JM and TK conceived and designed the research, analyzed data, and wrote the manuscript. All authors read and approved the manuscript.

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Compliance with ethical standards

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

References

Abbott WS (1925) A method of computing the effectiveness of an insecticide. J Econ Entomol 18:265–267

Abudulai M, Shepard BM, Mitchell PL (2003) Antifeedant and toxic effects of a neem (*Azadirachta indica* A. Juss)-based formulation Neemix(R) against *Nezara viridula* (L.) (Hemiptera: Pentatomidae). J Entomol Sci 38:398–408

Allen T, Link K, Ikawa M, Brunn L (1945) The relative effectiveness of the principal alkaloids of sabadilla seed. J Econ Entomol 38:293–296

Asolkar R, Koivunen M, Marrone P (2013) Isolated bacterial strain of the genus *Burkholderia* and pesticidal metabolites therefrom-formulations and uses. US Patent WO2013032693 A2

Basnet S, Maxey LM, Laub CA, Kuhar TP, Pfeiffer DG (2014) Stink bugs (Hemiptera: Pentatomidae) in primocane-bearing raspberries in southwestern Virginia. J Entomol Sci 49:304–312

Basnet S, Kuhar TP, Laub CA, Pfeiffer DG (2015) Seasonality and distribution pattern of brown marmorated stink bug (Hemiptera: pentatomidae) in Virginia vineyards. J Econ Entomol 108:1902–1909

Carson WG, Kund GS, Trumble JT (2014) Effect of insecticides on tomato insects, 2013. Arthropod Manag Tests 39:E6. doi:10.4182/amt.2014.E6

Casida JE (1980) Pyrethrum flowers and pyrethroid insecticides. Environ Health Perspect 34:189–202

Cissel W, Mason C, Whalen J, Hough-Goldstein J, Hooks C (2015) Effects of brown marmorated stink bug (Hemiptera:

pentatomidae) feeding injury on sweet corn yield and quality. J Econ Entomol 108:1065–1071

Desneux N, Decourtye A, Delpuech JM (2007) The sublethal effects of pesticides on beneficial arthropods. Annu Rev Entomol 52:81–106

Durmusoglu E, Karsavuran Y, Ozgen I, Guncan A (2003) Effects of two different neem products on different stages of *Nezara viridula* (L.) (Heteroptera: pentatomidae). J Pest Sci 76:151–154

Finney DJ (1971) Probit analysis, 3rd edn. Cambridge University Press, New York

Haye T, Abdallah S, Gariepy T, Wyniger D (2014) Phenology, life table analysis and temperature requirements of the invasive brown marmorated stink bug, *Halyomorpha halys*, in Europe. J Pest Sci 87:407–418

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

Hedstrom CS, Shearer PW, Miller JC, Walton VM (2014) The effects of kernel feeding by *Halyomorpha halys* (Hemiptera: Pentatomidae) on commercial hazelnuts. J Econ Entomol 107:1858–1865

Horowitz AR, Ishaaya I (2004) Biorational insecticides: Mechanisms, selectivity and importance in pest management. In: Horowitz AR, Ishaaya I (eds) Insect pest management: field and protected crops. Springer, Berlin, pp 1–20

Hull LA, Starner VA (1983) Impact of four synthetic pyrethroids on major natural enemies and pests of apple in Pennsylvania. J Econ Entomol 76:122–130

Isman MB (2006) Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu Rev Entomol 51:45–66

Kamminga KL, Herbert DA Jr, Kuhar TP, Malone S, Doughty H (2009) Toxicity, feeding preference, and repellency associated with selected organic insecticides against *Acrosternum hilare* and *Euschistus servus* (Hemiptera: pentatomidae). J Econ Entomol 102:1915–1921

Kuhar TP, Doughty H, Barlow V (2007) Laboratory bioassay of insecticides for the control of green stink bugs, 2006. Arthropod Manag Tests 32:L1. doi:10.1093/amt/32.1.L1

Kuhar TP, Kamminga K, Whalen J, Dively GP, Brust G, Hooks CRR, Hamilton G, Herbert DA (2012a) The pest potential of brown marmorated stink bug on vegetable crops. Plant Health Progress doi:10.1094/PHP-2012-0523-01-BR

Kuhar TP, Doughty H, Kamminga K, Wallingford A, Philips C, Aigner J (2012b) Evaluation of foliar insecticides for the control of brown marmorated stink bug in tomatoes in Virginia. Arthropod Manag Tests 37:E72. doi:10.4182/amt.2012.E72

