OXFORD

Horticultural Entomology

Phenology of Brown Marmorated Stink Bug in a California Urban Landscape

Chuck A. Ingels[1,3] and Kent M. Daane[2]

[1]University of California Cooperative Extension, Sacramento County, Sacramento, CA 94720; [2]Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, and [3]Corresponding author, e-mail: caingels@ucanr.edu

Abstract

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive pest that has been resident in California since 2006. To better understand its seasonal phenology, we used baited traps to estimate nymph and adult population densities in midtown Sacramento, the focal area of the Northern California invasion. Adult *H. halys* populations were found soon after trapping began in February (2015–2016) or March (2014); the first egg masses for 2014, 2015, and 2016 were found on 5 May, 17 April, and 12 April, respectively, and the first nymphs were found 3 June, 19 May, and 9 May, respectively. There were two generations per year, with one peak in June and another in September. Summer temperatures above 36°C in July and August were associated with reduced catches in traps of both nymphs and adults. This extreme heat may have helped to form two clear nymph peaks and suppressed egg deposition. In 2016, two trap types and four lures were also compared. Trap type influenced season-long nymph captures, with fewer nymphs in double cone traps than pyramid traps. Lure type influenced season-long trap catch, with more nymphs and adults trapped with the Rescue lure than the AgBio Combo lure, Alpha Scents, or Trécé Pherocon Combo lures, although this difference was only associated with the capture of nymphs and we did not compare for longevity or seasonal variation. These data are discussed with respect to *H. halys*' phenology from the mid-Atlantic region.

Key words: *Halyomorpha halys*, seasonal population dynamics, monitoring, traps

The brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive pest, considered to be native to Asia (Hoebeke and Carter 2003) and currently found throughout much of the United States and parts of Canada and Europe (Haye et al. 2015, Valentin et al. 2017). Since its first detection in North America in the 1990s, *H. halys* has been found in 43 states and the District of Columbia, although its population density and pest status vary among regions (Anonymous 2017, Hahn et al. 2017). To date, large populations are often found in the mid-Atlantic region, Tennessee and North Carolina, where *H. halys* has caused severe damage to tree and small fruit, vegetable and forage crops (Nielsen and Hamilton 2009, Leskey et al. 2012b, Joseph et al. 2014, Bakken et al. 2015, Acebes-Doria et al. 2016a, Philips et al. 2017). In other U.S. regions, such as Oregon, *H. halys* populations are either more moderate or may still be increasing (Wiman et al. 2015), but have not yet caused the levels of damage as those found in the mid-Atlantic region. For most of the United States and Canada, *H. halys* has been not detected, detected but with no evidence of a breeding population, or has established but populations are still early in the infestation process (Anonymous 2017). *H. halys* populations in California fit into this latter category where the pest has established

in many regions of the state, but its future population densities or damage have yet to be determined.

In California, *H. halys* was first detected in 2006 in Pasadena and San Marino (Los Angeles County), but in Northern California it was not until 2013 that a substantial population was found in Sacramento (Ingels and Varela 2014). Key among this stink bug's highly invasive characteristics are its wide host range (Bergmann et al. 2016a), which includes woody ornamentals (Bergmann et al. 2016b) and wild hosts (Bakken et al. 2015); it is on ornamental hosts, especially the tree of heaven (*Ailanthus altissima* (Mill.) Swingle [Sapindales: Simaroubaceae]) that this pest is most commonly found in Sacramento. Both large and small urban areas with *H. halys* populations are interspersed with California's billion-dollar agriculture industry, and Sacramento is close to commercial stone and pome fruits and vegetable plantings that are susceptible to *H. halys*. Nevertheless, until 2016, there had been no reports of *H. halys* on agricultural crops, although the populations appeared to be increasing in some urban regions. These established populations on urban ornamental plantings are, therefore, a concern for the State's diverse specialty crops, including grapes, stone and pome fruits, small berry crops, nut crops, and vegetables.

Studies from Asia on *H. halys*' biology were summarized by Lee et al. (2013); interestingly, while most regions of China, Japan, and Korea report one to two generations per year, four to six generations were reported in southern China, although this observation has not since been recorded with a known *H. halys* population. The number of annual generations and the period of feeding after adults emerge from overwintering sites until the season's end are important factors for developing regional IPM programs (Nielsen et al. 2008). Initial studies from the mid-Atlantic states that include aspects of *H. halys* phenology report one, but more commonly two generations per year, from the northern to the more southern states (Nielsen et al. 2008, Leskey et al. 2012a, Zobel et al. 2016). Similarly, Bakken et al. (2015) described the phenology of BMSB in North Carolina and Southern Virginia (part of the more southeastern range of this pest) and population trends and degree-days (DD) models also demonstrated one to two generations per year. However, an updated development model predicts the potential for bivoltinism throughout the United States, although critical photoperiods in the more northern regions of *H. halys*' distribution may have significant impacts on resulting population size (Nielsen et al. 2017).

In California, the number of *H. halys* generations could vary as the pest's potential geographic range of available host plants encompass a range of climatic conditions, from relatively mild temperatures in coastal and Northern California to hot and arid summers in the interior valleys. Here, we report on *H. halys* seasonal population dynamics in Sacramento from 2014 to 2016, based on pheromone-baited trap collections. Because trap and lure selection can impact collections (Joseph et al. 2013, Weber et al. 2014, Leskey et al. 2015c), we also evaluated trap and lure combinations for use in California's urban landscapes.

