Impact of Insecticides on the Invasive *Halyomorpha halys* (Hemiptera: Pentatomidae): Analysis of Insecticide Lethality

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ABSTRACT The efficacy of 37 insecticide treatments against adult *Halyomorpha halys* (Stål) was established based on exposure to 18-h old dry insecticide residue in laboratory bioassays. Individual adult *H. halys* were exposed to an insecticide residue for 4.5 h and then monitored daily for survivorship over a 7-d period. The proportion of dead and moribund insects was used as an estimate of overall insecticide efficacy against *H. halys* immediately after the exposure period and over the 7-d trial. Among all materials evaluated, 14 insecticides exhibited increasing efficacy, in which the percentage of dead and moribund insects (used as a measure of insecticide efficacy) increased by >10% after 7 d. By contrast, insecticide efficacy values of eight insecticides declined by >10% (based on recovery of adults from a moribund state) over the 7-d period with most belonging to the pyrethroid class. In this study, the efficacy value of neonicotinoid, acetamiprid, showed the greatest decline from 93 to 10% over 7 d. A lethality index (scale of 0–100) was developed to compare insecticides based on quantifying the immediate and longer-term effects of insecticide exposure on *H. halys*. Among all materials evaluated, dimethoate, malathion, bifenthrin, methidathion, endosulfan, methomyl, chlorpyrifos, acephate, fenpropathrin, and permethrin yielded the highest values (>75) because of a high degree of immediate mortality with very little recovery. Our results provide baseline information regarding potential of candidate insecticides against adult *H. halys* and highlight the need to consider longer-term effects in establishing overall efficacy ratings against this invasive species.

KEY WORDS pesticide, lethality index, insecticide efficacy, toxicity, susceptibility

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive species native to China, Japan, Korea, and Taiwan accidentally introduced into North America, likely in the mid 1990s (Hoebeke and Carter 2003), that has been officially detected in 38 states and the District of Columbia (Leskey et al. 2012a). *H. halys* is a polyphagous pest in its geographical range (Hoebeke and Carter 2003), and surveys conducted in the United States have identified a diverse array of crops that can serve as hosts (Bernon 2004). Recently, *H. halys* has emerged as a serious pest of orchard crops, small fruit, grape, vegetables, row crops, and ornamentals in the mid-Atlantic region (Leskey et al. 2012a). Estimating the economic and ecological impact associated with this invasive species remains difficult, but it is evident that feeding injury by *H. halys* can cause significant economic loss. Damage in apple in the mid-Atlantic region inflicted by *H. halys* resulted in losses in excess of 37 million dollars in 2010 (American/Western Fruit Grower 2011). In addition, *H. halys* is a serious nuisance pest in residential areas because it uses human-made structures as overwintering sites (Watanabe et al. 1994, Hamilton et al. 2008, Inkley 2012).

Considering the polyphagous and destructive feeding by *H. halys*, it is crucial to develop management programs for this invasive pest that can be applicable across diverse commodities and landscapes to reduce imminent and significant crop losses. Certainly, cultural and biological management programs offer greater potential for successful management in the long-term, compared with chemically based management programs (Pimentel 2005). However, as *H. halys* is a newly established invasive pest, there is a lack of basic biological knowledge, even in its native range, from which to develop sustainable pest management programs. These factors have resulted in the need for immediate insecticide-based management programs for *H. halys* (Leskey et al. 2012b) on various crops while other longer-term strategies can be developed.

Native stink bugs have long been managed with broad-spectrum insecticides such as organophosphates (Panizzi et al. 2000). However, since the passage of the Food Quality Protection Act (FQPA) of 1996, many broad-spectrum materials have been limited and prohibited through regulatory measures. To date, a limited number of compounds have been eval-

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uated against *H. halys.* Nielsen et al. (2008) used a scintillation glass-vial bioassay to evaluate residual activity of nine insecticides on *H. halys* and estimated LC_{50} values of the materials. They found that pyrethroid compounds could initially suppress *H. halys* within 24 h but that individuals were capable of recovering from this initial knockdown state over an additional 24-h period. Similarly, >33% of moribund adult *H. halys* recovered from direct exposure to a cyfluthrin application in a research apple orchard (Leskey 2011). In addition, anecdotal observations of high recovery rates of *H. halys* from insecticide exposure have been reported in commercial orchards. For this reason, it is important to document not only how quickly but also how decisively candidate insecticides suppress (e.g., kill or inactivate) *H. halys,* and the proportion of exposed individuals that recover from the initial insecticide effects. Otherwise, the overall potential of candidate insecticides could be overestimated if based on initial acute toxicity only. That is, candidate insecticides must be evaluated in terms of both initial effects and longer-term outcomes.

Therefore, the objectives of this study were to: 1) measure immediate effects of insecticide exposure on adult *H. halys,* 2) document the recovery and mortality rates of individuals over a 7-d period, and 3) establish the relative efficacy of all tested insecticides based on these two properties. This baseline knowledge will enable us to better predict insecticide efficacy against *H. halys* in the field and ultimately will assist with the construction of effective management programs.

Materials and Methods

Insect Source. For all bioassays, wild *H. halys* adults were collected from known human-made overwintering sites (e.g., storage sheds and houses) in Jefferson and Berkeley Counties, WV, and immediately brought back to the laboratory. Adults were then placed in screen cages (30 × 30 × 30 cm) for a minimum of 2 wk at a photoperiod of 16:8 (L:D) h, 25 ± 1°C, and 70 ± 10% relative humidity (RH) to break diapause and return adults to an actively foraging stage. Each cage was provisioned with a potted soybean plant and with peanuts, carrots, and/or sunflower seeds as food sources. Water was also provided in the cage, and food was changed twice weekly. Approximately 200 adults were held in each cage. Only those adults that began to actively forage and feed after the 2-wk period were used as test subjects in subsequent insecticide bioassays.

