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Research

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Behavior

Can the Dispersal Behavior of *Halyomorpha halys* (Hemiptera: Pentatomidae) Inform the Use of Insecticide-Treated Netting to Mitigate Homeowner Issues From its Fall Invasion?

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Abstract

Brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is a serious agricultural pest and can be a significant nuisance when it invades human dwellings during its fall dispersal to overwintering sites. Methods informed by behavioral data to exclude or reduce its entry into buildings are needed. The temporal and spatial distribution of adults on an invaded building was assessed over multiple years, revealing its seasonal dispersal pattern and that its numbers varied by wall aspect. Moreover, its density was higher in recessed doorways than on associated walls, raising questions about its behavioral response to dark, contrasting surfaces. This response was evaluated using black, framed panels of deltamethrin-incorporated netting, non-treated netting, and an open frame with no netting, deployed in pairs on the wall of a private residence. More dispersing adults landed on panels of non-treated netting than on open panels, but there was no difference between panels with treated and non-treated netting. Adults remained on treated panels for less time than on non-treated panels, and most walked rather than flew from both. Adult male and female *H. halys* collected during the dispersal period were exposed to panels of treated and non-treated netting in a laboratory, using durations derived from field recordings. Exposures to treated panels intoxicated but did not kill them over a 7-d assessment period. The deployment of insecticide-treated netting, guided by the behavior of adult *H. halys* alighting on buildings, is discussed in relation to potential options to mitigate homeowner issues from this serious annual problem.

Key words: brown marmorated stink bug, home invasion, dispersal behavior

Since its widespread and severe outbreak in the Mid-Atlantic United States in 2010, the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), has established or been detected in 44 U.S. States, four Canadian provinces (StopBMSB.org), and several European countries (Haye et al. 2014, Leskey and Nielsen 2018), and is continuing to spread in the United States and abroad. Being highly polyphagous and feeding on both wild and cultivated plants, *H. halys* is widely distributed in the landscape and has caused significant economic losses to a range of crops in some areas (Leskey et al. 2012a, Leskey and Nielsen 2018). Moreover, it has proved to be a major nuisance pest for some home and business owners when the adults fly to and enter these dwellings during their search for an overwintering site in September and October. *H. halys* also utilizes overwintering sites in nature (Lee et al. 2014). Although the distribution of the overwintering population between natural and human-made sites is unknown, many thousands of adults may inundate the exterior walls of some residences over several weeks in the fall, causing significant life quality issues for the owners. An extreme illustration of this is depicted in a television news broadcast from northern Italy on 4 October 2017 (UdineToday 2017).

These adults are adept at entering dwellings via various crevices and openings. Some immediately infest the living areas, while others find tight, dark, and dry spaces (e.g., in the attic) where they tend to aggregate, become quiescent, and enter a facultative diapause. Subsequently, an equally problematic and more prolonged issue arises when they become active prematurely during the winter months and find their way into the living spaces, presumably in response to heat and light. Inkley (2012) reported collecting >26,000 adult *H. halys* from the interior of his home in rural MD between January and June of 2011.

Progress toward monitoring and managing *H. halys* in affected crops has been substantial (Leskey et al. 2012b, Khrimian et al. 2014, Weber et al. 2014, Leskey et al. 2015, Morrison et al. 2018), but research to address its status as a nuisance pest has lagged significantly. It is apparent that some residences are more vulnerable to heavy invasion by *H. halys* and that many of these tend to experience the worst problems annually. Hancock (unpublished data) conducted a citizen scientist survey examining differences in adult *H. halys* counts on the walls of private residences in the Mid-Atlantic region during its fall dispersal in relation to structural features of the buildings and surrounding landscape. Higher counts were recorded from homes of certain exterior colors and structural materials than others and from homes in rural settings.

Aigner and Kuhar (2014) compared several light-based traps for capturing adult *H. halys* overwintering in buildings and showed that one trap appeared to be superior, although overall weekly captures by trap design were relatively low and the authors did not attempt to relate captures with the number of adults overwintering in the buildings. Morrison et al. (2017) concluded that pheromone-baited pyramid traps deployed inside infested buildings during the winter were ineffective for monitoring or managing infestations of overwintering *H. halys*. Extermination using insecticides inside dwellings has its attendant set of issues, not least of which are that vulnerable buildings tend to be infested annually, and difficulties associated with finding and treating overwintering aggregations.

Preventing or reducing *H. halys* movement to existing buildings may not be feasible without effective suppression of its populations in the landscape, but methods to exclude it from accessing the building interior seem possible and are perhaps the best line of defense. Physical exclusion via sealing entry points has been used with some success (Bergh, personal observation), but can be challenging for large and/or older structures. Application of certain insecticides to exterior walls is an option, but may require re-treatment during the dispersal period, can also be difficult on larger buildings, and can be costly if a pest control operator is used.

Recently, there is increasing interest in the potential utility of insecticide-treated netting for managing crop and nuisance issues from *H. halys*. In a laboratory study, Kuhar et al. (2017) exposed *H. halys* adults and nymphs to black ZeroFly netting (Vestergaard-Frandsen, Lausanne, Switzerland) with the pyrethroid, deltamethrin incorporated into it, and showed that both life stages were intoxicated or killed. Peverieri et al. (2017) reported similar results from a laboratory study in Italy in which adult *H. halys* were exposed to Storanet (BASF, Ludwigshafen, Germany) containing the pyrethroid, alpha-cypermethrin.

