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Seasonal Distribution of *Halyomorpha halys* (Hemiptera: Pentatomidae) Captures in Woods-to-Orchard Pheromone Trap Transects in Virginia

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Abstract

The invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), is a pest of numerous economically important crops in the USA. In the Mid-Atlantic region, it is a significant, direct pest in tree fruit orchards, many of which are bordered by woodlots containing a variety of its deciduous tree and shrub hosts. During the growing season, *H. halys* moves from woodland habitats into crops, but seasonal changes in its relative abundance between these adjacent habitats have not been examined. Using linear transects of six pheromone-baited pyramid traps that extended from 100 m into the interior of woodlots to 100 m into the interior of adjacent commercial apple orchards in Virginia, spatiotemporal changes in *H. halys* captures were measured during three growing seasons. Captures of *H. halys* adults and nymphs were recorded weekly from May through October, and annual data were separated into early, mid, and late-season captures. Only adults were captured during the early season, and there was no indication of a spatial trend in captures across traps in the transects among years. Beginning in mid-season and becoming increasingly apparent by late season, captures of *H. halys* adults and nymphs tended to become most frequent in traps at the woods and orchard edges and at 50 m into the orchard interior. These findings conform with and expand upon previous research documenting an edge effect for *H. halys* relative abundance and can inform and support the optimization of perimeter-based management strategies for *H. halys* in Mid-Atlantic apple orchards.

Key words: brown marmorated stink bug, monitoring, apple, forest, spatiotemporal

In 2010, a widespread and severe outbreak of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in parts of the Mid-Atlantic, U.S. seriously impacted the region's tree fruit industry. Its feeding on fruit caused about $37 million in damage to apples that year, and losses to the stone fruit crop that exceeded 90% in some areas (Leskey et al. 2012). Continued pressure from *H. halys* has led to increased use of broad-spectrum insecticides in eastern tree fruit orchards during the post-bloom period, which has disrupted IPM programs and resulted in more frequent secondary pest outbreaks (Leskey et al. 2012).

H. halys is highly polyphagous, feeding on more than 170 plant species in its invaded range (stopbmsb.org 2021), and both nymphs and adults can cause economic crop injury (Acebes-Doria et al. 2016a). Several studies have shown that injury from *H. halys* feeding is often most prevalent at the crop edges, including in apple (Joseph et al. 2014), pear (Maistrello et al. 2017), and peach orchards (Blaauw et al. 2016), in corn (Venugopal et al. 2014), soybean fields (Venugopal et al. 2014, 2015; Aigner et al. 2017), and in vineyards (Basnet et al. 2015). In the Mid-Atlantic region, tree fruit orchards and other crops are often bordered on one or more sides by woodlots containing many of the wild, deciduous tree and shrub hosts of *H. halys* (Acebes-Doria et al. 2017). Bergh et al. (2021) found that captures of *H. halys* in pheromone traps and its injury to apples and peaches at harvest were often higher at orchard edges adjacent to woods compared with other border habitats, including field and row crops. Rice et al. (2017) reported that the amount of injury recorded in Mid-Atlantic tomato fields was positively related to the size of adjoining woodlots.

H. halys is not known to reside permanently in any crop; rather, adults seek overwintering sites in natural settings (Lee et al. 2014a, Cullum et al. 2020) and human-made structures (Inkley 2012), from which they disperse in the spring (Bergh et al. 2017) to locate host plants and mates. In northern Italy, *H. halys* was shown to disperse short or long distances from overwintering sites depending on host availability and abundance, and ecosystem features (Bosco et al. 2020). The distance between the edge of crop fields and adjacent woodlands is typically well within the dispersal capacity of *H. halys* adults (Lee and Leskey 2015, Wiman et al. 2015) and nymphs (Lee et al. 2014b), and higher levels of injury at crop edges are undoubtedly driven by its immigration from adjacent habitats throughout the growing season, particularly from unmanaged woodlands (Bergh et al. 2021). Acebes-Doria et al. (2016b) demonstrated that *H. halys* nymphs provided a diet of two or more plant hosts had a higher survival rate and shorter developmental duration than nymphs on a single-host diet, although peach alone was highly suitable. Thus, the growth and size of *H. halys* populations in agricultural settings may be enhanced via access to the diversity of wild and cultivated hosts at the crop-woodland interface (Bakken et al. 2015, Acebes-Doria et al. 2017).