Materials and Methods

Study Sites and Host Plants

From early spring (2014) or late winter (2015 and 2016) through fall (2014–2016) incipient populations of *H. halys* were sampled in a relatively small (eight blocks) residential section of midtown Sacramento, California, where the stink bug was first found in 2013 (Ingels and Varela 2014). The sampled area had numerous host plants, which included butterfly bush (*Buddleja davidii* Franch. [Lamiales: Buddlejaceae]) that was used by *H. halys* in mid-spring, tree of heaven that was a host from early spring to late fall, and a group of mid- to late-summer ornamental host plants that included Chinese pistache (*Pistacia chinensis* Bunge [Sapindales: Anacardiaceae]), trident maple (*Acer buergerianum* Miq. [Sapindales: Aceraceae]), waxleaf privet (*Ligustrum japonicum* Thunb. [Lamiales: Oleaceae]), and Japanese zelkova (*Zelkova serrata* (Thunb.) Makino [Rosales: Ulmaceae]). There was also a community garden (ca. 200 m²) that was used year-round and had numerous spring to summer vegetables, including green beans (*Phaseolus vulgaris* L. [Fabales: Fabaceae]), bell pepper (*Capsicum annuum* L. [Solanales: Solanaceae]), sunflowers (*Helianthus* sp.), and tomatoes (*Solanum lycopersicum* L. [Solanales: Solanaceae]), and fruit trees including apple (*Malus pumila* Miller [Rosales: Rosaceae]), Asian pear (*Pyrus pyrifolia* (Burm.) Nak. [Rosales: Rosaceae]), sweet cherry (*Prunus avium* L. [Rosales: Rosaceae]), nectarine and peach (*Prunus persica* (L.) Batsch [Rosales: Rosaceae]), persimmon (*Diospyros kaki* L.f. [Ericales: Ebenaceae]), and mulberry (*Morus* sp.).

Insect Sampling

The Sacramento *H. halys* population was newly discovered and sampling procedures changed each year as the population was better delineated, and as national sampling programs provided a better description of effective traps and lures (Sargent et al. 2014; Weber et al. 2014; Morrison et al. 2015; Leskey et al. 2015a; c; Kuhar et al. 2017). In all years, a 5 cm strip of Hercon Vaportape II (Hercon Environmental, Emigsville, PA) was used in each trap to kill the collected stink bugs, with the strip replaced every 2 weeks (after Joseph et al. 2013). Traps were checked weekly, recording the number of *H. halys* nymphs and adults, as well as adult gender. In all years, traps were placed no closer than 50 m apart. To determine the beginning of egg laying, foliage on ornamental trees and shrubs, vegetables and fruit trees in the community garden was intensively searched twice each week starting in early April of each year until the first egg mass was found.

The deployment periods and trap and lure combinations used each year were as follows. In 2014, traps were deployed from 12 March to 1 October, using black pyramid traps (Dead-Inn Pyramid trap— 1.2 m [4 ft] AgBio, Inc. Westminster, CO) that were placed on the ground at 10 residential and businesses landscapes. Five traps were baited with AgBio Combo (MDT Smart lure) and five were baited with Rescue lures (commercial model SBTA, Sterling International, Inc., Spokane, WA). Both lures had two components, an aggregation pheromone combined with methyl (*E,E,Z*)-2,4,6-decatrienoate (MDT) (Weber et al. 2014). This was not a lure comparison because the two lure types were periodically switched at different locations as, in this first year of sampling, there were no data or experience with *H. halys* populations or host plant use in Sacramento.

In 2015, traps were deployed earlier and for a longer seasonal period (24 February to 26 October) and in 24 residential and business landscapes. Roughly, half of the traps were the black pyramid traps and about half were homemade 3.8-litre double cone traps, based on the Trécé double cone trap (see below), hung 2–4 m above ground in a diversity of tree and shrub species (tree of heaven, elm [*Ulmus* sp.], Japanese privet [*L. japonicum*], evergreen pear [*Pyrus kawakamii*], sweet cherry, Japanese maple [*Acer palmatum* Thunb. (Sapindales: Sapindaceae)], holly [*Ilex* sp.], and mock orange [*Pittosporum tobira* (Thunb.) W.T.Aiton (Apiales: Pittosporaceae)]). Traps were baited with the AgBio Combo lure. Although two different trap types were used in 2015, no comparison of trap types was made.

In 2016, traps were deployed from 19 February to 31 October; four sites were initially monitored from 19 February to 28 March, after which all 24 sites used in 2015 were monitored. In addition, we compared traps and lures, using 12 black pyramid traps and 12 experimental double cone traps (clear plastic, 18 cm tall × 10 cm wide) (Trécé Inc., Adair, OK), hung 2–4 m above the ground in branches of tree of heaven trees only. Traps were baited with four different lures: AgBio's Combo, Rescue's SBTA, Trécé's Pherocon BMSB Combo lure, and Alpha Scents two component BMSB lure (Alpha Scents, Inc., West Linn, OR); the load rate of pheromone and MDT in these lures was not available. The lures were replaced monthly and, to account for possible site variation in *H. halys* density, four traps in each of three sets were rotated weekly within each set.

Statistical Analysis

Data are presented as untransformed means (±SE) per sample date for seasonal population change, with data summarized across all host plants (almost all traps were placed in or near a tree of heaven). For trap and lure comparisons in 2016, data were analyzed with two-way and one-way analysis of variance (ANOVA), and treatment means were separated using Tukey's multiple comparison test at $P < 0.05$. Samples were analyzed as nymphs and adults separately, and nymphs and adults combined.