Investigation of practical methods and options to exclude adult *H. halys* from entering occupied dwellings in the fall is needed, and pyrethroid-treated netting may provide novel applications toward that end. To be optimally effective, the development of such methods should be informed by behavioral data from the adults that invade exterior walls. Here, we first report the results of a multi-year assessment of the temporal and spatial distribution of adult *H. halys* counts on the walls of a building near Winchester, VA. These data raised questions about whether visual stimuli affected their alightment location or movement to certain locations on the building, prompting comparisons of panels of black, insecticide-treated and non-treated netting on this behavior and the duration of their exposure. Finally, the results from exposing adults to treated and untreated netting are presented, using exposure durations derived from field measurements on panels of treated netting.

Materials and Methods

Temporal and Spatial Distribution of *H. halys* Adults on Building Surfaces

Virginia Tech's Alson H. Smith, Jr. Agricultural Research and Extension Center (AHSAREC; 39°06′39.92″N, 78°16′48.15″W) is a single-story building near Winchester, VA that is surrounded by fruit orchards, field crops, woodlots, and scattered private residences (Fig. 1A). Its exterior is predominantly of medium gray, textured concrete block with beige block trim and its doorways are recessed (Fig. 1B). Following the widespread *H. halys* outbreak that began in summer 2010, many adults were observed flying to and alighting on the exterior walls of this building during the period of their dispersal to overwintering sites and that some walls and doorways were invaded most heavily. Thus, to examine the temporal patterns of this behavior and their spatial distribution on the building, counts were made of the adults on all exterior walls and in the doorways, by wall aspect, in 2012, 2013, and 2015–2017. Sampling began between 1 and 17 September in 2012, 2013, and 2015 and, based on results from those years, began on 15 September in 2016 and 2017. Sampling was conducted on most days through 20–29 October, with the exception of some cold, rainy, and/or very windy days and some weekend days. The number of sampling days in 2012, 2013, 2015, 2016, and 2017, respectively, were 35, 48, 52, 42, and 35. Across all years, daily sampling was usually at 1500 hours and not later than 1700 hours, and took ≤30 min per day. In 2015, counts were also made at 0800, 1000, 1200, 1400, 1500, 1600, and 1800 hours on 8 d between 16 September and 8 October when weather conditions were warm, dry, and relatively calm. Air temperature (°C) was recorded at the beginning of each sample interval during this 8-d period.

Experimental Panels and Field Site

Portable panels were used to assess the behavioral response of dispersing adult *H. halys* to visual stimuli on building walls. Frames (1 m^2) were constructed of 2.54 × 2.54 cm pine. A fitted square of black, polyethylene netting (mesh size = 32–33 holes/cm^2) (Vestergaard-Frandsen, Lausanne, Switzerland) with the pyrethroid insecticide, deltamethrin (0.4% w:w technical grade) incorporated into it, was stapled to the back of one frame and a square of the same netting that did not contain insecticide was attached to another. A fitted panel of cardboard that had been spray painted black (Satin Paint and Primer in One, Rust-Oleum Corp., Vernon Hills, IL) was nailed to these frames so that the black surface was appressed to the netting. A third frame had neither netting nor cardboard attached to it. Hereafter, we refer to these three treatments as, 1) open panel, 2) non-treated panel, and 3) treated panel. An eye-screw was inserted into the top of each frame near each corner, and a string tied at its ends to these was used to suspend the panels from two plastic hooks (Command Strips, 3M Corp., Maplewood, MN) mounted on a wall, enabling leveling of each frame.

The study site was an isolated, single-story residence in a 3.65 ha clearing atop a forested knoll in Rappahannock Co., VA (38°44′50.70″N, 78°06′54.14″W) at 370 m elevation and with a 360° view of other mountains in the distance and woodlands, agricultural land, and scattered homes below (Fig. 1C). Its exterior walls were of a textured, taupe colored concrete and the owners had experienced heavy invasion by *H. halys* each fall for numerous years. Based on the homeowner's observations about the relative density of *H. halys* on the different walls of the residence, the panels were deployed on the north half of an east-facing garage wall that was 8.6