In combination, results from previous studies have led to the conclusion that *H. halys* is a perimeter-driven threat, prompting numerous investigations of the effectiveness of management programs focused on intervention at the crop borders, toward reducing the need for insecticide applications against it to the entire crop (Blaauw et al. 2015, Short et al. 2017, Morrison et al. 2018, Leskey et al. 2020, Akotsen-Mensah et al. 2020). Most such studies have incorporated data from pheromone trap-based monitoring of *H. halys*, as have other investigations of its seasonal phenology and abundance (Acebes-Doria et al. 2018, 2020; Leskey et al. 2015). However, *H. halys* monitoring has typically involved traps deployed only at the edge of woods next to crops or at the crop border adjoining woods, while no studies have examined spatiotemporal effects on *H. halys* captures in traps deployed as transects that link woodlands and the adjacent crop. An improved understanding of seasonal changes in the presence and relative abundance of *H. halys* in cultivated crops and adjoining woodlands may provide important insights for developing and optimizing perimeter-based management tactics against it. Here, results from *H. halys* trapping across three seasons using woods-to-orchard transects of pheromone-baited traps to evaluate seasonal changes in the relative abundance of adults and nymphs are reported.

Materials and Methods

Field Sites

In 2014, 2018, and 2019, trapping was conducted at five commercial apple orchards in Frederick Co., VA, all of which had unmanaged woodland along at least one edge. In the respective years, orchards were 20.1 ± 10.3 ha, 19.7 ± 10.1 ha, and 9.5 ± 1.7 ha in size, and separated by 3.5 ± 1.4 km, 4.9 ± 2.9 km, and 0.7 ± 0.3 km. Woodlands adjacent to the orchards were 61.8 ± 21.4 ha, 61.5 ± 21.5 ha, and 56.0 ± 23.7 ha in size in the respective years, and all were >200 m wide. The mean (± SEM) distance between the edges of adjacent woodlands and orchards in 2014, 2018, and 2019 was 10.7 ± 4.3 m, 7.5 ± 1.7 m, and 8.2 ± 1.5 m, respectively.

Each orchard was comprised of mixed cultivars and all were owned by the same company, which managed about 455 ha of orchards in Frederick county. Because these orchards produced fruit exclusively for processing, more stink bug injury was tolerated than for fresh market fruit. Thus, insecticide programs for *H. halys* were relatively minimal and identical across all orchards, providing the opportunity to document seasonal changes in *H. halys* abundance at multiple locations under standardized and much less aggressive management programs than used in orchards with fruit produced for fresh market consumption.

H. halys Trapping

Black coroplast pyramid traps (1.22 m tall, AgBio, Westminster, CO) were used each year. In 2014, these were baited with a grey rubber septum (West Pharmaceutical Services, Lititz, PA) containing 10.7 mg of the *H. halys* aggregation pheromone (8 mg *cis*-10,11-epozy-1-bisabolen-3-ol, 2.7 mg *trans*-10,11-epoxy-1-bisabolen-3-ol) (Khrimian et al. 2014) and a lure containing ~119 mg of methyl (2*E*,4*E*,6*Z*)-decatrienoate (MDT) (Sterling International Inc., Spokane, WA), which synergizes *H. halys* captures when deployed in combination with its pheromone (Weber et al. 2014). Both lures were suspended inside a ventilated, clear plastic collection jar atop the trap base, and the pheromone and MDT lures were replaced at 2- and 4-week intervals, respectively. A strip of dichlorvos (Vaportape II, Hercon Environmental, Emigsville, PA) within the collection jar served as the killing agent and was replaced at 2-week intervals. In 2018 and 2019, commercial BMSB Dual lures (Trécé, Inc., Adair, OK), containing 5 mg of *H. halys* pheromone and 50 mg of MDT were used, and replaced at 12-week intervals, per manufacturer recommendations. These were suspended from the top of the outside of an unventilated collection jar, and a piece of deltamethrin-incorporated netting (Vestergaard, Frandesen Inc., Lausanne, Switzerland) secured to the funnel within the collection jar served as the killing agent.