Results

Seasonal Phenology

In determining the seasonal phenology of BMSB, we are assuming that the pheromone traps accurately reflect the seasonality of the bugs in the landscape. In both 2014 and 2015, adult *H. halys* populations were found soon after trapping began in March, but in low densities compared with spring 2016 (Fig. 1). The first egg masses for 2014, 2015, and 2016 were found on 5 May, 17 April, and 12 April, respectively, and the first nymphs were found on 3 June, 19 May, and 9 May, respectively (Fig. 1). In 2014 and 2015, these initial nymph counts were low for a 1- to 3-wk period that preceded the more measurable first-generation (F1) peak in June and a larger second-generation (F2) peak in September. The adult seasonal density pattern was similar in 2014 and 2015, with the overwintering (P) and F1 trap captures <4 adults per trap per week, and the F2 population nearly twice as large and peaking in mid- to late-September. The 2016 seasonal phenology was different in two aspects. First, the P population was larger and more active, with trap captures from February through April averaging 7.0 ± 0.9 adults per trap per week (Fig. 1C). Next, the F1 nymph peak was higher than the F2 peak and there was a 4-week period from the end of July through August when almost no adults or nymphs were trapped (Fig. 1C).

Nielsen et al. (2008) reported that 537.63 DD are needed for the development from egg to adult and an additional 147.65 DD are needed for the preoviposition period of the female, with minimum and maximum developmental temperature thresholds of 14.17 and 35.76°C, respectively; therefore, we used 685.28 DD and 1370 DD to estimate model parameters. Three different periods were used for the biofix and accumulation of DD: 1) the initiation of the F1 egg mass, based on our visual search of host plant canopies, 2) the critical photoperiod of 12.7 h daylight (2 April), and 3) 1 January. Using the observed initiation of the F1 egg mass as the simplest model, F2 egg laying would begin on 19 July 2014, 16 July 2015, and 13 July 2016, and F3 would potentially start on 23 September 2014, 21 September 2015, and 22 September 2016 (Fig. 1). Using 2 April as the initial biofix provided a slightly earlier pattern, with F2 egg laying initiated on 5 July 2014, 12 July 2015, and 13 July 2016, and F3 would potentially start 8 September 2014, 16 September 2015, and 22 September 2016. Using 1 January as the initial biofix provided a very early prediction for F2 of 23 June 2014, 27 June 2015, and 28 June 2016, and F3 would potentially start 27 August 2014, 30 August 2015, and 3 September 2016. The observed seasonal phenology best fits patterns described by the initiation of F1 egg deposition or the critical 12.7 h daylength photoperiod. In 2014, there was a nearly continuous but low adult capture from March to the
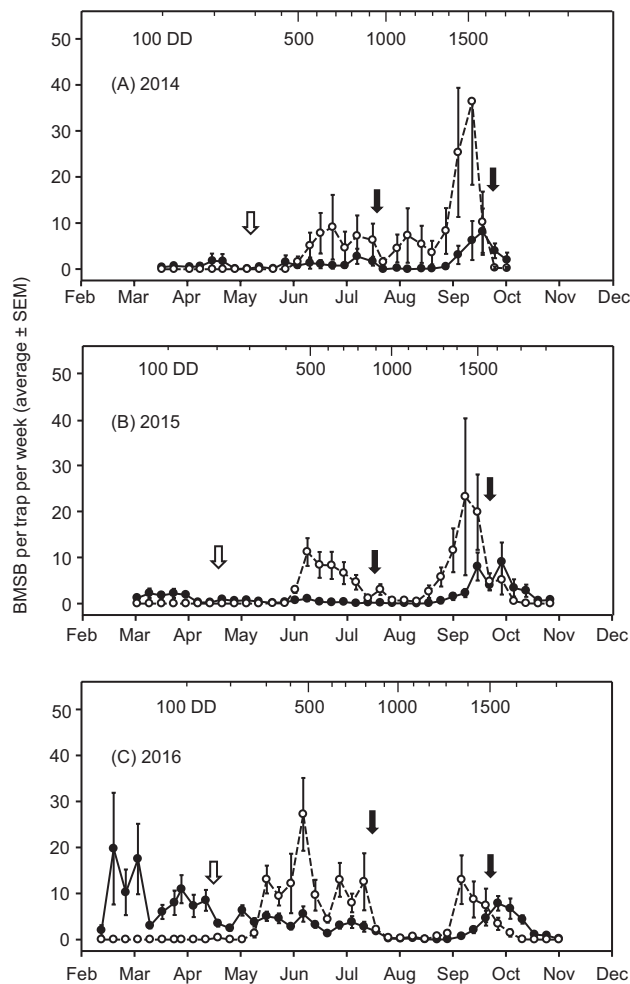

Fig. 1. Seasonal abundance (±SE) of *Halyomorpha halys* nymphs (open circles) and adults (filled circles) per trap per week on ornamental host plants in midtown Sacramento, CA, in (A) 2014, (B) 2015, and (C) 2016. Blank arrows indicate the date that the first egg masses were found; Solid arrows indicate the predicted beginning of egg laying for F2 and potentially F3, respectively, based on the BMSB development model from the date of first egg mass find. DD accumulation since 1 January for each year are provided on the upper x-axis and the beginning of each month is on the lower x-axis.

first clear peak in September, combined with the constant capture of nymphs from May until a clear peak in September; the pattern suggests an overlap of generations. In 2015, the observed pattern fit the predicted seasonal phenology with more clearly defined P, F1, and F2 adult populations and two clear nymph peaks. In 2016, a mild winter and two extreme heat events during the summer altered the pattern found in previous years. The average high temperature in February was unusually warm at $19.9 \pm 0.7°C$ (compared with 16.8 ± 0.6 and 18.4 ± 0.5 in 2014 and 2015, respectively), and with 10 d at or above 22°C. As mentioned previously, the seasonal pattern in the first half of 2016 suggested a large and overlapping second generation; however, in July and August 2016, temperatures were hotter and drier than normal for Sacramento with 7 and 6 d, respectively, above 35.76°C (Fig. 2), and average low relative humidity below 16%. Likely due to this heat, trap counts declined to near zero from late July through late August, and the September nymph trap counts were substantially lower and had a slightly earlier peak than in the two previous years (the 2016 late summer accumulated nymph trap counts were about a third and half of that in 2014 and 2015, respectively).