Kuhar T, Doughty H, Kamminga K, Lilliston L (2012c) Evaluation of insecticides using a bean dip bioassay for control of brown marmorated stink bug, 2011. Arthropod Manag Tests 37:L1. doi:10.4182/amt.2012.L1

Kuhar T, Doughty H, Kamminga K, Wallingford A, Philips C, Aigner J (2013a) Evaluation of foliar insecticides for the control of brown marmorated stink bugs in bell peppers in Virginia—2012 test 1. Arthropod Manag Tests 38:E39. doi:10.4182/amt.2013.E39

Kuhar T, Doughty H, Kamminga K, Wallingford A, Philips C, Aigner J (2013b) Evaluation of foliar insecticides for the control of brown marmorated stink bugs in bell peppers in Virginia—2012 test 2. Arthropod Manag Tests 38:E40. doi:10.4182/amt.2013.E40

Kuhar T, Doughty H, Kamminga K, Wallingford A, Philips C, Aigner J (2013c) Evaluation of foliar insecticides for the control of brown marmorated stink bugs in bell peppers in Virginia—2012 test 3. Arthropod Manag Tests 38:E41. doi:10.4182/amt.2013.E41

Kuhar TP, Morehead JA, Dimeglio T (2015a) Diagnosing stink bug injury to vegetables. Virginia Cooperative Extension Publication Number ENTO-173NP. https://pubs.ext.vt.edu/ENTO/ENTO-173/ENTO-173.html. Accessed 15 Jan 2016

Kuhar T, Morrison R, Leskey T, Aigner J, Dively G, Zobel E, Brust G, Whalen J, Cissel W, Walgenbach J, Rice K, Fleischer S, Rondon S (2015b) Integrated pest management for brown marmorated stink bug in vegetables: a synopsis of what researchers have learned so far and management recommendations using an integrated approach. Northeastern IPM Center Bulletin posted on StopBMSB.org Website. http://www.stopbmsb.org/stopBMSB/assets/File/BMSB-in-Vegetables-English.pdf. Accessed 15 Jan, 2015

Lee D, Short B, Joseph S, Bergh J, Leskey T (2013) Review of the biology, ecology, and management of *Halyomorpha halys* (Hemiptera: pentatomidae) in China, Japan, and the Republic of Korea. Environ Entomol 42:627–641

Lee D-H, Short BD, Nielsen AL, Leskey TC (2014) Impact of organic insecticides on the survivorship and mobility of Halyomoorpha halys (Stål) (Hemiptera: pentatomidae) in the laboratory. Fla Entomol 97:414–421

Leskey TC, Hamilton GC, Nielsen AL, Polk D, Rodriguez-Saona C, Bergh JC, Herbert DA, Kuhar T, Pfeiffer D, Dively G, Hooks C, Raupp M, Shrewsbury P, Krawczyk G, Shearer PW, Whalen J, Koplinka-Loehr C, Myers E, Inkley D, Hoelmer K, Lee D-H, Wright SE (2012a) Pest status of the brown marmorated stink bug, *Halyomorpha halys* (Stål) in the USA. Outlooks on Pest Manag 23:218–226

Leskey TC, Lee D-H, Short BD, Wright SE (2012b) Impact of insecticides on the invasive *Halyomorpha halys* (Stål) (Hemiptera: pentatomidae): analysis on the insecticide lethality. J Econ Entomol 105:1726–1735

Leskey TC, Lee D-H, Short BD, Butler BR, Wright SE (2012c) Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in Mid-Atlantic tree fruit orchards in the United States: Case studies of commercial management. Psyche J Entomol 2012:1–14

Leskey TC, Short BD, Lee D-H (2013) Efficacy of insecticide residues adult *Halyomorpha halys* (Stål) (Hemiptera: pentatomidae) mortality and injury in apple and peach orchards. Pest Manag Sci. doi:10.1002/ps.3653

McPherson JE, McPherson RM (2000) Stink bugs of economic importance in America North of Mexico. CRC Press, Boca Raton, p 253

Mizell RF, Riddle TC, Blount AS (2008) Trap cropping system to suppress stink bugs in the southern coastal plain. Proc Fla State Hortic Soc 121:377–382

Nielsen AL, Hamilton GC (2009) Seasonal occurrence and impact of *Halyomorpha halys* (Hemiptera: Pentatomidae) in tree fruit. J Econ Entomol 102:1133–1140