Bioassay. We developed our insecticide bioassay based on the underlying assumption that the primary threat by *H. halys* to cultivated hosts is posed by adults invading from other cultivated or wild hosts or from overwintering sites. This movement pattern increases the likelihood that most immigrating individuals will not encounter finished wet insecticide applications, but instead dry insecticide residue on the crop. The bioassay method we ultimately developed (measuring insecticide effects against *H. halys* following a prescribed exposure period to a dry residue of a candidate insecticide applied to a glass petri dish arena) was based on guidelines published by the International Organization of Biological Control (Candolfi et al. 2000).

Insecticides were mixed with water alone (as carrier) in accordance with the label recommendations for tree fruit in the mid-Atlantic (Pfeiffer et al. 2011) at a concentration equal to the use of 936 liters of finished spray material per hectare (Table 1). Finished sprays were atomized onto glass petri dish arenas (100 × 15 mm) at a volume equal to a delivery rate per unit area (≈505 μl per glass petri dish arena) similar to that encountered in commercial orchards when using properly calibrated airblast spray equipment (Pfeiffer et al. 2011). Insecticide residues were allowed to dry completely for 18 h in a fume hood before testing. Water alone was used as a control. In total, 37 treatments were evaluated that included 35 different active ingredients. In one treatment, we attempted to enhance the lethality of thiamethoxam by mixing it with kaolin clay that could potentially serve as a particle delivery system and improve contact uptake of the material. We also evaluated two formulations of the material tolfenpyrad.

In total, 30 adult *H. halys* (sex ratio = 1:1) were evaluated for each insecticide. A single individual represented a replicate as it was followed individually for 7 d. Each test subject was placed individually in the center of each treated petri dish arena and the arena was lidded to confine the adult. Exposure time to the insecticide residue was 4.5 h; this exposure time was established based on a conservative, biologically relevant estimate of continuous foraging activity by adult *H. halys* under field conditions (unpublished data). After 4.5 h, exposed insects were removed from arenas placed individually in clean 30-ml clear plastic cups (Jetware, Hatfield, PA) with sundried tomatoes, dried figs, sunflower seeds, and/or peanuts and wet cotton wick.

The condition of each *H. halys* was determined immediately after the exposure period and then daily for 7 d based on the following criteria:

1. Alive: Adult capable of moving with no sign of uncoordinated or uncontrolled activities;
2. Moribund: Adult obviously incapacitated and incapable of directed movement, but still responding to stimuli; and
3. Dead: Adult showing no movement and no response.

Insecticide Efficacy (E_t). For each insecticide, the percentage of dead and moribund insects was used as an estimate of the insecticide efficacy against *H. halys* at a given observation time (E_t). Counts of moribund and dead individuals were combined to calculate E_t based on the fact that a moribund insect cannot damage plants. However, by rating dead and moribund individuals separately when evaluating insecticide efficacy, it was possible to calculate the percentage of exposed individuals that recovered from insecticide exposure over time. That is, a decrease in E_t over time indicates that there was recovery by *H. halys* from a moribund state.

Table 1. Insecticides evaluated against *Halyomorpha halys* in laboratory bioassays

Class	Insecticide	Recommended field rate[a] (per ha)	Tested rate[a] (per ha)
Carbamates	Carbaryl	1,169–7,012 ml	4,675 ml
	Formetanate HCl	556–1,389 g	1,389 g
	Methomyl	556–1,112 g	1,112 g
	Oxamyl	2,338–9,350 ml	3,506 ml
Organophosphates	Acephate	n/a	1,100 g
	Chlorpyrifos	1,753–4,675 ml	4,675 ml
	Diazinon	1,753–4,675 ml	4,675 ml
	Dimethoate	1,112 g	1,112 g
	Malathion	3,506–7,013 ml	7,013 ml
	Methidathion	3,506–14,025 ml	14,025 ml
	Phosmet	1,478–6,113 g	4,446 g
Pyrethroids	Beta-cyfluthrin	98–196 g	182 g
	Bifenthrin	448–2,241 g	2,241 g
	Cyfluthrin	98–196 g	182 g
	Esfenvalerate	336–1,015 g	1,015 g
	Fenpropathrin	747–1,494 g	1,260 g
	Gamma-cyhalothrin	71–144 g	144 g
	Lambda-cyhalothrin	179–359 g	359 g
	Permethrin	280–1,120 g	1,120 g
	Zeta-cypermethrin	90–280 g	280 g
Neonicotinoids	Acetamiprid	175–560 g	560 g
	Clothianidin	140–420 g	224 g
	Dinotefuran[b]	1,120 g	1,120 g
	Imidacloprid	280–560 g	560 g
	Thiacloprid	140–560 g	560 g
	Thiamethoxam	140–385 g	315 g
Glycoside	Abamectin	700–1,400 g	1,400 g
Ryanodine receptor activator	Cyantraniliprole	1,400 g	1,400 g
Organochlorine	Endosulfan	1,566–7,784 ml	3,904 ml
Pyridinecarboxamide	Flonicamid	140–196 g	196 g
Oxadiazine	Indoxacarb	210–420 g	420 g
Particle film	Kaolin clay	27,788–111,150 g	13,894 g
Quinazolinone	Pyrifluquinazon	12–150 g	150 g
Tetramic acid	Spirotetramat	420–630 g	630 g
Pyridazinone	Tolfenpyrad[c] (EC)	n/a	1,471 g
Pyridazinone	Tolfenpyrad[c] (SC)	n/a	1,471 g
Particle film + Neonicotinoids	Kaolin clay + Thiamethoxam	27,788–111,150 g + 140–385 g	13,894 g + 315 g

[a] The application rate was per 936 liters per hectare, which is recommended for the application for tree fruit.
[b] The application rate was based on the use of Safari 20 SG for nonbearing tree fruit.
[c] EC, emulsifiable concentrate; SC, suspension concentrate.