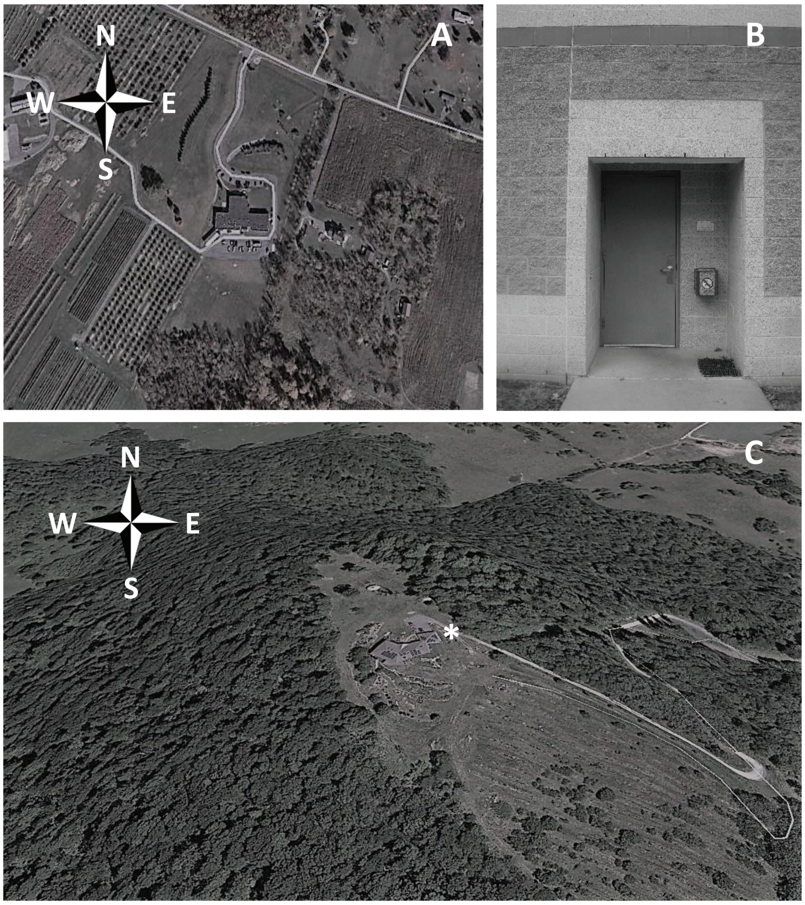

Fig. 1. (A) Aerial view of Virginia Tech's research center near Winchester, VA, where counts of adult *Halyomorpha halys* on the exterior surfaces were made during its fall dispersal to overwintering sites in 2012–2017, except 2014; (B) recessed east doorway of the building; (C) aerial view of the 2017 study site near Flint Hill, VA. Asterisk indicates east-facing garage wall on which panels were deployed.

m long × 3.35 m tall and had a window (2.03 m long × 1.08 m tall) at its midpoint. The hooks were mounted on the wall beneath the roof overhang, and the frames were suspended from them so that the top was 61 cm below the top of the wall. On each day of recording, two frames were positioned equidistantly between the north corner of the wall and the window, with 41 cm between them and the netting on non-treated and treated panels facing outward.

Alightment on Open Versus Non-treated Panels

Our first study examined whether a black panel on a building wall affected the alightment frequency of adult *H. halys*. On six consecutive days from 21 September 2017 to 26 September 2017, the open and non-treated panels were mounted on the wall and one observer per panel, seated about 2 m from the wall, recorded the frequency of landings and the time of each landing between 1430 and 1530 hours. Ideal weather prevailed during this period, with a mean ± SD temperature of 28.7 ± 2.9°C, relative humidity of 48.0 ± 5.9%, and a wind speed of 7.8 ± 4.7 km/h. Full sun or partial cloud occurred on 5 d and a high, thin overcast on one day, with no precipitation.

At the end of each recording session, the panels were returned to the laboratory and their positions were reversed each day. For this and the following study, only landings by adults observed making what appeared to be direct flights to the panels from some distance away were recorded. Landings following what we called 'short hop' flights (i.e., flew from the wall nearby and alighted on the panel) were not recorded. For the first 2 d, we did not differentiate between landings on the wall within the open panel and its frame or on the non-treated panel and its frame. During this time, we recognized that landings on the open panel tended to be mostly on its frame and not on the wall within the frame, and that those on the non-treated panel tended to me mostly on the black, netted surface. Consequently, on the final 4 d of this study, landings on the frame of both panels were recorded separately from those on the wall inside the frame or on the netting.

Alightment on Non-treated Versus Treated Panels

This study examined whether the treated panel affected the alightment frequency of adult *H. halys* and the duration of time spent on it. On six nonconsecutive days between 27 September 2017 and 5 October 2017, non-treated and treated panels were deployed using the same protocols described above, except that four seated observers participated. Two observers recorded landings on the frame and on the netting of each panel separately and the others (one per panel) recorded the duration between landing on and leaving the panel for a subset of adults on each. On 6 October, four observers recorded only the duration on the non-treated and treated panels. Our recording rule was to terminate observation of any individual that had not left the netting after 30 min, but there was only one instance of this. The behavior of adults leaving the screen (walking or flying off) was also recorded; leaving by walking was determined when none of the insect's tarsi were in contact with the netting as it walked onto the frame. Optimal weather conditions also occurred during this period, with a mean ± SD temperature of 26.7 ± 3.1°C, relative humidity at 40.0 ± 5.0%, and a wind speed of 7.1 ± 3.0 km/h. No precipitation occurred and most days were either full sun or partially cloudy, with one day of overcast.

Effects of Exposure to Non-treated and Treated Panels

After completing the daily observations described above, adult *H. halys* were collected from the walls of the same building, and predominantly from walls that had not been used for the panel comparisons. Males and females were held in separate screened cages in a laboratory at the AHSAREC. On 11 October, these adults were exposed to the same treated and non-treated (control) panels used in the field by placing the panels flat on the surface of a table in a laboratory. Five participants each removed a single, active insect from a cage and, at the timer's mark, dropped it onto a random location on the netting, ensuring that it was upright. Insects missing a body part were discarded and replaced in a subsequent exposure. The bottom half of a 50 × 9 mm, tight-locking Petri dish (Falcon 35–1006, Becton Dickinson and Co., Franklin Lakes, NJ) was immediately placed over each insect, allowing it to walk but to remain in contact with the netting. Three exposure durations were used, derived from the recordings on treated panels in the field, and included the mean duration (4.25 min) and plus and minus one standard deviation (7.25 min and 1.25 min, respectively). Males and females were exposed separately, with 40 replicates of each sex per exposure duration and treatment.