At each site, six pheromone traps were deployed as a linear transect extending from the woods into the adjacent orchard, positioned at, 1) 100 m into the woods, 2) 50 m into the woods, 3) woods edge, 4) orchard edge, 5) 50 m into the orchard, and 6) 100 m into the orchard (Fig. 1). Traps were emptied weekly to record captures of *H. halys* nymphs and adults from 23 April 2014 to 14 October 2014, 5 May 2018 to 10 October 2018, and 3 May 2019 to 18 October 2019.

Statistical Analysis

Analyses were conducted separately by year, trapping interval, and life stage using RStudio Version 1.1.463 (R Core Team 2020), and outcomes of generalized linear mixed effect models were considered

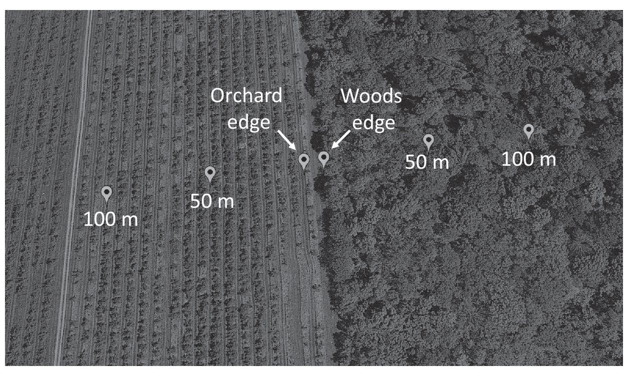

Fig. 1. Representative field site in Frederick county, Virginia at which 6 pheromone-baited pyramid traps for *Halyomorpha halys* were deployed as a linear transect linking unmanaged woodlots and adjacent commercial apple orchards.

significant at $P < 0.05$. As has been used in previous studies (Basnet et al. 2015, Leskey et al. 2015, Morrison et al. 2015, Short et al. 2017, Maistrello et al. 2017; Acebes-Doria et al. 2018, 2020), seasonal captures were divided into three, approximately equal trapping intervals of about eight weeks in duration: early season (late April/early May to late June), mid-season (late June to mid-August), and late season (mid-August to mid-October). This was justified based on large differences in *H. halys* captures among different portions of the growing season, which are typical for *H. halys* monitoring studies and presumably associated with its increasing population density as the season progressed, and to differences in the relative numbers of nymphs and adults among these periods. Due to heavily zero-inflated data across all data sets, a zero-inflated Poisson (ZIP) model was chosen using the 'pscl' package (Zeileis et al. 2008, Jackman et al. 2015). When there was a significant effect of trap location, the 'emmeans' package was used to calculate the difference between trap locations through estimated marginal means (EMMs), and the Tukey method was utilized for post hoc comparisons of EMMs.

Results

Early Season Adult Captures

Adult captures in the early season each year were low (Fig. 2). The effect of trap location was significant in 2014 ($\chi^2 = 23.17$, DF = 5, $P < 0.001$), 2018 ($\chi^2 = 23.17$, DF = 5, $P < 0.001$), and 2019 ($\chi^2 = 16.72$, DF = 5, $P = 0.005$), although the only instance of significantly different captures among traps occurred in 2019, when there were higher captures at the orchard edge than at 100 m into the woods.

