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# Biology, Ecology, and Management of Brown Marmorated Stink Bug (Hemiptera: Pentatomidae)

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**ABSTRACT.** Brown marmorated stink bug, *Halyomorpha halys* Stål, is an invasive, herbivorous insect species that was accidentally introduced to the United States from Asia. First discovered in Allentown, PA, in 1996, *H. halys* has now been reported from at least 40 states in the United States. Additional invasions have been detected in Canada, Switzerland, France, Germany, Italy, and Lichtenstein, suggesting this invasive species could emerge as a cosmopolitan pest species. In its native range, *H. halys* is classified as an outbreak pest; however, in North America, *H. halys* has become a major agricultural pest across a wide range of commodities. *H. halys* is a generalist herbivore, capable of consuming >100 different species of host plants, often resulting in substantial economic damage; its feeding damage resulted in US$37 million of losses in apple in 2010, but this stink bug species also attacks other fruit, vegetable, field crop, and ornamental plant species. *H. halys* has disrupted integrated pest management programs for multiple cropping systems. Pesticide applications, including broad-spectrum insecticides, have increased in response to *H. halys* infestations, potentially negatively influencing populations of beneficial arthropods and increasing secondary pest outbreaks. *H. halys* is also challenging because it affects homeowners as a nuisance pest; the bug tends to overwinter in homes and outbuildings. Although more research is required to better understand the ecology and biology of *H. halys*, we present its life history, host plant damage, and the management options available for this invasive pest species.

**Key Words:** biological control, chemical control, crop damage, invasive, Pentatomidae

## Origin and Spread

*Halyomorpha halys* (Stål), brown marmorated stink bug, is a polyphagous stink bug native to China, Japan, Korea, and Taiwan (Hoebeke and Carter 2003, Lee et al. 2013a) and is believed to have been introduced into the United States from a single introduction originating from Beijing, China (Xu et al. 2014). The first known *H. halys* populations were reported in 1996 from Allentown, PA, but went misidentified as the native brown stink bug, *Euschistus servus* (Say), until 2001, when Karen Bernhard (Lehigh County Cooperative Extension, Allentown, PA) speculated that the stink bug entering Allentown residences and buildings in the mid- to late fall was not *E. servus*. Based on Ms. Bernhard's hunch, specimens were sent to Cornell University for identification, resulting in the first confirmed report of an established *H. halys* population in the United States (Hoebeke and Carter 2003).

Following confirmation of its identity, reports of *H. halys* throughout Pennsylvania began to occur. In New Jersey, a review of unidentified stink bugs collected from black light traps maintained by the Rutgers Cooperative Extension Vegetable Integrated Pest Management Program revealed that *H. halys* was present in Phillipsburg, NJ, as early as 1999 (Hamilton 2009). Since then, *H. halys* has spread throughout the state (Nielsen et al. 2013). By 2005, *H. halys* had been detected in other parts of the mid-Atlantic United States (Delaware, Maryland, Virginia, and West Virginia) and in California and Oregon (G. H., unpublished data). In 2010, *H. halys* population abundance in mid-Atlantic states exploded (Leskey et al. 2012b), resulting in increased awareness by the agricultural sector and the general public, which generated detections in additional states.

Today, *H. halys* is present in at least 41 states and the District of Columbia (Leskey et al. 2014). A potential detection in Arkansas is awaiting verification and a Colorado find remains unofficial (Leskey and Hamilton 2013). In Delaware, Maryland, New Jersey, Pennsylvania, Virginia, and West Virginia, *H. halys* is currently considered a severe agricultural and nuisance pest, an agricultural and nuisance pest in New York, North Carolina, Ohio, and Tennessee, and a nuisance-only pest in California, Michigan, Indiana, New Hampshire, Massachusetts, Connecticut, and Rhode Island (Leskey and Hamilton 2012). In Oregon and Washington, brown marmorated stink bug has recently shifted from being a nuisance-only pest to an agricultural pest (Wiman et al. 2014).

## Pest Status in Other Invaded Regions

Given its expanding range in the United States and its tendency to stowaway in cargo, it is no surprise that *H. halys* has spread beyond Asia and the invaded range of the United States. Based on bioclimatic variables, conditions appear favorable for establishment and spread of this pest species in Europe and North America, as well as parts of Australia and New Zealand (Zhu et al. 2012). Over the last several years, *H. halys* adults have been sporadically intercepted or collected singly on three continents [Europe: Liechtenstein (Arnold 2009), Germany (Heckmann 2012), France (Callot and Brua 2013), Italy (European and Mediterranean Plant Protection Organization [EPPO] 2013); Australia: Australia (Walker 2009), New Zealand (Harris 2010); North America: Canada (Fogain and Graff 2011)]. Established populations, however, have only been confirmed outside the United States in Canada (H. F. and T. G., unpublished data) and Switzerland (Wermelinger et al. 2008), and evidence suggests potential establishment in the Alsace region of France (EPPO 2013).