Initial Versus Final Efficacy (E_0 *versus* E_7). To examine the relationships between initial and final efficacy for each insecticide, 37 treatments and water control were plotted for their initial efficacy at day 0 (E_0) on the x-axis and the final efficacy at day 7 (E_7) on the y-axis (PROC REG, SAS version 9.2; SAS Institute 2008). From this, insecticides were grouped based on the magnitude of their initial efficacy (E_0), as well as the change after 7 d (E_7 - E_0). The initial insecticide efficacy was classified as 'low,' 'moderate,' or 'high.' The low and high efficacy intervals were set as $E_0 \leq 10\%$ and $E_0 \geq 90\%$, respectively. These categories were established with a practical purpose; the two ends, $E_0 \leq 10\%$ and $E_0 \geq 90\%$, represent very poor and highly effective insecticides, respectively, with regard to initial impact on *H. halys.* In addition, changes in insecticide efficacy over the 7-d period (E_7 - E_0) were classified as 'stable,' 'increasing,' or 'decreasing.' If the efficacy difference was within ±10% from the original E_0, the insecticide was classified as stable. If the efficacy value changed by >10% after the 7-d period, the insecticide was classified as increasing [$(E_7 - E_0) > 10\%$] or decreasing [$(E_7 - E_0) < -10\%$]. Note that insecticides with low initial efficacy values ($E_0 \leq 10\%$) cannot be classified as decreasing because its efficacy cannot decrease by >10% from the initial value. Likewise, insecticides with high initial efficacy values ($E_0 \geq 90\%$) cannot be classified as increasing because efficacy cannot increase by >10% from the original E_0.

Insecticide Efficacy Change Over Time. We examined the dynamics of insecticide efficacy changes over time to evaluate how quickly a given insecticide suppressed *H. halys* and/or how quickly the insects recovered from a moribund state after initial insecticide exposure. We first calculated the difference between E_t and E_0 (E_t - E_0) for each insecticide at days 0–7. We then plotted the differences (E_t - E_0) during the 7-d observations. This allowed us to standardize this parameter across insecticides where all the values were set to zero at day 0 and the efficacy changes were expressed as departures from the initial efficacy over time. The patterns of these efficacy changes over time were compared among the insecticide groups with different initial efficacy ratings [low ($E_0 \leq 10\%$), moderate ($10\% < E_0 < 90\%$), and high ($E_0 \geq 90\%$)] using repeated measures analysis of variance (ANOVA) (PROC MIXED, SAS version 9.2; SAS Institute 2008). In the analysis, each insecticide was designated as unit where repeated measures were

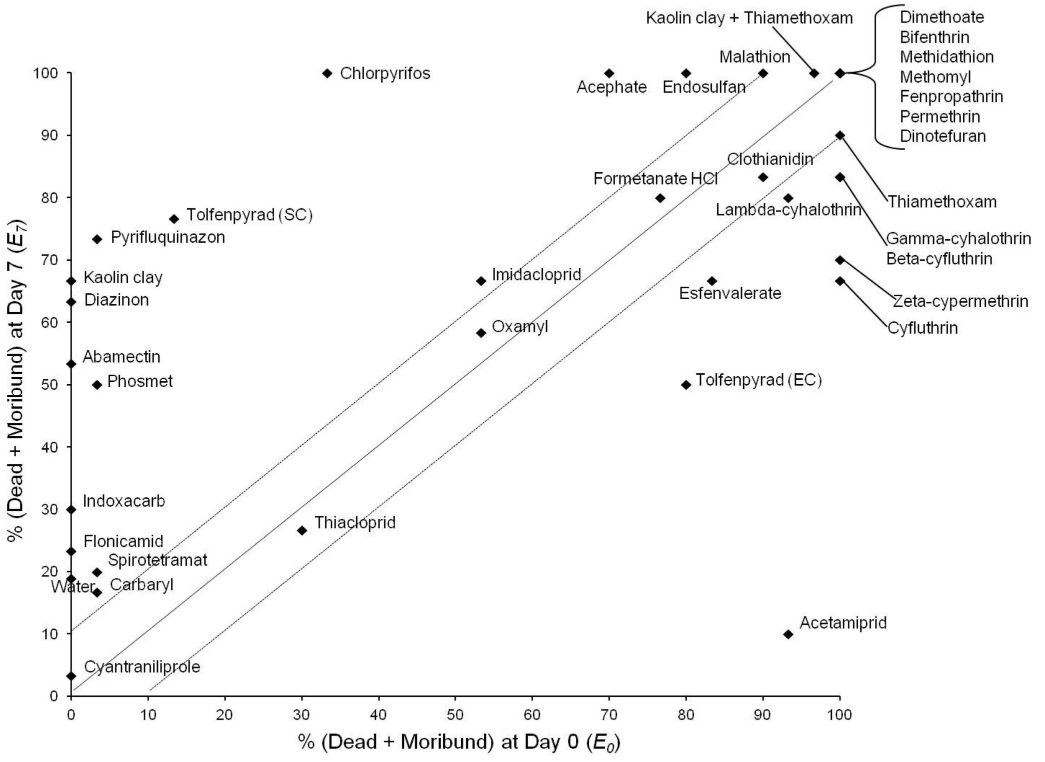

Fig. 1. The insecticide efficacy values at day 0 (E_0) and at day 7 (E_7) for 37 insecticides and water control. The slope of the solid line is 1, and the two dashed lines represent ±10% change efficacy values from the solid line.

taken and the significance of interaction term between time and insecticide group (low, moderate, and high) was tested.