Trap and Lure Comparison

From 18 April to 31 October 2016 and across all trap and lure treatments tested, 5387 BMSB were collected from 648 weekly samples. By development stage, weekly trap averages were 5.6 ± 0.6 nymphs, 1.6 ± 0.1 adult females, and 1.2 ± 0.9 adult males. Using a two-way ANOVA, there was a significant difference among tested lures ($F_{5,752}$; df = 1, 3, 3; $P = 0.001$), but no difference among tested trap types ($F_{2,465}$; df = 1, 3, 3; $P = 0.117$) and no interaction between trap and lures tested ($F_{1,796}$; df = 1, 3, 3; $P = 0.147$).

Because there was no trap × lure interaction, a one-way ANOVA was used to separately compare traps and lures tested. Lure type influenced season-long trap catch. Combining data from double cone and pyramid traps, more BMSB (nymphs and adults) were trapped with the Rescue lure (13.3 ± 2.2 per trap per week) than the AgBio (6.2 ± 0.8), Alpha Scents (6.3 ± 1.0) or Trécé (7.2 ± 1.1) lures ($F_{5,823}$; df = 3, 644; $P < 0.001$) (Fig. 3). When separating BMSB by development stage, this difference was associated primarily with the capture of nymphs ($F_{4,946}$; df = 3, 644; $P = 0.002$) and to a lesser extent the capture of adult males ($F_{3,738}$; df = 3, 644;

$P = 0.011$); there was no difference among lures for adult females ($F_{2,491}$; df = 3,644; $P = 0.059$). The pattern was slightly different when separating season-long counts by the two trap types tested (Fig. 4). For double cone traps, there was no difference among lures for nymphs ($F_{1,389}$; df = 3, 314; $P = 0.246$), adult males ($F_{0,741}$; df = 3, 314; $P = 0.528$), or adult females ($F_{0,951}$; df = 3, 314; $P = 0.416$) (Fig. 3A), whereas for pyramid traps baited with Rescue lures, there were more nymphs ($F_{3,939}$; df = 3, 326; $P = 0.009$) and adult males than AgBio lures ($F_{3,281}$; df = 3, 326; $P = 0.021$), but not more adult females ($F_{2,372}$, df = 3, 326; $P = 0.070$) (Fig. 3B). Using log transformed data and a one-way ANOVA, we were able to show a slight influence of trap type on season-long catch, with fewer nymphs in the double cone traps than the pyramid traps ($F_{4,114}$; df = 1, 256; $P = 0.044$), although there was no difference in captured adult males ($F_{0,161}$; df = 1,646; $P = 0.688$) or adult females ($F_{0,318}$; df = 1, 646; $P = 0.573$) (Fig. 4).

Discussion

H. halys has been present in California since 2006, primarily located on ornamental hosts in urban locations. The Sacramento population had an overwintering adult (P) population active in February, and the mid-April egg mass finds, and the mid-May first nymph catches in 2015 and 2016 occurred far earlier than those reported elsewhere; nevertheless, there still appeared to be only two generations per year.
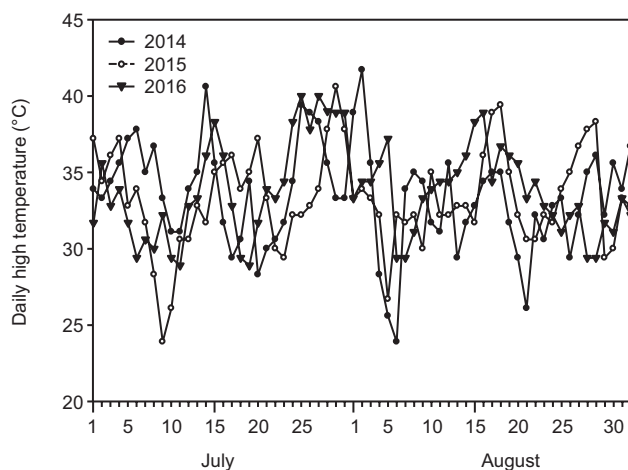

Fig 3. Captures of *Halyomorpha halys* per trap per week (±SE) in 2016 in double cone or pyramid traps for adult males and females and nymphs. Bars with shared letters are not significantly different from one another (Tukey's HSD test, α = 0.05).