Immediately following these exposures, the insects were placed individually in 37 ml, opaque, lidded cups (Dixie Cup, Fort James Corp., Norwalk, CT) labeled with the sex, treatment, exposure duration, and replicate. Water and food were not provided, as adult *H. halys* are not known to require either during the overwintering period. These were held in plastic cup trays in a dark, controlled-environment chamber at 25°C and the status of each adult was recorded at about 24-h intervals for 7 d using three categories, 1) live, 2) moribund, and 3) dead. Live bugs were upright, often walking, and showed coordinated leg and antennal movement. Moribund bugs were most often observed on their back and had uncoordinated or lethargic leg and antennal movement when shaken or prodded lightly, while dead bugs showed no movement when prodded.

Statistical Analysis

Statistical analyses used JMP Pro 13 (SAS Institute 2016) and SAS 9.4 (SAS Institute, Cary, NC) (SAS Institute 2012) and outcomes were considered significant at $P < 0.05$. The seasonal and daily temporal distribution of adult *H. halys* counts was depicted using descriptive statistics. To examine their overall distribution by wall aspect, counts on all east-, west-, north-, and south-facing walls plus doorways were pooled for each of the 5 d between 15 September and 15 October when daily counts were highest each year. These data were analyzed using Generalized Linear Mixed Models (PROC GLIMMIX) with Kenward-Roger degrees of freedom adjustment and the Poisson distribution, with aspect as the main effect and year as a random effect. Where main effects were significant, pairwise Tukey–Kramer adjusted least-square means tests were performed to determine differences among treatments. To compare the density of bugs among these surfaces (wall and doorway), the surface area (m^2) of each wall and doorway (three doorway walls, including door, and ceiling) was calculated. Data from the same 5 d of peak counts per year were pooled for doorways and walls separately, by aspect, and converted to counts per m^2 of surface area. Data were log transformed for normality and analyzed with PROC GLIMMIX, using the residual degrees of freedom method and the normal distribution, with aspect and surface type (door or wall) as the main effects and year as a random effect. Where main effects were significant, pairwise Tukey–Kramer adjusted least-square means tests were performed to determine differences among surface/aspect combinations. The number of landings recorded on open versus non-treated panels and on non-treated versus treated panels, and the duration of time spent on non-treated versus treated panels, were compared using Student's *t*-test. The frequency of landings on frames, the wall within the open panel, or the netting of the untreated or treated panels was compared using Pearson's chi-squared contingency analyses. The same analysis was used to compare the number of adults that walked or flew from the netting on untreated versus treated panels after alighting on them. The rate of landings on open versus non-treated panels and on treated versus non-treated panels over the 60-min observation period was depicted using descriptive statistics. The effect of exposure to treated panels in the laboratory, as recorded on day 7 (moribund plus dead), was compared between males and females for each exposure duration using Pearson's chi-squared analysis, and the same analysis was used for comparisons between treated and untreated panels for males and females.

Results

Temporal and Spatial Distribution of *H. halys* Adults on Building Surfaces

Total annual counts of adult *H. halys* in 2012, 2013, 2015, 2016, and 2017, respectively, were 7,170, 5,666, 3,808, 2,012, and 633. Data from 2012, 2013, and 2015 revealed that 88.2 ± 3.3% SD of total annual counts occurred between 15 September and 15 October, thus prompting the onset of sampling on 15 September in 2016 and 2017. Counts throughout the day over 8 d in 2015 revealed lowest numbers of adults at 0800 and 1000 hours, followed by a steady increase through 1500 hours and a slight increase between 1500 and 1600 hours, after which their numbers tended to diminish gradually through 1800 hours (Fig. 2), confirming that our daily sampling at 1500 hours was appropriate. The number of adults was relatively low from early through mid-September, and then increased gradually until an initial peak of dispersal that tended to occur within 1–2 d of 21 September, the autumnal equinox (Fig. 3). Thereafter, 2 or 3 periods of highest counts were typical from late September until about the end of the first week of October, after which their numbers tended to decline.

There was a significant effect of wall aspect on adult counts ($F_{3,1} = 987.15$, $P < 0.05$), with significantly higher numbers on east and north than on south and west walls plus doorways (Fig. 4A). Analysis of counts per m^2 of surface area revealed significant effects of aspect ($F_{3,32} = 73.45$, $P < 0.0001$) and surface type ($F_{1,32} = 527.13$, $P < 0.0001$) and a significant interaction between them ($F_{3,32} = 8.62$, $P < 0.001$). Regardless of aspect, significantly higher densities of adults per m^2 were found in doorways than on their corresponding walls, with highest density in the east and north doorways (Fig. 4B).