Lethality Index. A lethality index was developed to directly compare candidate insecticides with consideration for changes in the states of *H. halys* over time after insecticide exposure. The index was calculated using the following equation:

$$\text{Lethality Index} = \left[\sum_{\text{day}=0}^{7} \frac{(\text{No. insects alive} \times 0.0) + (\text{No. insects moribund} \times 0.5) + (\text{No. insects dead} \times 1.0)}{240}\right] \times 100 \quad [1]$$

This equation assigns a value of 1.0, 0.5, or 0.0 to individuals classified as dead, moribund, or alive, respectively. Therefore, insecticides showing a slow onset or allowing recovery by the insects will have a lower lethality index value. The moribund state was assigned to a value of 0.5 because the individual was considered to be equally likely to recover or succumb. This is divided by 240 (30 adults × 8 evaluation days). The maximum value of the lethality index is 100; the minimum value is 0. The lethality index was compared among the insecticide groups of interests using ANOVA (PROC GLM, SAS version 9.2; SAS Institute 2008). The lethality index was log-transformed for the analysis.

Results

Initial Versus Final Efficacy. Overall, there was a significant positive correlation among insecticides between their initial efficacy and final efficacy (R^2 = 0.44; Fig. 1). Nevertheless, it is noteworthy that relatively high variations were present across the final efficacy (i.e., y-axis), especially for the insecticides with low ($E_0 \leq 10\%$) or high ($E_0 \geq 90\%$) initial efficacy. For the insecticides with low initial efficacy ($E_0 \leq 10\%$), the efficacy of nine out of 10 insecticides improved by >10% (=E_7 - E_0) after the 7-d period (above the upper dashed line, Fig. 1). Among them, the efficacy values of abamectin, diazinon, kaolin clay,

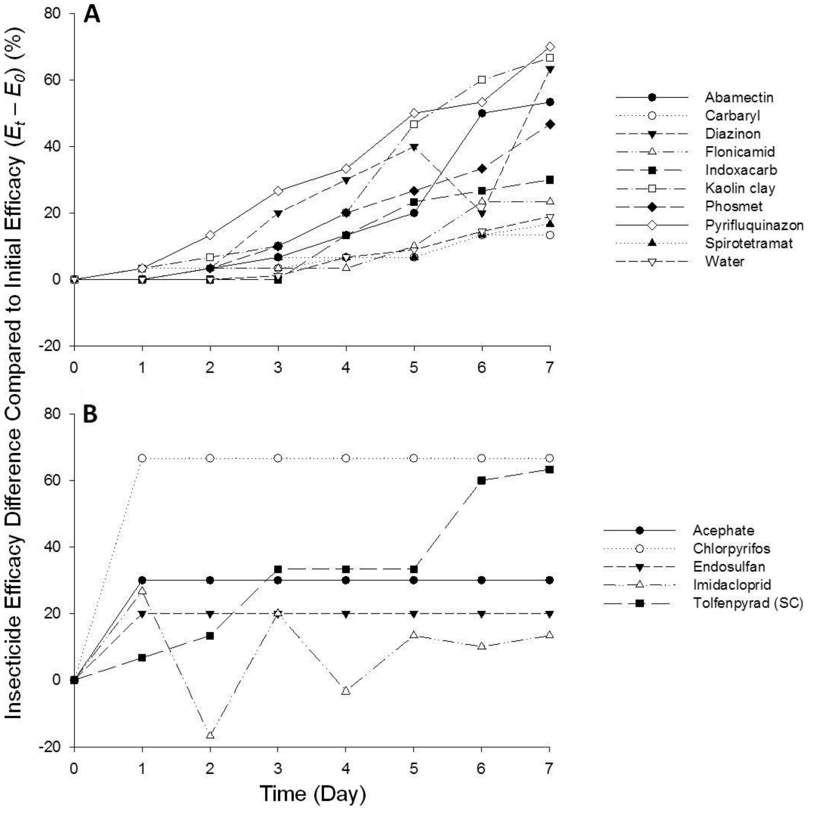

Fig. 2. Dynamics of insecticide efficacy changes over time for the insecticides that increased their efficacy value by >10% after 7 d. The dynamics were standardized across the insecticides as the departures from the initial efficacy over time (E_t - E_0). (A) Insecticides with low initial efficacy ($E_0 \leq 10\%$). (B) Insecticides with moderate initial efficacy ($10\% < E_0 < 90\%$).

and pyrifluquinazon increased by >50% after 7 d. For the insecticides with moderate initial efficacy values ($10\% < E_0 < 90\%$), the efficacy of five insecticides improved by >10% ($=E_7$ - E_0) after the 7-d period. In particular, the efficacy of chlorpyrifos increased from 33 to 100%. By contrast, the efficacy values of esfenvalerate and tolfenpyrad (EC) declined by 17 and 30%, respectively after the 7-d period (below the lower dashed line, Fig. 1). For those insecticides with high initial efficacy values ($E_0 \geq 90\%$), seven out of 17 insecticides showed a consistent 100% efficacy value at both day 0 and 7 (Fig. 1). In contrast, the efficacy values of six insecticides declined by >10% ($=E_7$ - E_0) after 7 d. Notably, the efficacy of acetamiprid declined from 93% at day 0 to 10% over 7 d, indicating that most of the moribund *H. halys* recovered from the initial exposure to the material. The percentage of dead and moribund insects (E_t) in the water control increased from 0 to 19% over the 7-d period. This represents the natural mortality level of the insects over 7 d under the experimental setting in this study.