Fig. 2. Daily high temperatures in July and August (2014–2016), as recorded by the CIMIS Bryte station #155 (Yolo County), ~3 miles from midtown Sacramento.
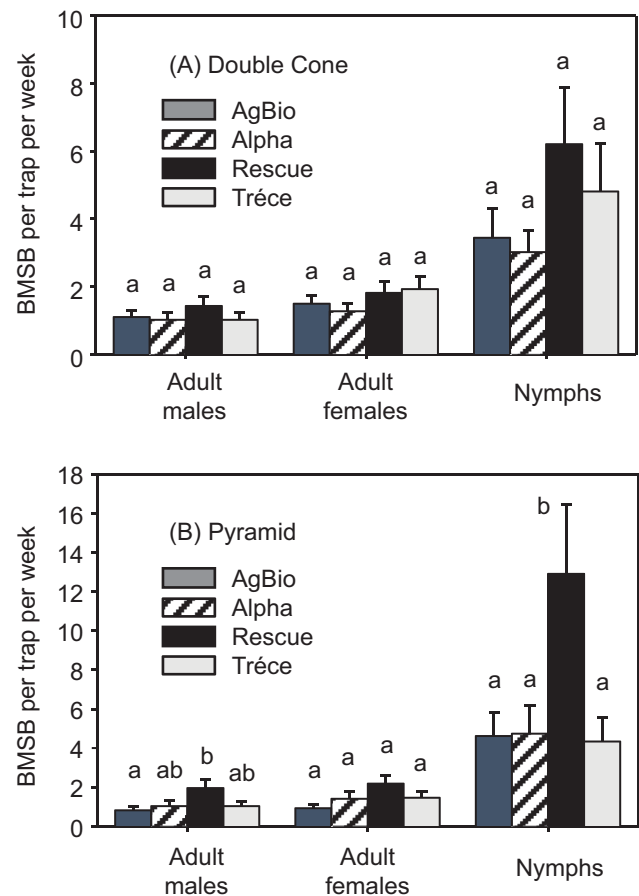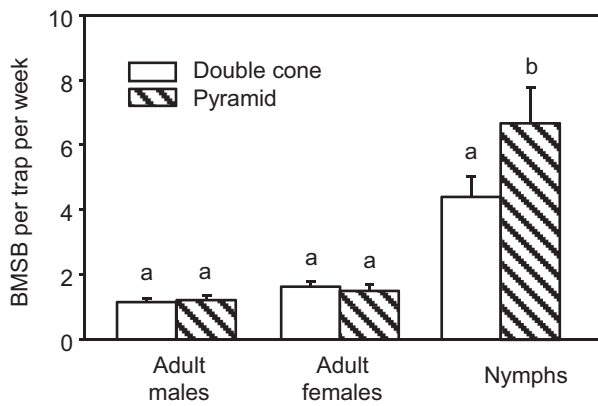
Fig. 4. Captures of *Halyomorpha halys* per trap per week (±SE) in 2016 using four different lures placed in (A) double cone or (B) pyramid traps for adult males and females and nymphs. Bars with shared letters are not significantly different from one another (Tukey's HSD test, α = 0.05).

In the northeastern United States (New Jersey and Pennsylvania), *H. halys* was initially thought to be univoltine, but an updated model predicts bivoltinism (Nielsen et al. 2017). In some mid-Atlantic regions, it has a partial F2 (Bakken et al. 2015) or two overlapping generations (Leskey et al. 2012a; Joseph et al. 2013). In 2015 and 2016, the Sacramento population had two distinct nymph peaks, but in 2014, the nymph population appeared to be continuous from May or June to October (Fig. 1), and this coincided with relatively mild seasonal temperatures during this period, as well as later in the 2014 summer. The decline, or 'break' in nymph and adult captures in July and August 2015 and 2016, may have been more related to high summer temperatures, resulting in either adult and nymph mortality or lowered activity. While two generations seem to be clearly evident, the height of the second peak could also be due to adults from F1 and F2 combined as emergence from overwintering sites is not synchronous (Bergh et al. 2017). In 2016, 7 d of 38°C or higher (July 23–29) may have been far more consequential than a simple threshold that uses only a high temperature point rather than a prolonged period of 4–5 h heat, and the population 'crash' occurred after this period of hot, dry weather. While Aigner and Kuhar (2016) showed higher temperatures could be tolerated by adults, they used only a maximum of 4-h exposure period and this period was often reached for temperatures above 35°C in the 2016 summer. In comparison, in 2015, there were only 4 d over the 38°C in July and August and only 2 consecutive days at this temperature. Following this milder 2015 summer was the large overwintering adult (P) population and earlier and larger F1 nymph population of 2016.

For several days after hatching, first-instar nymphs aggregate and stay closely associated with the egg mass, probing the egg chorion for the gut symbionts that deposited during oviposition. Bansal et al. (2014) found in the *H. halys* digestive tract an extended midgut surrounded by four rows of densely packed crypts that contain gammaproteobacterial symbionts, which inoculates the young nymphs while they probe. The symbionts are used by members of the order Hemiptera that consume phloem sap as their primary food source to obtain the necessary amino acids and vitamins. Taylor et al. (2014) showed that surface-sterilizing egg masses negatively affected development and survivorship of both nymphs and adults, and the impact was even more dramatic in the subsequent generation. Therefore, the overall fitness of *H. halys* is highly dependent on the presence of gut symbionts. Excess heat also has a detrimental effect on gut symbionts. Prado et al. (2010) found that survivorship and reproductive

rates of *Chinavia* (*Acrosternum*) *hilare* (Say) and *Murgantia histrionica* (Hahn) at 30°C were lower than at 25°C, and they surmised that the decrease in host fitness was coupled with, and potentially mediated by, symbiont loss at 30°C. We surmise that the heat wave of late July 2016 greatly reduced the gut symbiont available to first-instar nymphs during what was likely the peak period of F2 hatch, which contributed to the nymphal population decline seen in August and into September.