Alightment on Open Versus Non-treated Panels

Across all sampling days, significantly more adult *H. halys* landed on the non-treated panel (44.83 ± 14.31 SD per day) than on the open panel (19.17 ± 5.98 per day) ($t = 4.052$, $P < 0.01$) during the 1-h sampling period. The rate of landings during the sampling period was essentially constant for each treatment, but lower for the open than the non-treated panel (Fig. 5A). During the 4 d when landings

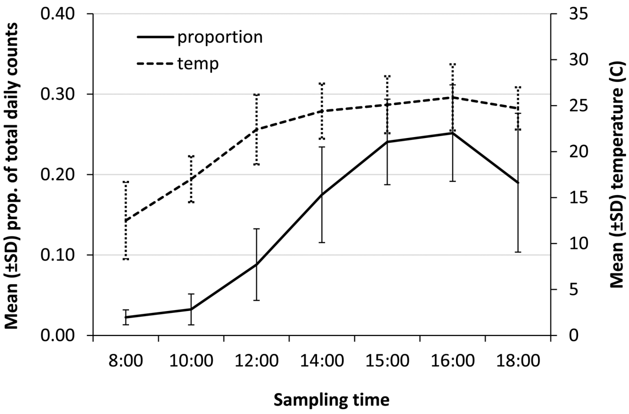

Fig. 2. Mean (SD) proportion of daily counts of adult *Halyomorpha halys* at 1–2 h intervals on the exterior walls and recessed doorways of Virginia Tech's research center near Winchester, VA on 8 d between 16 September 2015 and 8 October 2015, during its dispersal to overwintering sites.

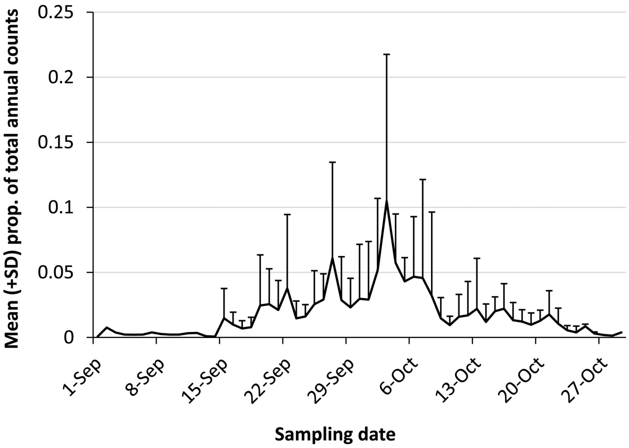

Fig. 3. Mean (SD) counts of adult *Halyomorpha halys* on the exterior walls and recessed doorways of Virginia Tech's research center near Winchester, VA during its fall dispersal to overwintering sites in 2012–2017, except 2014. Error bars are provided for the dates on which sampling was conducted in at least 3 yr. Total annual counts in the consecutive years were 7,170, 5,666, 3,808, 2,012, and 633.

on the panel or the wall within the open panel were recorded separately from those on the frame, landing frequency on the wall within the open panel (34.7% of landings) was significantly lower than on the black netting of the non-treated panel (76.8% of landings) ($\chi^2 = 37.482$, $P < 0.001$).

Alightment on Non-treated Versus Treated Panels

There was not a significant difference between the number of landings on non-treated (34.5 ± 43.6 SD per day) and treated (36.0 ± 31.0 SD per day) panels ($t = -0.3606$, $P = 0.6371$). Most landings were on the black netting and not the frame of non-treated (83.7%) and treated (82.2%) panels, with no significant difference between treatments ($\chi^2 = 0.043$, $P = 0.836$). The rate of landings during the sampling period was essentially constant and very similar between the treatments (Fig. 5B). However, adults spent significantly less time on treated (4.26 ± 3.04 SD min) than non-treated panels (7.27 ± 6.74 min) ($t = 2.783$, $P < 0.01$). Most adults walked off rather than flew from both untreated (91.7%) and treated panels (88.5%), with no significant difference between them ($\chi^2 = 0.292$, $P = 0.589$).

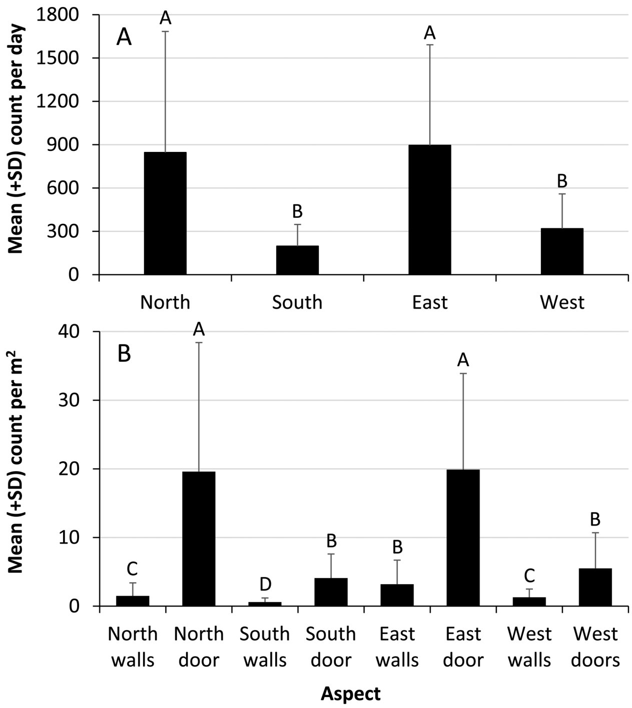

Fig. 4. Counts of adult *Halyomorpha halys* on the exterior walls and recessed doorways of Virginia Tech's research center near Winchester, VA during its dispersal to overwintering sites in 2012–2017, except 2014. Calculations were based on pooled data from the 5 d of peak counts annually; total counts across these days in the respective years were 5,001, 3,019, 2,157, 840, and 270; (A) mean (SD) counts from walls plus doorways by aspect, and (B) mean (SD) counts by wall and doorway surface area (m^2) and aspect. Letters above bars indicate significant differences at $P < 0.05$, based on GLMMIX using the Poisson distribution of counts and the pairwise Tukey–Kramer least-square means test.