Insecticide Efficacy Change Over Time. The dynamics of insecticide efficacy changes (E_t - E_0) were plotted over time for each insecticide. We examined efficacy change patterns for the 14 insecticides with efficacy values that increased by >10% ($=E_7$ - E_0) after the 7-d period (Fig. 2). Water was in this group but was not included in the data analysis. Overall, insecticides that exhibited low initial efficacy values ($E_0 \leq 10\%$), showed gradual increases in their overall efficacy throughout the 7-d period (Fig. 2A). However, the efficacy of insecticides with moderate initial efficacy ($10\% < E_0 < 90\%$) increased more rapidly within 3 d (Fig. 2B), compared with those with low initial efficacy (Fig. 2A) (F = 4.51; df = 7, 84; P = 0.0003). The maximum efficacy values of three insecticides (acephate, chlorpyrifos, and endosulfan) were reached after 24 h, at which the percentage of dead and moribund *H. halys* (E_1) reached 100%. In particular, the efficacy of chlorpyrifos increased by 67% after 24 h.

For the eight insecticides with efficacy values decreasing by >10% ($=E_7$ - E_0) after the 7-d period, the decrease in the efficacy values occurred generally during the first 3 d, regardless of the value of their initial efficacies (Fig. 3). Particularly, the efficacy values of acetamiprid declined by 80% during the first 3 d of the trial. There was no significant difference in the decrease patterns between insecticides with moderate and high initial efficacy values (F = 0.09; df = 7, 42; P = 0.9986) (Fig. 3A,B).

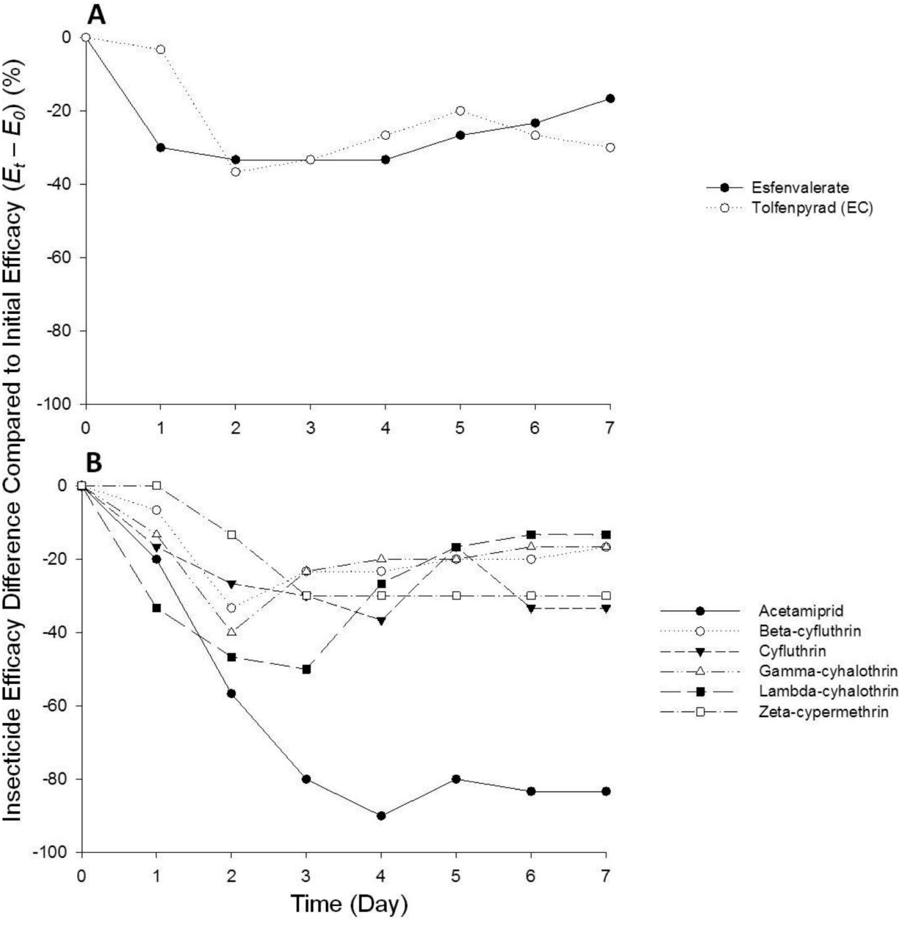

Fig. 3. Dynamics of insecticide efficacy changes over time for insecticides that decreased their efficacy value by >10% after 7 d. The dynamics were standardized across the insecticides as the departures from the initial efficacy over time (E_t - E_0). (A) Insecticides with moderate initial efficacy (10% < E_0 < 90%). (B) Insecticides with high initial efficacy (E_0 ≥ 90%).

Lastly, for the 15 insecticides with stable efficacy (Fig. 4), the majority of efficacy values did not increase or decrease by >10% during the 7-d observation, regardless of the magnitude of their initial efficacy (F = 0.57; df = 14, 84; P = 0.8847).

Lethality Index. The lethality index for each insecticide is presented in a descending order in conjunction with its initial efficacy (E_0) and efficacy change after 7 d (E_7 - E_0) (Table 2). There was a large variation in the lethality indices among the 37 insecticide treatments, ranging from 1.7 for cyantraniliprole to 93.3 for dimethoate. The median lethality index was 52.1 for zeta-cypermethrin; 25 and 75% quantiles were 20.4 for diazinon and 77.1 for permethrin, respectively. All insecticides with low initial efficacy values (E_0 ≤ 10%) were ranked below the 30% quantile (Table 2). Fifteen out of 17 insecticides with high initial efficacy values (E_0 ≥ 90%) were ranked above the median lethality index score. Collectively, the mean lethality index of the insecticides with low initial efficacy values was significantly lower than the insecticides with either moderate or high initial efficacy values (F = 29.49; df = 2, 34; P < 0.0001). There was no significant difference between the moderate and high initial efficacy groups (P = 0.4706) (Fig. 5).