Mid-Season Adult Captures

Adult captures in mid-season also were low across all years (Fig. 3). There was a significant effect of trap location in 2014 ($\chi^2 = 48.01$, DF = 5, $P < 0.001$), 2018 ($\chi^2 = 48.01$, DF = 5, $P < 0.001$), and 2019 ($\chi^2 = 17.00$, DF = 5, $P < 0.01$). In 2014, captures were concentrated mainly at the orchard and woods edge. This was not apparent in 2018, but in 2019, most captures overall were in traps at 50 m into the woods and at the woods and orchard edges.

Late Season Adult Captures

Each year, much higher adult captures were recorded in the late season than during earlier sampling periods (Fig. 4), and there was a significant effect of trap location in 2014 ($\chi^2 = 904.98$, DF = 5, $P < 0.0001$), 2018 ($\chi^2 = 904.98$, DF = 5, $P < 0.0001$), and 2019 ($\chi^2 = 993.27$, DF = 5, $P < 0.0001$). Across all years, captures during this period tended to be concentrated among traps at the woods edge, orchard edge, and 50 m into the orchard.

Mid-Season Nymph Captures

Captures of nymphs began in mid-season and were substantially higher overall in 2014 than in 2018 and 2019 (Fig. 5). There was a significant effect of trap location on mid-season captures in 2014 ($\chi^2 = 74.30$, DF = 5, $P < 0.0001$), 2018 ($\chi^2 = 30.19$, DF = 5, $P < 0.0001$), and 2019 ($\chi^2 = 28.49$, DF = 5, $P < 0.0001$). In 2014 and 2018, nymph captures were predominantly in traps at the woods and orchard edge, although means did not separate statistically in 2018. This trend was not observed in 2019.

Late Season Nymph Captures

Each year, nymph captures were highest in the late season and much higher in 2014 than in 2018 and 2019 (Fig. 6). Trap location had a significant effect on captures in 2014 ($\chi^2 = 904.98$, DF = 5, $P < 0.0001$), 2018 ($\chi^2 = 82.29$, DF = 5, $P < 0.0001$), and 2019 ($\chi^2 = 94.91$, DF = 5, $P < 0.0001$). In 2014, there was a clear indication of highest captures at the orchard and woods edges, and in 2018 and 2019, numerically highest captures were recorded at the woods edge.

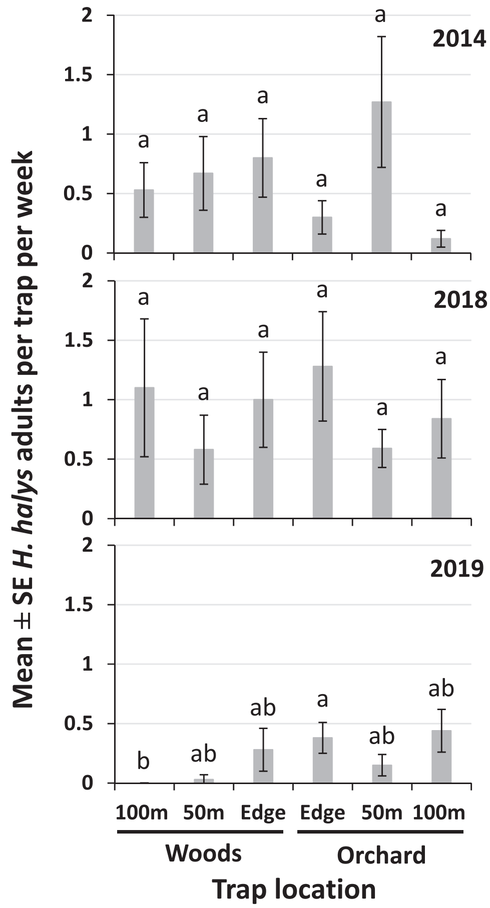

Fig. 2. Mean weekly captures of *Halyomorpha halys* adults in the early season (May to late June), using linear transects of 6 pheromone-baited pyramid traps linking unmanaged woodlots and adjacent commercial apple orchards at five sites in Virginia in 2014, 2018, and 2019. Bars in each graph with different letters are significantly different at $P < 0.05$, based on generalized linear mixed effect models with a zero-inflated Poisson distribution and the Tukey test.