Effects of Exposure to Non-treated and Treated Panels

Overall, very few adult male or female *H. halys* exposed to the non-treated, control panel were moribund or dead during the 7-d assessment period (Fig. 6D–F and J–L). On day 7, there was not a significant difference between the number of affected (moribund plus dead) males and females that had been exposed to the treated panel for 1.25 min ($\chi^2 = 1.385$, $P = 0.378$) or 4.25 min ($\chi^2 = 3.646$, $P = 0.093$). Exposure to the treated panel for 7.25 min resulted in significantly more moribund plus dead males than females on day 7 ($\chi^2 = 7.812$, $P = 0.010$). Exposure of males to the treated panel resulted in substantial numbers of moribund individuals 24 h after exposure. This was most pronounced among those exposed for the two longest durations (Fig. 6A–C), but many males recovered from the exposure. However, on day 7, significantly more males were affected following exposure to the treated than the control panel across all exposure durations (1.25 min: $\chi^2 = 7.314$, $P = 0.014$, 4.25 min: $\chi^2 = 13.066$, $P < 0.001$, 7.25 min: $\chi^2 = 7.812$, $P = 0.010$). Similarly, the most pronounced effect on females exposed to the treated panel was intoxication at 24 h after exposure (Fig. 6G–I), although overall, fewer females than males showed this symptom. Like males, many females tended to recover from this exposure over the assessment period. However unlike males, on day 7 there was not a significant difference in the number of affected females between the treated and control panel for any exposure duration (1.25 min: $\chi^2 = 2.882$, $P = 0.200$, 4.25 min: $\chi^2 = 3.529$, $P < 0.114$, 7.25 min: $\chi^2 = 3.116$, $P = 0.240$).

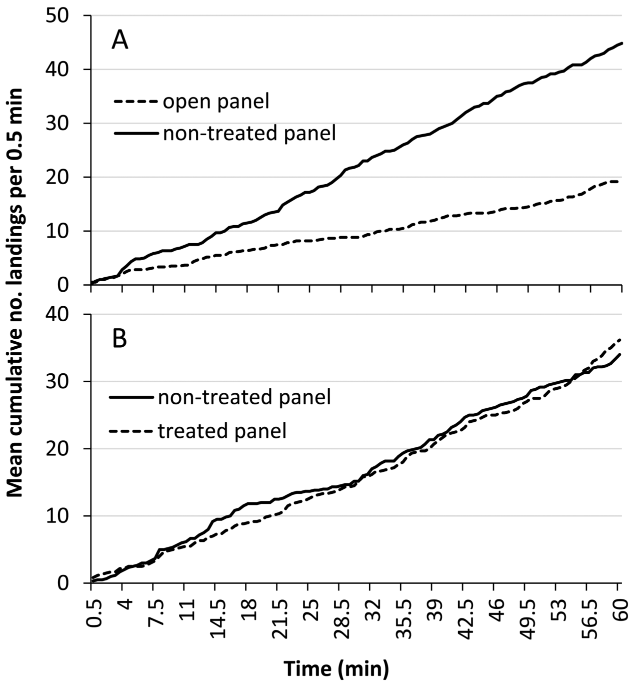

Fig. 5. Rate of landings by adult *Halyomorpha halys* per 0.5-min interval over 60 min on experimental panels mounted in pairs on an exterior wall of a private residence near Flint Hill, VA, during the period of its dispersal to overwintering sites in fall, 2017; (A) open versus non-treated panel, (B) non-treated versus insecticide-treated panel.

Discussion

These studies provide new information about the temporal pattern of adult *H. halys* dispersal to overwintering sites in the fall and their spatial distribution on an invaded building. Adult density was highest on the shaded north and east walls and in the recessed doorways of the building exterior, regardless of aspect, prompting questions about their behavioral response to dark, contrasting surfaces on a building. A panel of black netting on a building wall increased the frequency of their alightment, independent of whether the netting was treated with deltamethrin insecticide, providing proof-of-concept that this netting might be used in tactics to exclude adult *H. halys* from the building interior. Adults spent less time on the insecticide-treated panel than on the non-treated panel and the duration of exposure to the treated panel was sufficient to intoxicate many adults, but not to kill them, suggesting that this potential tactic needs to be further explored and refined.

In 2013 and 2015, when counts of *H. halys* on the building exterior began in early September, adults were seen throughout that month, but in much lower numbers than from late September until early to mid-October. The diel pattern of adult dispersal was identical to that of *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae) during its fall dispersal in North Carolina (Nalepa et al. 2005); peak daily movement to buildings by both species was between 1400 and 1600 hours, and subsided thereafter. The onset of mass dispersal by *H. halys* on or near 21 September coincided with the autumnal equinox and confirmed with reports from citizen scientist volunteers that counts of adult *H. halys* on private residences the Mid-Atlantic region also showed a marked increase on or near that date (Hancock, unpublished data). These observations suggest that a critical day length may trigger a behavioral transition from feeding to dispersing by adults that are physiologically prepared to overwinter.

After this first peak of dispersal, subsequent days of highest adult counts occurred between about 27 September and 7 October, although in some years relatively large numbers were recorded on individual days through mid-October. After about 21 September, the days on which peak counts occurred were somewhat less predictable, with the exception of cool, windy, and/or rainy days, when counts were always low. The protracted movement of adults to the building through most of October likely reflected a staggered completion of development of nymphs from eggs laid in July and August (Nielsen et al. 2016, Acebes-Doria et al. 2017).