Among the 37 insecticide treatments tested in this study, 26 insecticides were from the following four major classes: carbamates (n = 4), organophosphates (n = 7), pyrethroids (n = 9), and neonicotinoids (n = 6) (Tables 1 and 2). There was no significant difference in the lethality index among the four insecticide classes (F = 1.40; df = 3, 22; P = 0.2703). However, general patterns were found among the classes with regard to their initial efficacy and changes over time. For example, insecticide efficacy values of carbamates and organophosphates never decreased by >10% (=E_7 - E_0) after the 7-d period (Table 2), indicating that there was no measurable recovery by *H. halys* from the initial exposure to these two chemical classes. By contrast, most pyrethroid insecticides produced high initial efficacy values, but these values declined by >10% after 7 d for six out of nine insecticides in this class (Table 2). This indicates that recovery by *H. halys*

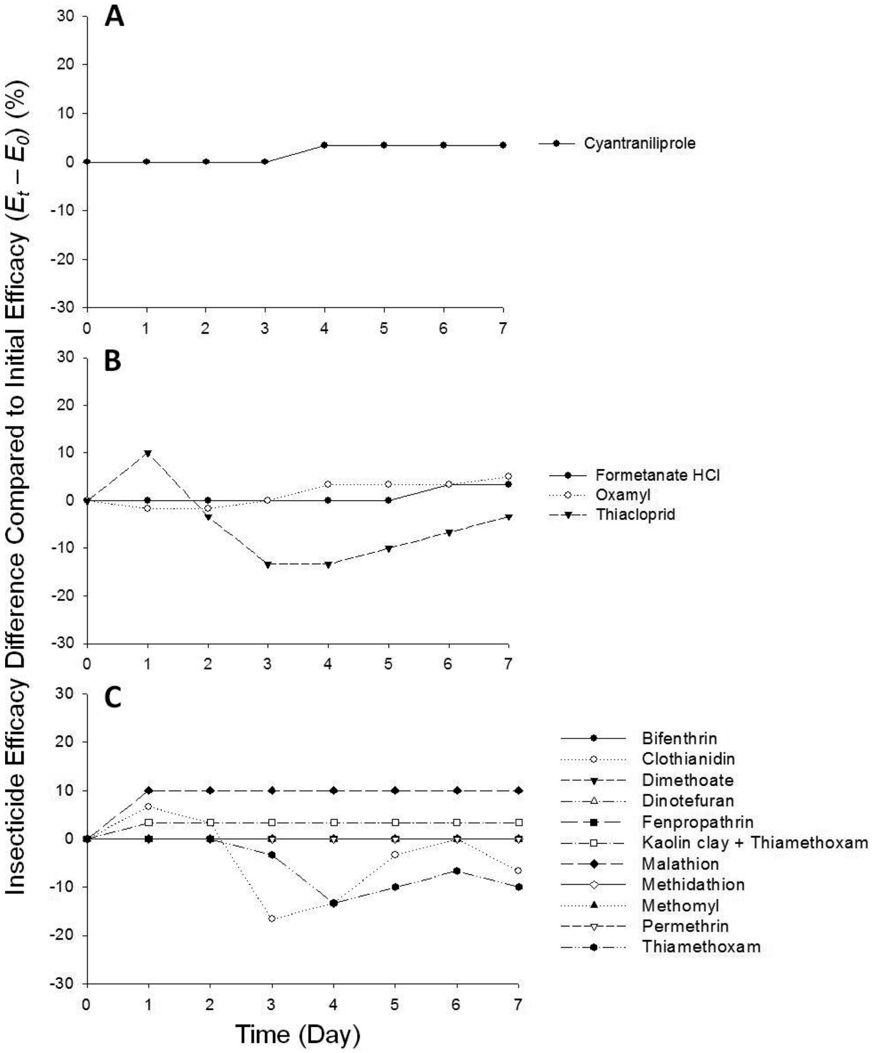

Fig. 4. Dynamics of insecticide efficacy changes over time for the stable insecticides that changed their efficacy value within ±10% after 7 d. The dynamics were standardized across the insecticides as the departures from the initial efficacy over time (E_t - E_0). (A) Insecticides with low initial efficacy ($E_0 \leq 10\%$). (B) Insecticides with moderate initial efficacy ($10\% < E_0 < 90\%$). (C) Insecticides with high initial efficacy ($E_0 \geq 90\%$).

occurred after initial exposure to these pyrethroid chemicals.

Discussion

Because *H. halys* is a newly established invasive pest in the United States, insecticides will play a key role in managing this pest on various crops at least in the short term. Indeed, the use of insecticides has substantially increased in commercial orchards because of the damage inflicted by *H. halys* (Leskey et al. 2012b) and subsequent economic loss in the mid-Atlantic region (American/Western Fruit Grower 2011). Therefore, it is critical to establish the efficacy of candidate insecticides for this new invasive pest. There was a significant difference in the overall impact on *H. halys* among the 37 insecticide treatments tested. This is evident from the large variation among lethality indices generated for each insecticide. Furthermore, the efficacy values of eight insecticides declined by >10% during the 7-d trial, indicating that >10% of *H. halys* were able to recover from a moribund condition after exposure to these materials. This finding calls attention to the importance of considering the recovery rate of *H. halys* from insecticide exposure, as well as the initial acute effects.