Discussion

Three years of *H. halys* monitoring, using captures in pheromone-baited traps as a proxy for its relative abundance, revealed spatiotemporal changes in captures across woods-to-orchard trap transects during the season. Further resolution of these changes was achieved by partitioning each season into three, approximately equal sampling periods (early, mid, late) that generally coincided with the different phases of *H. halys* population development annually. As each season progressed, adult captures tended to become more concentrated in traps at the orchard and woods edges and at 50 m into the orchard than at other woods and orchard locations. As has been shown in other studies (Leskey et al. 2015; Acebes-Doria et al. 2018, 2020), nymph captures occurred only in mid and late season, but generally displayed similar distributions among traps as adults during both sampling periods, and captures of both life stages were highest in the late season. These trends were likely associated with

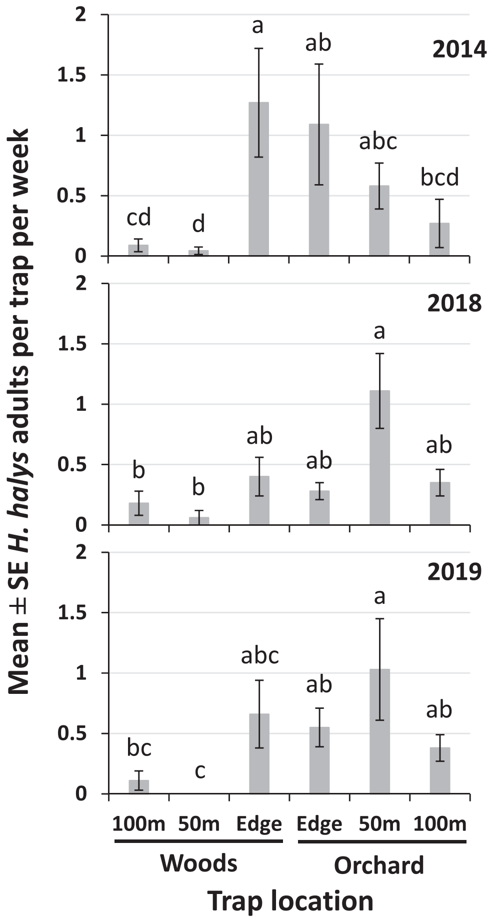

Fig. 3. Mean weekly captures of *Halyomorpha halys* adults in mid-season (late June to mid-August), using linear transects of 6 pheromone-baited pyramid traps linking unmanaged woodlots and adjacent commercial apple orchards at five sites in Virginia in 2014, 2018, and 2019. Bars in each graph with different letters are significantly different at $P < 0.05$, based on generalized linear mixed effect models with a zero-inflated Poisson distribution and the Tukey test.