Nalepa et al. (2005) proposed a sequence of behavioral events that guide the dispersal to and selection of overwintering sites by *H. axyridis*, including long-range orientation to macrosites that present prominent and contrasting visual stimuli in the landscape, and increasingly shorter-range orientations to specific locations associated with these macrosites, within which overwintering aggregations may form. It is likely that adult *H. halys* also orient initially to visual stimuli associated with particular macrosites, such as buildings and natural landscape features. For example, large numbers of *H. halys* adults have been observed at rocky promontories atop ridgelines during the fall dispersal period in the Mid-Atlantic region (Leskey, personal communication). With respect to the movement of *H. halys* to buildings, closer-range sensory cues appeared to influence the alightment location; total counts were consistently highest on east and north walls, which were in full shade during the period when daily counts peaked. This effect of wall aspect validated reports from many homeowners (Bergh, personal observation), including the home where the netting panels were evaluated, and those from citizen scientists (Hancock, unpublished data). Moreover, the density of adults was always higher in the recessed doorways than on the associated walls. Differences in the temperature and light intensity between the walls and doorways were not measured, but one or both may have provided orientation and/or alightment cues. Because most of these counts occurred at one time point (about 1500 hours), it is not possible to determine whether the insects flew directly to the doorways or arrived in them after alighting on a wall. However, in combination, these results indicated that certain qualities of the east- and north-facing walls and associated doorways influenced the adult's orientation to them. Differences in the number of adults recorded on walls by aspect did not appear to be associated with differences in the landscape around the building, which did not change during the study. The main east-, west-, north-, and south-facing walls were about 25, 105, 557, and 216 m, respectively, from the nearest wild tree hosts, whether a tree line or woodlot. Higher bug density in the darker, recessed doorways, regardless of aspect, may suggest that these areas appeared to the insect as a potential access point to the protected locations where they overwinter, prompting our hypothesis that panels of contrasting, black netting on a building wall might affect their alighting behavior.

This hypothesis appears to have been supported by the results of paired comparisons of open and non-treated panels deployed on an east-facing wall during the period of daily peak dispersal, when the wall and the panels were in full shade. Significantly greater numbers of adults alighted on the black, non-treated panel than on the wall within the open panel. Furthermore, the panel of insecticide-treated netting did not affect their landing frequency, indicating a possible role for this netting in manipulating their alighting behavior. However, the very low mortality of adult males and females exposed to treated panels for durations derived from field observations certainly highlights the need for possible refinements to increase the exposure duration, as discussed below.

Kuhar et al. (2017) evaluated the response of adult *H. halys* collected from the walls of a building in the fall to the same deltamethrin-treated netting used in the present study, although fundamental differences in their protocols preclude direct comparisons with our