In particular, *H. halys* demonstrated substantial recovery from six out of nine pyrethroid insecticides after initial exposure to these materials (Table 2). Nielsen et al. (2008) reported a similar pattern from scintillation glass-vial bioassays during 48-h observations, in which *H. halys* recovered from a moribund state after exposure to five pyrethroids including beta-cyfluthrin, cyfluthrin, fenpropathrin, bifenthrin, and

Table 2. Lethality index of each candidate insecticide as well as the initial efficacy rating and the change in efficacy over the 7-d trial

Rank	Insecticide	Class[a]	Lethality index	Initial efficacy[b] (E_0)	Efficacy change[c] (E_7 - E_0)
1	Dimethoate	O	93.3	High	Stable
2	Malathion	O	92.5	High	Stable
3	Bifenthrin	P	91.5	High	Stable
4	Methidathion	O	90.4	High	Stable
5	Endosulfan	—	90.4	Moderate	Increasing
6	Methomyl	C	90.1	High	Stable
7	Chlorpyrifos	O	89.0	Moderate	Increasing
8	Acephate	O	87.5	Moderate	Increasing
9	Fenpropathrin	P	78.3	High	Stable
10	Permethrin	P	77.1	High	Stable
11	Dinotefuran	N	67.3	High	Stable
12	Kaolin clay + Thiamethoxam	—	66.7	High	Stable
13	Gamma-cyhalothrin	P	64.2	High	Decreasing
14	Formetanate HCl	C	63.5	Moderate	Stable
15	Thiamethoxam	N	56.3	High	Stable
16	Clothianidin	N	55.6	High	Stable
17	Beta-cyfluthrin	P	54.8	High	Decreasing
18	Lambda-cyhalothrin	P	52.9	High	Decreasing
19	Zeta-cypermethrin	P	52.1	High	Decreasing
20	Cyfluthrin	P	49	High	Decreasing
21	Oxamyl	C	46.8	Moderate	Stable
22	Esfenvalerate	P	43.3	Moderate	Decreasing
23	Imidacloprid	N	39.2	Moderate	Increasing
24	Tolfenpyrad (SC)	—	36.5	Moderate	Increasing
25	Tolfenpyrad (EC)	—	33.3	Moderate	Decreasing
26	Pyrifluquinazon	—	28.3	Low	Increasing
27	Kaolin clay	—	23.1	Low	Increasing
28	Diazinon	O	20.4	Low	Increasing
29	Phosmet	O	20.0	Low	Increasing
30	Acetamiprid	N	18.8	High	Decreasing
31	Thiacloprid	N	18.3	Moderate	Stable
32	Abamectin	—	16.3	Low	Increasing
33	Indoxacarb	—	11.3	Low	Increasing
34	Spirotetramat	—	9.8	Low	Increasing
35	Carbaryl	C	9.0	Low	Increasing
36	Flonicamid	—	7.7	Low	Increasing
37	Cyantraniliprole	—	1.7	Low	Stable

[a] C, carbamates; N, neonicotinoids; O, organophosphates; P, pyrethroids; —, others; EC, emulsifiable concentrate; SC, suspension concentrate (see Table 1).
[b] E_0 = the percentage of dead and moribund insects at day 0. Low for $E_0 \leq 10\%$; Moderate for $10\% < E_0 < 90\%$; High for $E_0 \geq 90\%$.
[c] Increasing for $(E_7 - E_0) > 10\%$; Decreasing for $(E_7 - E_0) < -10\%$; Stable for $-10\% \leq (E_7 - E_0) \leq 10\%$.

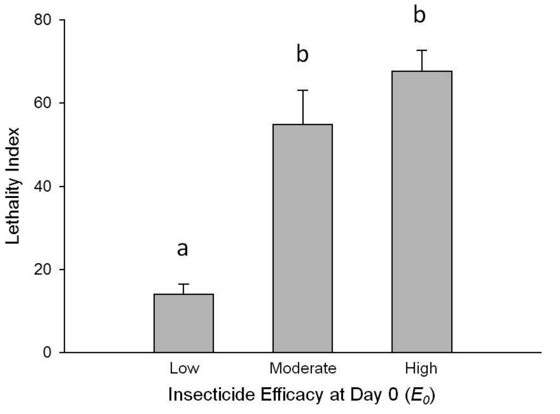

Fig. 5. Mean lethality index (±SE) for the three insecticide groups classified by their initial efficacy values at day 0 (E_0); Low ($E_0 \leq 10\%$), Moderate ($10\% < E_0 < 90\%$), and High ($E_0 \geq 90\%$). Means not followed by the same letter are significantly different ($P < 0.05$).

lambda-cyhalothrin. In our study, we also observed the recovery by *H. halys* from beta-cyfluthrin, cyfluthrin, and lambda-cyhalothrin; however, *H. halys* did not recover from exposure to bifenthrin and fenpropathrin. Interestingly, there was no evidence of recovery by the other two pentatomids, *Euschistus servus* (Say) and *Podisus maculiventris* (Say), from exposure to cyfluthrin residue in petri dish area (Tillman and Mullinix 2004). Indeed, they reported that cyfluthrin caused significantly higher mortality after 4 d, compared with 1 d after treatment. These findings suggest that recovery by pentatomids from pyrethroid insecticides can be variable among species.

The efficacy of four insecticides decreased by >30% (=E_7 - E_0) over 7 d. This includes acetamiprid, tolfenpyrad (EC), zeta-cypermethrin, and cyfluthrin. Although the initial efficacy values of these four insecticides was ≥80% (with E_0 values of zeta-cypermethrin and cyfluthrin at 100%), substantial recovery by *H. halys* from the initial knockdown effect occurred within 3 d (Figs. 1 and 3). This phenomenon is also reflected in the lethality index with these four chemicals ranking at or well below the median lethality index value because of the substantial *H. halys* recovery (Table 2). Indeed, these insecticides exemplify the importance of considering the long-term fate of exposed individuals when establishing efficacy ratings.