We observed two generations per year, but based on accumulated DDs, a third generation (F3) might have begun in October of each year and if these nymphs could survive the winter this might lead to two strongly overlapping generations or a partial third generation with no or poor survival. It should be noted that we used maximum (35.76°C) and minimum (14.17°C) developmental temperature thresholds based on the Nielsen et al. (2008) study using an eastern U.S. population that is believed to originate near Beijing, China (Xu et al. 2014). However, invasive *H. halys* populations appear to be genetically diverse with at least four separate introductions in North America and three in Europe (Valentin et al. 2017), and some of the *H. halys* populations in Europe have a higher maximum (36.5°C) and lower minimum (12.97°C) developmental temperature tolerance (Haye et al. 2014). A wider range of development temperatures could increase the possibility of three annual generations in warmer parts of California, although the seasonal phenology is also regulated by high summer temperatures and required post diapause cues before oviposition can begin in the spring (Nielsen et al. 2016). Moreover, any egg deposition in October may not have resulted in a cohort that survived through the winter period.

In mid-Atlantic states, emergence of overwintering adult (P) *H. halys* peaks from May to June and is often characterized by movement from an overwintering host or refuge to a summer host(s). The movement from overwintering sites is asynchronous, which can lead to overlapping F1 and F2 generations late in the season (Leskey et al. 2012b, Joseph et al. 2015, Bergh et al. 2017). The seasonal movement of *H. halys* among wild and cultivated host plants is currently being defined better (Venugopal et al. 2015; Acebes-Doria et al. 2016b, 2017). An atypical factor in the Sacramento population was the reliance on the tree of heaven as a primary host plant during the growing season (but not year-round). Whereas in Virginia, West Virginia, and Maryland, researchers report mass movement of adults to overwintering sites between late September and early October (Leskey et al. 2012b, Joseph et al. 2013), there appeared to be little mass movement in the Sacramento population, although this may be an artifact of Sacramento's relatively low populations reducing the observed movement. Given these factors, and no applied insecticide, we expected an annual increase in the overall *H. halys* abundance. In fact, Nielsen et al. (2016) developed a stochastic model based on *H. halys* stage-specific phenology and population dynamics across different geographic regions and predicted that *H. halys* would have a relatively high 10-yr population growth in Davis, CA, which is near Sacramento and has a similar climate. Hot, dry temperatures, and poorer host quality in July and August in Sacramento may have had a negative impact on *H. halys* population growth. During this period, the tree of heaven trees sampled were not watered, thus host condition could be an additional impact, as found with other hemipterans (Daane and Williams 2003). Aigner and Kuhar (2016) exposed adults to varying high temperatures under laboratory conditions and reported 5, 12, and 38% mortality after only a 4 h of exposure at 35, 38, and 40°C, and Nielsen et al. (2008) reported a maximum developmental temperature threshold of 35.67°C; these temperatures were often recorded in July and August.

Numerous trap designs have been tested for *H. halys*, and one of the more effective traps is the black, ground-deployed pyramid trap (Leskey et al. 2012a). In conjunction with the seasonal phenology data, in 2016, we also compared two trap designs and four lures to confirm the pyramid trap worked well for the urban landscape found in Sacramento. The ground-based pyramid trap has a disadvantage in the urban landscape in that the traps can be tampered with or accidentally knocked over in high traffic areas, whereas our tested double cone trap could be hung in the tree canopy and was less apparent. We found no difference in adult capture between the two traps tested; however, more nymphs were captured in the pyramid trap (Fig. 3). Our studies built upon previous *H. halys* trapping studies. For example, researchers previously reported that nymph captures were lower in pyramid traps placed in the canopy compared with those on the ground (Morrison et al. 2015) and this may have been the primary difference in our studies as well, rather than trap design (Leskey and Hogmire 2005, Hogmire and Leskey 2006, Sargent et al. 2014, Morrison et al. 2015). The four lures we tested all had a combination of the pheromone and MDT, which has been shown to elicit a synergistic response (Weber et al. 2014). There was little difference among the four lures tested; a season-long average found that the Rescue lure had more adult male and nymph captures in the pyramid traps, although we did not test for lure longevity, pheromone or MDT load or release rate, or seasonal differences. However, past studies have found a strong dose response in trap capture for both pheromone and MDT (Leskey et al. 2012a, b). Therefore, the increased trap capture with Rescue lures was likely a result of higher pheromone and/or MDT loadings because all lures contained these components.

This is the first report of the seasonal phenology of *H. halys* in California, and we showed that the Sacramento population studied had a similar pattern as that reported in warmer mid-Atlantic urban and crop regions, with two generations per year (Nielsen et al. 2008, Leskey et al. 2012a, Zobel et al. 2016), an overwintering adult (P) population associated with urban structures or large trees (Lee et al. 2014), and peak populations generally occurring in September (Leskey et al. 2015c, Nielsen et al. 2016). There were slight annual variations in the Sacramento population pattern, assumed to be associated with variations in summer and winter temperatures. Many regions of California can have mild winters and warm (coastal) or hot (inland valleys) summers. Using a DD model based on maximum and minimum temperatures of an eastern U.S. *H. halys* population (Nielsen et al. 2008), we show a possible deposition of F3 egg masses in October (Fig. 1). This third generation is highly unlikely in Sacramento as studies in the mid-Atlantic region showed that adult females that eclose after a critical photoperiod during summer enter diapause and begin an overwintering period reproductively immature (Nielsen et al. 2017). We did observe, however, a larger adult population in winter 2016 as well as a larger number of adults following the spring and summer until extreme heat in July was associated with a reduction in trap counts (Figs 1C and 2). Therefore, in years with mild winters and summers, deposition of F3 eggs in September may be possible, especially in Southern California. Still, eclosion of nymphs from late-season egg masses or the overwintering survival of any resulting nymphs is unknown. Trapping studies throughout California are ongoing and populations are increasing near vineyards in Northern California (K. Daane and D. Shields, unpublished data) and stone fruit orchards in the interior valleys (J. Rijal, personal communication). It is likely that *H. halys* will move from its urban base into more agricultural areas and require insecticide treatment to protect some of California's agricultural crop.