**Canada.** The first documented occurrence of *H. halys* in Canada was in 1993 when a specimen was intercepted in British Columbia from a shipment originating in Asia. Since then, additional interceptions from shipments originating in China, Japan, Korea, and the United States have been recorded sporadically in the provinces of British Columbia, Ontario, and Quebec (Fogain and Graff 2011). Numerous homeowner reports in Ontario beginning in 2010 strongly suggested presence of an established population. In July 2012, presence of eggs, nymphs, and adults in Hamilton, ON, confirmed official establishment of breeding populations of *H. halys* in Canada (H. F. and T. G., unpublished data). Numbers of *H. halys* collected from residential locations in greater Toronto and Hamilton continue to increase, and homeowner discoveries have been reported in new locations within the province. Despite regular scouting and monitoring efforts in 2012 and 2013, *H. halys* has not been found in agricultural crops in Canada and remains a minor household and nuisance pest in urban areas around Toronto and Hamilton (H. F. and T. G., unpublished data). Although *H. halys* has only been found in natural habitats (primarily on invasive buckthorn, *Rhamnus* spp.), the proximity of these populations to major fruit-growing regions (e.g., Niagara Peninsula) has raised serious concerns about its potential movement into agricultural crops.

**Switzerland (and Other Parts of Europe).** The first established population of *H. halys* in Europe was officially documented in 2007 in Zurich, Switzerland (Wermelinger et al. 2008); however, photographic evidence suggests this species was present in the region as early as 2004 (T. H., unpublished data). Between 2007 and 2010, homeowner reports of *H. halys* in Zurich increased exponentially (Mueller et al. 2011), and now it has expanded its range to include the cantons of Basel-Stadt, Basel-Land, Aargau, Bern, St. Gallen, Schaffhausen, and Ticino (Wyniger and Kment 2010, Haye and Wyniger 2013). The original population in Zurich appears to have been the source of *H. halys* in these cantons, rather than new introductions coming from Asia or North America (Gariepy et al. 2014). Similarly, the well-established Swiss populations are likely sources of *H. halys* occurrences in neighboring Liechtenstein (Arnold 2009), Germany (Heckmann 2012), France (Callot and Brua 2013), and Italy (EPPO 2013). Although established in Switzerland for at least 9 yr, *H. halys* remains mostly an urban and household pest; however, 38 local host plant species (native and otherwise) have been identified as hosts for *H. halys* (Haye and Wyniger 2013) and some ornamental species can harbor heavy infestations (Wermelinger et al. 2008). Moreover, some evidence suggests that *H. halys* may become an agricultural pest in the near future; fruit-bearing trees in private gardens in Zurich have been injured (T. H. and T. G., unpublished data) and peppers (*Capsicum annuum* L.) in Aargau have sustained economic damage (Sauer 2012).

## Description of Life Stages

White and black banding on their antenna and abdominal edges distinguishes adults *H. halys* from native stink bug species in the United States (Fig. 1). Claspers located on the last ventral abdominal segment differentiate adult males from females (Fig. 2). Females lay egg masses on the underside of leaves and freshly deposited eggs are light green, and turn white (Fig. 3) before hatching. Brown marmorated stink bugs have five instars. First instars (Fig. 4) have black heads, red eyes, and reddish orange abdomens with black markings; the neonates emerge 3–6 d after oviposition, and feed from eggshells, possibly acquiring endosymbionts (Taylor et al. 2014). Second instars (Fig. 5) emerge 3–5 d after first instars, disperse from egg masses, and feed on host plants. Third instars are dark brown (Fig. 6) and molt 12–13 d after eggs hatch, whereas fourth (Fig. 7) and fifth instars (Fig. 8) emerge 19–20 and 26–27 d after egg hatch, respectively. Development from egg to adult requires 538 DD (32–35 d at 30°C) with a minimum and maximum developmental threshold of 14 and 35°C (Nielsen et al. 2008a).