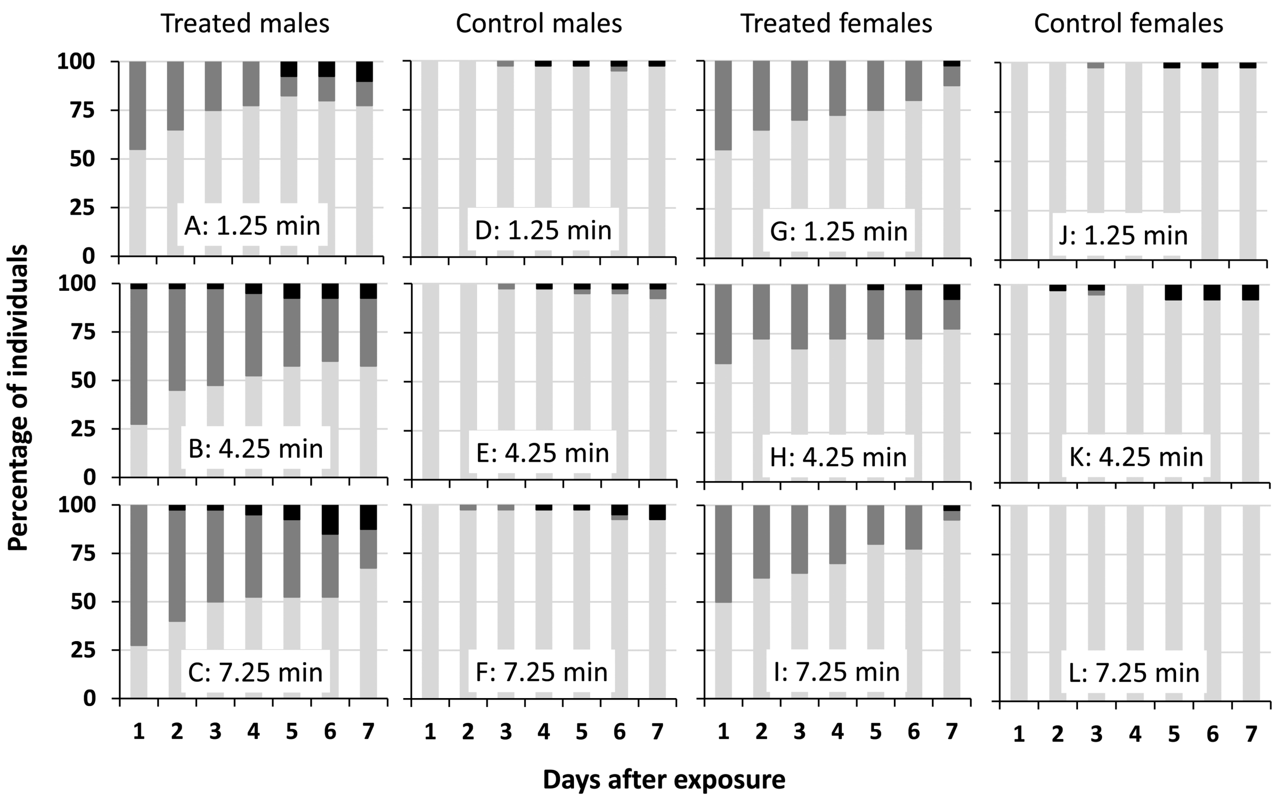

Fig. 6. Status of (A) male and (B) female *Halyomorpha halys* adults over 7 d following three durations of exposure to panels of insecticide-treated and non-treated netting in a laboratory. Exposure durations represent the mean ± 1 SD duration recorded for adults that landed on treated panels in the field. Black, dark gray, and light gray sections of bars represent dead, moribund, and live individuals, respectively.

results. They exposed groups of ten adult *H. halys* (male plus female) simultaneously to the netting, which lined 1-liter plastic containers, for 10 s, 1 min, and 10 min, and evaluated the response after 24 h, when moribund and dead individuals were combined into one category (i.e., mortality). The percentage mortality reported following 10 s, 1 min, and 10 min exposures was about 40, 48, and 92%, respectively. While we recorded dead individuals at 24 h after exposure on only one occasion (2.5% dead males following a 4.25-min exposure) (Fig. 6B), 45% of both males and females were moribund at 24 h after a 1.25-min exposure, concurring with the results from the 1-min exposure reported by Kuhar et al. (2017).

Substantial differences between these two studies were that we exposed males and females separately, used separate categories for moribund and dead, and tracked their status over 7 d. In this regard, our study was more similar to that of Peverieri et al. (2017), who exposed individual adult male and female *H. halys* collected from overwintering sites in January to alpha cypermethrin-incorporated netting (Storanet, BASF, Ludwigshafen a. R., Germany) lining the bottom of a Petri dish. Following exposures of 5, 15, 30, 45, and 60 min, they monitored the status of each insect daily for ≥5 d, using live, moribund, and dead as the response variables. Regardless of exposure duration, most affected individuals were moribund after 24 h, but mortality was usually not evident until ≥2 d following the exposure. The mortality of males and females increased with increasing exposure duration and was higher in males than females for each duration. Exposures for 5 and 15 min resulted in many individuals recovering over time, as we observed, and as was shown by Leskey et al. (2012b) for adult *H. halys* exposed to dry pyrethroid residues in a laboratory assay. The shortest exposure duration (5 min) used by Peverieri et al. (2017) resulted in much higher male (50%) and female (40%) mortality than we observed, possibly due to the different active ingredients used, their concentration, and/or the physiological state of the tested insects.

These different studies indicate that, 1) adult *H. halys* that alight on pyrethroid-treated netting will become moribund following a relatively short exposure duration and, 2) longer exposure times increase mortality, raising questions about the ultimate fate of moribund individuals in the field and about ways to increase the duration of their exposure. Assuming that paralyzed adults eventually fall to the ground and remain there for some time (especially given the effect of cooler fall nights on their metabolism and recovery rate), ground-dwelling invertebrate and vertebrate predators may consume at least some of them. It may be possible to re-expose or increase the exposure duration of adults to the netting. For example, intoxicated insects that fall from a wall may upon recovery walk up the same wall, where they could again encounter treated netting near the wall base. Because most adult *H. halys* that alighted on the treated panel walked rather than flew from it, the average exposure time could be increased to some extent by increasing the size of the netting surface. Also, because these insects tend to follow edges as they walk, folds in the panel netting may guide them, toward increasing the exposure duration. Combining treated panels like those used here with other treated surfaces on a building might increase mortality. Nalepa et al. (2005) noted that many *H. axyridis* alighted on parts of buildings that provided 'contrasting linear elements,' such as gutters, drainpipes, and porch frames, among others, conforming to our observation that *H. halys* alighted more frequently on the frame of the open, control panel than on the wall inside it. Similarly, we observed that many adults alighted and walked on the corner of the building nearest the panels at the study site. Consequently, a frame of treated netting fitted to such corners could be another source of exposure. Furthermore, adult *H. halys* that alight on a building tend to move up the wall to its intersection with the roof. Treated netting attached to the underside of an L-shaped frame mounted on a wall at this intersection might increase the number of bugs exposed and their total exposure duration as they walk along the crease. It is unknown whether this black netting used alone (i.e., without a black background) would induce the same behavioral response as reported here, although the results of Nalepa et al. (2005) suggest not, given that significantly more *H. axyridis* alighted on black targets with the highest degree of contrast, compared with those of lower contrast. Our data on the effect of wall aspect on *H. halys* counts can guide the deployment location(s) of such devices, or individual homeowners could deploy them based on their experience with the pest.

Insecticide-treated netting appears to have potential applications to mitigate both agricultural and nuisance pest issues from *H. halys*, but is in very early stages of development for both applications. Its long residual efficacy in the field, ease of use, and competitive cost may prove to be distinct advantages for affected homeowners, who sorely need relief from this important annual problem.

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