References Cited

Acebes-Doria, A. L., T. C. Leskey, and J. C. Bergh. 2016a. Injury to apples and peaches at harvest from feeding by *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) nymphs early and late in the season. Crop Prot. 89: 58–65.

Acebes-Doria, A. L., T. C. Leskey, and J. C. Bergh. 2016b. Host plant effects on *Halyomorpha halys* (Hemiptera: Pentatomidae) nymphal development and survivorship. Environ. Entomol. 45: 663–670.

Acebes-Doria, A. L., T. C. Leskey, and J. C. Bergh. 2017. Temporal and directional patterns of nymphal *Halyomorpha halys* (Hemiptera: Pentatomidae) movement on the trunk of selected wild and fruit tree hosts in the mid-atlantic region. Environ. Entomol. 46: 258–267.

Aigner, J. D., and T. P. Kuhar. 2016. Lethal high temperature extremes of the brown marmorated stink bug (Hemiptera: Pentatomidae) and efficacy of commercial heat treatments for control in export shipping cargo. J. Urban Agricul. 32: 1–6.

Anonymous. 2017. Northeastern IPM Center (http://www.stopbmsb.org/where-is-bmsb/state-by-state/ (Accessed 20 July 2017).

Bakken, A. J., S. C. Schoof, M. Bickerton, K. L. Kamminga, J. C. Jenrette, S. Malone, M. A. Abney, D. A. Herbert, D. Reisig, T. P. Kuhar, et al. 2015. Occurrence of brown marmorated stink bug (Hemiptera: Pentatomidae) on wild hosts in nonmanaged woodlands and soybean fields in North Carolina and Virginia. Environ. Entomol. 44: 1011–1021.

Bansal, R., A. P. Michel, and Z. L. Sabree. 2014. The crypt-dwelling primary bacterial symbiont of the polyphagous pentatomid pest *Halyomorpha halys* (Hemiptera: Pentatomidae). Environ. Entomol. 43: 617–625.

Bergh, J. C., W. R. Morrison, S. V. Joseph, and T. C. Leskey. 2017. Characterizing spring emergence of adult *Halyomorpha halys* using experimental overwintering shelters and commercial pheromone traps. Entomol. Exp. Appl. 162: 336–345.

Bergmann, E., K. M. Bernhard, G. Bernon, M. Bickerton, S. Gill, C. Gonzales, G. C. Hamilton, C. Hedstrom, K. Kamminga, C. Koplinka-Loehr, et al. 2016a. Host plants of the brown marmorated stink bug in the U.S. Northeastern IPM Center. (http://www.stopbmsb.org/where-isbmsb/host-plants/) (Accessed 20 July 2017).

Bergmann, E. J., P. D. Venugopal, H. M. Martinson, M. J. Raupp, and P. M. Shrewsbury. 2016b. Host plant use by the invasive *Halyomorpha halys* (Stål) on woody ornamental trees and shrubs. PLoS One. 11: e0149975.

Daane, K. M., and L. E. Williams. 2003. Manipulating vineyard irrigation amounts to reduce insect pest damage. Ecol. Appl. 13: 1650–1666.

Hahn, N. G., C. Rodriguez-Saona, and G. C. Hamilton. 2017. Characterizing the spatial distribution of brown marmorated stink bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae), populations in peach orchards. PLoS One. 12: e0170889.

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

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

Hoebeke, E. R., and M. E. Carter. 2003. *Halyomorpha halys* (Stal) (Heteroptera: Pentatomidae): a polyphagous plant pest from Asia newly detected in North America. Proc. Entomol. Soc. Wash. 105: 225–237.

Hogmire, H. W., and T. C. Leskey. 2006. An improved trap for monitoring stink bugs (Heteroptera: Pentatomidae) in apple and peach orchards. J. Entomol. Sci. 41: 9–21.

Ingels, C., and L. Varela. 2014. Brown marmorated stink bug. Pest Note. University of California Integrated Pest Management Program. Publ. no. 74169, Davis, CA.

Joseph, S. V., J. C. Bergh, S. E. Wright, and T. C. Leskey. 2013. Factors affecting captures of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), in baited pyramid traps. J. Entomol. Sci. 48: 43–51.

Joseph, S. V., M. Nita, T. C. Leskey, and J. C. Bergh. 2015. Temporal effects on the incidence and severity of brown marmorated stink bug (Hemiptera: Pentatomidae) feeding injury to peaches and apples during the fruiting period in virginia. J. Econ. Entomol. 108: 592–599.

Joseph, S. V., J. W. Stallings, T. C. Leskey, G. Krawczyk, D. Polk, B. Butler, and J. C. Bergh. 2014. Spatial distribution of brown marmorated stink bug (Hemiptera: Pentatomidae) injury at harvest in mid-atlantic apple orchards. J. Econ. Entomol. 107: 1839–1848.

Kuhar, T. P., B. D. Short, G. Krawczyk, and T. C. Leskey. 2017. Deltamethrin-incorporated nets as an integrated pest management tool for the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae). J. Econ. Entomol. 110: 543–545.

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

Lee, D. H., J. P. Cullum, J. L. Anderson, J. L. Daugherty, L. M. Beckett, and T. C. Leskey. 2014. Characterization of overwintering sites of the invasive brown marmorated stink bug in natural landscapes using human surveyors and detector canines. PLoS One. 9: e91575.