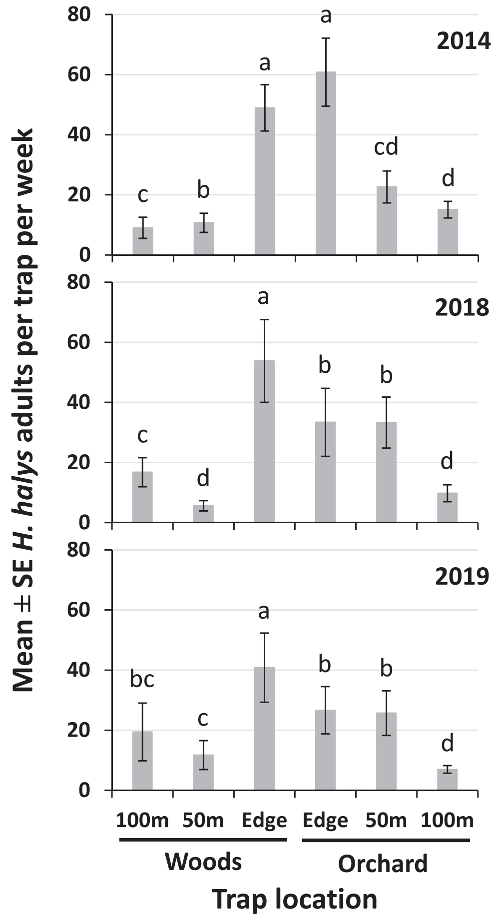

Fig 4. Mean weekly captures of *Halyomorpha halys* adults in late season (mid-August–mid-October), using linear transects of 6 pheromone-baited pyramid traps linking unmanaged woodlots and adjacent commercial apple orchards at five sites in Virginia in 2014, 2018, and 2019. Bars in each graph with different letters are significantly different at $P < 0.05$, based on generalized linear mixed effect models with a zero-inflated Poisson distribution and the Tukey test.

the higher probability of injury from *H. halys* at harvest on trees at the border of commercial apple orchards next to woods than on trees in the orchard interior (Joseph et al. 2014) and with increasing levels of apple injury from mid-season onward, shown in exclusion cage studies by Joseph et al. (2015). Similar spatial trends were reported from visual counts of *H. halys* abundance in soybean (Venugopal et al. 2015, Aigner et al. 2017) and corn fields (Venugopal et al. 2015) bordering woods.

The overall lack of differences in adult *H. halys* captures among traps during the early season may have been associated with aspects of its biology and behavior. Adults overwinter in natural settings, including beneath the loose bark of dead trees in forests (Lee et al. 2014a), and also in buildings and other human-made structures (Inkley 2012), but are not known to overwinter in fruit orchards. Bergh et al. (2017) examined the emergence of marked adult *H. halys* from experimental overwintering shelters deployed in forest settings and their capture in pheromone-baited traps encircling the shelters. While unmarked adults were captured at all sites, very few marked adults were captured, leading them to suggest that the marked adults dispersed from the overwintering sites. Flight mill data seem to support this behavior; Lee and Leskey (2015) reported that adult *H. halys* that emerged from overwintering sites in June showed significantly longer flight durations than field-collected individuals in July, August, October, and January–April. While no studies have focused specifically on the latency between *H. halys* emergence from overwintering sites and their response to pheromone lures, Bosco et al. (2020) reported that *H. halys* in northern Italy were captured in pheromone baited traps or on plants near baited traps soon after their emergence from overwintering sites. While host-use by adult *H. halys* following their emergence from overwintering sites remains poorly understood, potential early season hosts are widely distributed in the Mid-Atlantic landscape, including wild *Rubus* L. species, mulberry (*Morus* spp. L.), hackberry (*Celtis occidentalis* L.), and in the case of this study, apples, *Malus domestica* Borkhausen. Thus, the results of the present study may suggest that adults from scattered overwintering populations dispersed throughout the landscape in search of feeding and reproductive hosts. Comparatively low adult captures during the early season likely reflected the combined effects of the size of the population entering overwintering sites the previous autumn, a patchy distribution of aggregations of overwintering adults in the landscape, and overwintering mortality.

Spatiotemporal changes in captures among traps in the transects as the season progressed appeared to reflect a tendency of adults to utilize hosts at or near habitat edges for feeding and reproduction.