The efficacy value of acetamiprid showed the largest decline (from 93 to 10% over 7 d), indicating that most moribund *H. halys* recovered after initial exposure to this neonicotinoid material (Fig. 3). However, this type of recovery was not observed with adult *E. servus* and *P. maculiventris* in which the insects were exposed to the residues of acetamiprid for 24 h and then monitored over 3-d in petri dish arenas (Tillman and Mullinix 2004). The study by Nielsen et al. (2008) also did not report recovery by *H. halys* after exposure to neonicotinoids, but observations were made only until 48 h after exposure. However, results reported by Nielsen et al. (2008) were similar to ours in that *H. halys* was not as susceptible to acetamiprid compared with other neonicotinoids such as dinotefuran and thiamethoxam. In addition, Tillman and Mullinix (2004) cited other studies reporting that acetamiprid has little activity against *E. servus* in the field (Greene and Capps 2002, Ngo et al. 2002, Willrich et al. 2002). Therefore, these results strongly suggest that acetamiprid is not a promising material for controlling *H. halys* or other pentatomids.

At the completion of this study, there have been no published reports on the mechanism by which *H. halys* recovers from the effects of insecticides. However, this recovery should be documented and considered in terms of insecticide resistance monitoring. For example, Snodgrass et al. (2005) collected baseline data and reported that among *E. servus*, *Acrosternum hilare* (=*Chinavia hilaris* (Say)), and *Nezara viridula* (L.) obtained from soybean fields in the southeastern United States, *E. servus* was generally more tolerant to pyrethroid and organophosphate insecticides compared with the other two species. It seems critical that similar studies are needed for *H. halys* populations, particularly considering the increased use of broad spectrum insecticides against this invasive species (Leskey et al. 2012b). Indeed, potential resistance to several organophosphates and to endosulfan was detected in some populations of *E. heros* F. collected from soybean fields in Brazil (Sosa–Gomez et al. 2001).

Contrasting to the recovery by *H. halys* from the aforementioned insecticides, the efficacy values of 14 insecticides evaluated in our study increased by >10% (=E_7 - E_0) over the 7-d period with six materials increasing by >50% (=E_7 - E_0). These insecticides include abamectin, diazinon, kaolin clay, pyrifluquinazon, tolfenpyrad (SC), and chlorpyrifos (Fig. 1). However, except for chlorpyrifos, the efficacy increase was gradual and this resulted in lower lethality indices (Fig. 2). For this reason, the lethality indices of these insecticides, except for chlorpyrifos, were below the 40% quantile (Table 2). In contrast, the lethality index of chlorpyrifos was above the 80% quantile, reflecting its immediate increase in efficacy during the first 24 h. Although there are few trials testing chlorpyrifos against pentatomids, Kay et al. (1993) recommended the use of chlorpyrifos on rice to control a grain-feeding pentatomid, *Eysarcoris trimaculatus* (Distant), based on their bioassays. In tree fruit production, airblast applications of chlorpyrifos are not permitted for use after bloom (Pfeiffer et al. 2011), though this material is labeled on other crops such as soybeans, which has proven to be a good host for *H. halys* (Nielsen et al. 2011).

Among the 37 insecticide treatments tested, 10 insecticides scored above the 75% quantile in the lethality index rankings. They included dimethoate, malathion, bifenthrin, methidathion, endosulfan, methomyl, chlorpyrifos, acephate, fenpropathrin, and permethrin (Table 2). These insecticides appear to have a greater potential for controlling *H. halys,* compared with other chemicals. However, there are additional but important factors that must be considered when making recommendations based on our results. First, lethality of all candidate insecticides was evaluated in a controlled laboratory setting in which *H. halys* were confined on dry insecticide residue for 4.5 h. This no-choice bioassay did not allow *H. halys* to avoid insecticide residue during the exposure period. However, some insects have demonstrated that they can avoid insecticide materials through their sensory perception, and this behavioral change may decrease the overall efficacy (Haynes 1988). Thus, we cannot rule out the possibility that *H. halys* may be able to detect and avoid insecticide applications under field conditions. Second, test subjects were exposed to 18-h old dry insecticide residue. Although this methodology provides baseline information on efficacy of relatively new but dry residue, it does not provide data on the impact of wet spray material or older residues. Third, the use of certain insecticides is often limited by regulatory measures. For example, dimethoate, malathion, bifenthrin, and acephate are not labeled for use on apples on which *H. halys* have caused significant fruit injury and subsequent economic losses to growers (American/Western Fruit Grower 2011). In addition, the use of endosulfan will be prohibited on most crops by 2012 in the United States through EPA regulations (EPA 2010). Finally, the aforementioned broad-spectrum insecticides can have immediate adverse effects on the complex of natural enemies and this can lead to outbreaks of secondary pests in the field (Hardin et al. 1995). Recently, resurgence of woolly apple aphid and San Jose scale populations was reported in apple orchards in the mid-Atlantic region in which growers have substantially increased the use of broad-spectrum insecticides to manage *H. halys* (unpublished data).

Our current study demonstrates that the selection of candidate insecticides against *H. halys* should consider both the intensity of the initial acute toxicity as well as the change over time. The lethality index developed can serve as a useful standard to evaluate the overall efficacy of insecticides for *H. halys* or other target arthropods because this metric captures both immediate and longer-term outcomes by candidate insecticides on the pests. To our knowledge, few studies have taken into account the recovery by pentatomids from an initial moribund state over the course of a 7-d period. We believe this approach provides a more robust examination of overall efficacy of particular insecticides.

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