Leskey, T. C., and H. W. Hogmire. 2005. Monitoring stink bugs (Hemiptera: Pentatomidae) in mid-Atlantic apple and peach orchards. J. Econ. Entomol. 98: 143–153.

Leskey, T. C., S. E. Wright, B. D. Short, and A. Khrimian. 2012a. Development of behaviorally-based monitoring tools for the brown marmorated stink bug (Heteroptera: Pentatomidae) in commercial tree fruit orchards. J. Entomol. Sci. 47: 76–85.

Leskey, T. C., B. D. Short, B. R. Butler, and S. E. Wright. 2012b. Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in Mid-Atlantic tree fruit orchards in the United States: case studies of commercial management. Psyche 2012: 1–14.

Leskey, T. C., D. H. Lee, D. M. Glenn, and W. R. Morrison. 2015a. Behavioral responses of the invasive *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) to light-based stimuli in the laboratory and field. J. Insect Behav. 28: 674–692.

Leskey, T. C., A. Khrimian, D. C. Weber, J. C. Aldrich, B. D. Short, D. H. Lee, and W. R. Morrison, III. 2015b. Behavioral responses of the invasive *Halyomorpha halys* (Stål) to traps baited with stereoisomeric mixtures of 10,11-epoxy-1-bisabolen-3-ol. J. Chem. Ecol. 41: 418–429.

Leskey, T. C., A. Agnello, J. C. Bergh, G. P. Dively, G. C. Hamilton, P. Jentsch, A. Khrimian, G. Krawczyk, T. P. Kuhar, D. H. Lee, et al. 2015c. Attraction of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) to traps baited with semiochemical stimuli across the United States. Environ. Entomol. 44: 746–756.

Morrison, W. R., III, J. P. Cullum, and T. C. Leskey. 2015. Evaluation of trap designs and deployment strategies for capturing halyomorpha halys (Hemiptera: Pentatomidae). J. Econ. Entomol. 108: 1683–1692.

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

Nielsen, A. L., G. C. Hamilton, and D. Matadha. 2008. Developmental rate estimation and life table analysis for *Halyomorpha halys* (Hemiptera: Pentatomidae). Environ. Entomol. 37: 348–355.

Nielsen, A. L., S. Chen, and S. J. Fleischer. 2016. Coupling developmental physiology, photoperiod, and temperature to model phenology and dynamics of an invasive heteropteran, *Halyomorpha halys*. Front. Physiol. 7: 165.

Nielsen, A. L., S. Fleischer, G. C. Hamilton, T. Hancock, G. Krawczyk, J. C. Lee, E. Ogburn, J. M. Pote, A. Raudenbush, A. Rucker, et al. 2017. Phenology of brown marmorated stink bug described using female reproductive development. Ecol. Evol. 7: 6680–6690.

Philips, C. R., T. P. Kuhar, G. P. Dively, G. Hamilton, J. Whalen, and K. Kamminga. 2017. Seasonal abundance and phenology of *Halyomorpha halys* (Hemiptera: Pentatomidae) on different pepper cultivars in the mid-atlantic (United States). J. Econ. Entomol. 110: 192–200.

Prado, S. S., K. Y. Hung, M. P. Daugherty, and R. P. Almeida. 2010. Indirect effects of temperature on stink bug fitness, via maintenance of gut-associated symbionts. Appl. Environ. Microbiol. 76: 1261–1266.

Sargent, C., H. M. Martinson, and M. J. Raupp. 2014. Traps and trap placement may affect location of brown marmorated stink bug (Hemiptera: Pentatomidae) and increase injury to tomato fruits in home gardens. Environ. Entomol. 43: 432–438.

Taylor, C. M., P. L. Coffey, B. D. DeLay, and G. P. Dively. 2014. The importance of gut symbionts in the development of the brown marmorated stink bug, Halyomorpha halys (Stål). PLoS One. 9: e90312.

Valentin, R. E., A. L. Nielsen, N. G. Wiman, D. H. Lee, and D. M. Fonseca. 2017. Global invasion network of the brown marmorated stink bug, *Halyomorpha halys*. Sci. Rep. 7: 9866.

Venugopal, P. D., G. P. Dively, and W. O. Lamp. 2015. Spatiotemporal dynamics of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) in and between adjacent corn and soybean fields. J. Econ. Entomol. 108: 2231–2241.

Weber, D. C., T. C. Leskey, G. C. Walsh, and A. Khrimian. 2014. Synergy of aggregation pheromone with methyl (E,E,Z) -2,4,6-decatrienoate in attraction of *Halyomorpha halys* (Hemiptera: Pentatomidae). J. Econ. Entomol. 107: 1061–1068.

Wiman, N. G., J. E. Parker, C. Rodriguez-Saona, and V. M. Walton. 2015. Characterizing damage of brown marmorated stink bug (Hemiptera: Pentatomidae) in blueberries. J. Econ. Entomol. 108: 1156–1163.

Xu, J. W., D. M. Fonseca, G. C. Hamilton, K. A. Hoelmer, and A. L. Nielsen. 2014. Tracing the origin of US brown marmorated stink bugs, *Halyomorpha halys*. Biol. Invasions 16: 153–166.

Zobel, E. S., C. R. R. Hooks, and G. P. Dively. 2016. Seasonal abundance, host suitability, and feeding injury of the brown marmorated stink bug, *Halyomorpha halys* (Heteroptera: Penatomidae), in selected vegetables. J. Econ. Entomol. 109: 1289–1302.