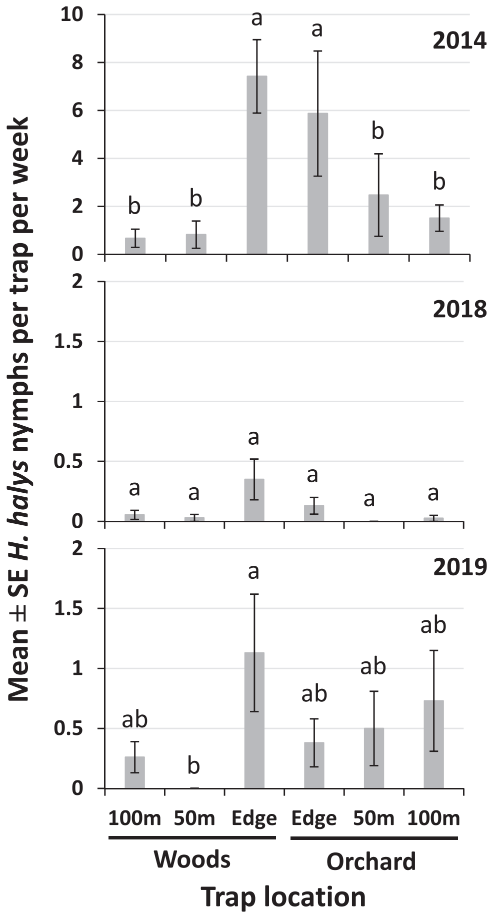

Fig 5. Mean weekly captures of *Halyomorpha halys* nymphs in mid-season (late June to mid-August), using linear transects of 6 pheromone-baited pyramid traps linking unmanaged woodlots and adjacent commercial apple orchards at five sites in Virginia in 2014, 2018, and 2019. Bars in each graph with different letters are significantly different at $P < 0.05$, based on generalized linear mixed effect models with a zero-inflated Poisson distribution and the Tukey test. Different y-axis scales among the figures are to enhance data clarity, following different captures among years.

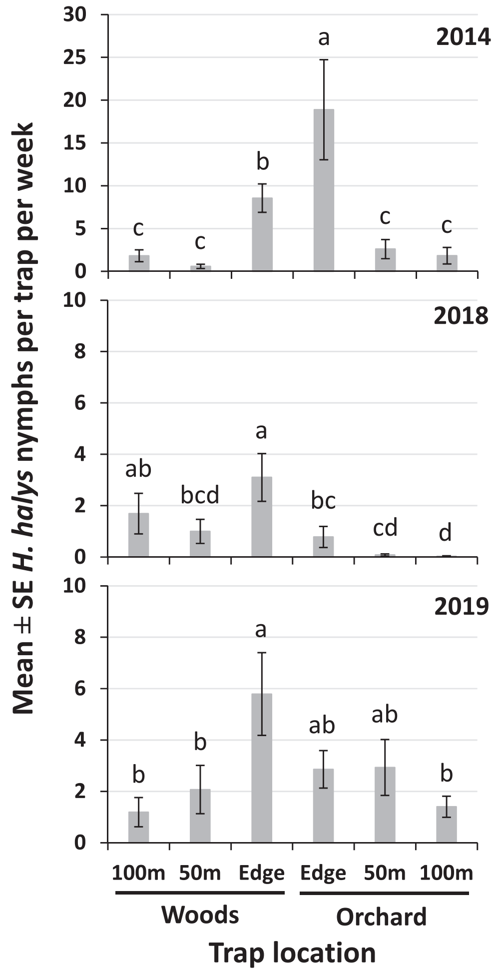

Fig 6. Mean weekly captures of *Halyomorpha halys* nymphs in late season (mid-August–mid-October), using linear transects of 6 pheromone-baited pyramid traps linking unmanaged woodlots and adjacent commercial apple orchards at five sites in Virginia in 2014, 2018, and 2019. Bars in each figure with different letters are significantly different at $P < 0.05$, based on generalized linear mixed effect models with a zero-inflated Poisson distribution and the Tukey test. Different y-axis scales among the figures are to enhance data clarity, following different captures among years.