Nielsen AL, Shearer P, Hamilton GC (2008) Toxicity of insecticides to *Halyomorpha halys* (Hemiptera: Pentatomidae) using a glass-vial bioassay. J Econ Entomol 101:1439–1442

Nielsen AL, Hamilton GC, Shearer PW (2011) Seasonal phenology and monitoring of the non-native *Halyomorpha halys* in soybean. Environ Entomol 40:231–238

Nielsen AL, Dively G, Pote JM, Zinati G, Mathews C (2016) Identifying a potential trap crop for a novel insect pest, *Halyomorpha halys* (Hemiptera: pentatomidae) in organic farms. Environ Entomol 45:472–478

Owens DR, Herbert DA Jr, Dively GP, Reisig DD, Kuhar TP (2013) Does feeding by Halyomorpha halys (Hemiptera: Pentatomidae) reduce soybean quality and yield? J Econ Entomol 106:1317–1323

Pfeiffer DG, Jordan TA, Laub CA, Mays RS (2010) Elimination of brown marmorated stink bug from wine grape clusters at harvest—2010. In: Proceedings of the Cumberland–Shenandoah fruit workers conference, Winchester, p 27–28.

Riba M, Martí J, Sans A (2003) Influence of azadirachtin on development and reproduction of *Nezara viridula* L. (Heteroptera: Pentatomidae). J Appl Entomol 127:37–41

Rice K, Bergh C, Bergmann E, Biddinger D, Dieckhoff C, Dively G, Fraser H, Garriepy T, Hamilton G, Haye T, Herbert DA, Hoelmer K, Hooks C, Jones A, Krawczyk G, Kuhar T, Martinson H, Mitchell W, Nielsen A, Pfeiffer D, Raupp M, Rodriguez-Saona C, Shearer P, Shrewsbury P, Venugopal D, Whalen J, Wiman N, Leskey T, Tooker J (2014) Biology, ecology, and management of brown marmorated stink bug (Hemiptera: Pentatomidae). J Integr Pest Manag 5:1–13

Rock GC (1979) Relative toxicity of two synthetic pyrethroids to a predator *Amblyseius fallacis* and its prey *Tetranychus urticae*. J Econ Entomol 72:293–294

SAS Institute Inc. (2007) JMP user's guide. SAS Institute Cary

Schmutterer H (1990) Properties and potential of natural pesticides from the neem tree, *Azadirachta indica*. Annu Rev Entomol 35:271–297

Seymour J, Bowman G, Crouch M (1995) Effect of neem seed extract on feeding frequency of *Nezara viridula* L. (Hemiptera: Pentatomidae) on pecan nuts. J Aust Entomol Soc 34:221–223

Soergel DC, Ostiguy N, Fleischer SJ, Troyer RR, Rajotte EG, Krawczyk G (2015) Sunflower as a potential trap crop of *Halyomorpha halys* (Hemiptera: Pentatomidae) in pepper fields. Environ Entomol 44:1581–1589

Sokal RR, Rohlf SJ (1995) Biometry (3rd edition). W. H. Freeman, New York, p 419

Tillman PG (2006) Sorghum as a trap crop for *Nezara viridula* L. (Heteroptera: Pentatomidae) in cotton in the southern United States. Environ Entomol 35:771–783

Trdan S, Žnidarčič D, Valič N (2006) Field efficacy of three insecticides against cabbage stink bugs (Heteroptera: pentatomidae) on two cultivars of white cabbage. Int J Pest Manag 52:79–87

Trope TN (2016) Trap-cropping and barrier crops for brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in organic vegetable crop systems. Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg

Wallingford AK, Kuhar TP, Pfeiffer DG, Tholl DB, Freeman JH, Doughty HB, Schultz PB (2013) Host plant preference of harlequin bug (Hemiptera: pentatomidae), and evaluation of a trap cropping strategy for its control in collard. J Econ Entomol 106:283–288

Walton R (1946) Sabadilla and DDT to control the squash bug. J Econ Entomol 39:273

Wiman NG, Parker JE, Rodriguez-Saona C, Walton VM (2015) Characterizing damage of brown marmorated stink bug (Hemiptera: pentatomidae) in blueberries. J Econ Entomol 108:1156–1163

Zehnder G, Gurr G, Kühne S, Wade M, Wratten S, Wyss E (2007) Arthropod pest management in organic crops. Annu Rev Entomol 52:57–80