This is supported by nymph captures that were most common at the woods and orchard edges by late in the season. Moreover, Acebes-Doria et al. (2017) documented a different species composition of deciduous trees and shrubs between the edge and interior of woodlands in Virginia and West Virginia, and a greater diversity of *H. halys* hosts along the woods' edge. In that study, four of the five most abundant species at the forest edge were known hosts of *H. halys*. Of these, tree of heaven, *Ailanthus altissima* (Mill.) Swingle, was most prevalent, comprising 24.6% of all trees. Acebes-Doria et al. (2016b) also showed that the developmental rate and survivorship of *H. halys* nymphs was significantly improved on a mixed host diet and that the suitability of tree of heaven increased as the season progressed and the seed pods matured. Thus, the diversity of suitable host plants at the edge of forests and/or adjacent to the forest edge (e.g., fruit orchards), may benefit *H. halys* adults and nymphs and at least partially explain the seasonal changes in captures across the trap transects. Indeed, Bergh et al. (2021) found that *H. halys* captures and its injury to fruit at harvest were often highest at apple orchard borders adjacent to woods than other adjoining habitats.

Most studies that have shown an edge effect on *H. halys* abundance or feeding injury in crops such as apple (Joseph et al. 2014), peach (Blaauw et al. 2016), pear (Maistrello et al. 2017), grape (Basnet et al. 2015), soybean, and corn (Venugopal et al. 2014, 2015), did not relate these variables to specific sources of pest pressure. Assuming that differences in *H. halys* captures among traps reflected differences in localized populations, the present results expand upon those from previous research. Transects of pheromone traps linking woodlands and adjacent fruit orchards showed that increasing pest pressure from *H. halys* as the season progressed was associated with a tendency for higher populations at and near orchard borders and at the woods' edge than elsewhere in either habitat. These findings further support the widely held contention that *H. halys* is a perimeter-driven threat to vulnerable crops (Lopez et al. 2021, Aigner et al. 2017, Leskey and Nielsen 2018, Leskey et al. 2020). Moreover, they suggest that temporal increases in the number of *H. halys* that can invade fruit orchards from the woods' edge are likely associated with reports of increasing crop injury as the season processes (Joseph et al. 2015) and higher injury at crop edges at harvest (Joseph et al. 2014). Using visual scouting, Aigner et al. (2017) showed similar late-season increases in the abundance of *H. halys* adults in woodlands adjoining Virginia soybean fields, and it is reasonable to assume that the occurrence of this spatiotemporal trend at woodland margins may be independent of the adjacent crop system.

In combination with data showing highest injury from *H. halys* at or near crop edges (Joseph et al. 2014, Venugopal et al. 2015, Blaauw et al. 2016, Maistrello et al. 2017), the higher captures in traps at woodland margins and orchard edges reported here also provide further support for the utility of crop perimeter-based management tactics against it. Indeed, in Mid-Atlantic apple orchards, border row sprays (Akotsen-Mensah et al. 2020, Leskey et al. 2020) and pheromone-based attract-and-kill on border row trees (Morrison et al. 2018, Leskey et al. 2020) have yielded levels of *H. halys* injury to fruit that were comparable to conventionally managed orchards. Importantly, *H. halys* management using these perimeter-based tactics required fewer insecticide inputs across a much-reduced area, compared with conventional programs. Similarly, an Integrated Pest Management-Crop Perimeter Restructuring tactic in Mid-Atlantic peach orchards that incorporated perimeter sprays for *H. halys* controlled its damage effectively and reduced insecticide use overall compared with standard treatment practices (Blaauw et al. 2015). These tactics may have greatest utility from mid-season onward, during the period when pest pressure from *H. halys* tended to increase at the woodland and orchard margins. Moreover, they may be expected have most impact at orchard borders next to woods, where *H. halys* captures were often higher than at borders adjoining other, non-woods habitats (Bergh et al. 2021). Inclusion of an action threshold for *H. halys*, using captures in pheromone-baited traps to trigger insecticide applications to orchards (Short et al. 2017), would further enhance the efficiency of tactics such as orchard border sprays.

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