## Biology

In southern China, *H. halys* is multivoltine with four to six generations (Hoffmann 1931). In the mid-Atlantic United States where population densities are currently the greatest, it has one to two generations per year (Nielsen et al. 2008a). Nonreproductive adults overwinter in artificial and natural shelters, and gradually emerge from these sites beginning in April. Termination of diapause does not occur immediately upon leaving overwintering sites and is likely driven by photoperiod (threshold of 14.8–15.5 h; Yanagi and Hagihara 1980). Photoperiod, however, also interacts with temperature, and once the daylength threshold has been met, it may override photoperiod requirements for diapause termination. Females require an additional 148 DD before becoming reproductively mature (Nielsen et al. 2008a). Reproductively mature *H. halys* can disperse into crops, but hardwood trees and shrubs may be important intermediate hosts after leaving overwintering sites, before crop invasion. Females are polyandrous and typically lay clusters of 28 eggs (mean = 26.08 ± 0.31) on the underside of leaves (Kawada and Kitamura 1983, Nielsen et al. 2008a). Brown marmorated stink bug can complete development on peach (*Prunus persica* (L.)) and tree of heaven (*Ailanthus altissima* [Miller] Swingle) but has >100 host plants that include tree fruit, small fruit, vegetable, ornamental and field crop species (Leskey et al. 2012a, 2013a).

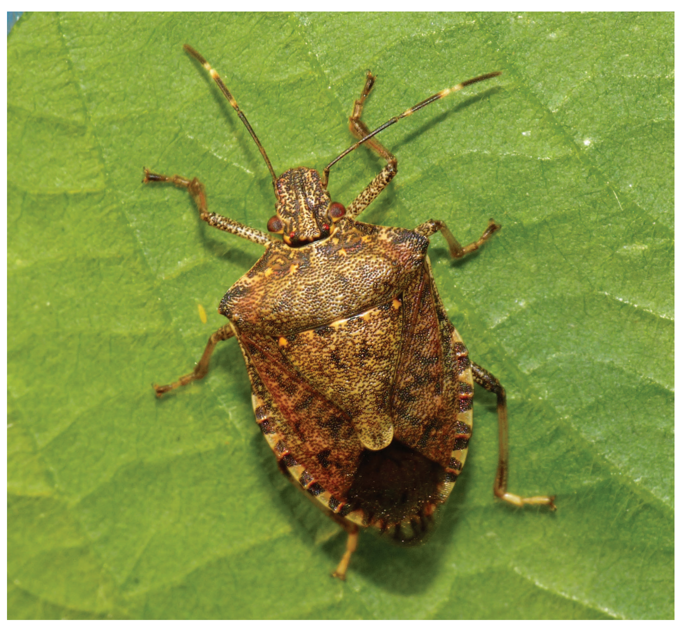

**Fig. 1.** Adult brown marmorated stink bug. (Photo by Ian Grettenberger, Penn State University.)

**Fig. 2.** Female (left) and male (right) brown marmorated stink bugs. Males have claspers on the terminal abdominal segment. (Photo by Ian Grettenberger.)

**Fig. 3.** Brown marmorated stink bug eggs. (Photo by Ian Grettenberger.)

The strong capacity of *H. halys* to disperse at landscape scales throughout the year may aid its polyphagous behavior. In flight-mill studies, tethered adults from wild populations flew an average of 2 km in 24 h (T.C.L, unpublished data). With field observations, *H. halys* flies about 3 m/s along a straight line from take-off to landing (Lee et al. 2013b). Flight also occurs at night as adults seek out mates or alternative food sources; therefore, black light traps can be effective monitoring tools for landscape-level movement of *H. halys*. Although flight activity varies through the year, a large peak in black light captures tends to occur at 685 DD (Nielsen et al. 2013). Some of the longest flights may occur at the onset of the winter aggregation period in the late summer and fall (Wiman et al. 2014). Nymphs actively disperse by walking and second through fifth instars show strong tendencies in the laboratory and field to move (Lee et al. 2014a).

**Fig. 4.** First instar brown marmorated stink bugs. (Photo by Ian Grettenberger.)

Brown marmorated stink bug is well-known as a nuisance pest; large numbers of adults often invade human-made structures to overwinter inside protected environments (Inkley 2012). This behavior is rather unique among Pentatomidae and may improve overwintering survivorship of *H. halys* relative to other species such as *Nezara viridula* L. (Kiritani 2007). Similar to other pentatomid species, *H. halys* also will overwinter, at least in the mid-Atlantic region, in natural settings, including dry crevices in dead, standing trees with thick bark, particularly oak (*Quercus* spp.) and locust (*Robinia* spp.; Lee et al. 2014b). For trees with overwintering *H. halys*, searches of 20% of above-ground tree area yielded approximately six adults per tree (Lee et al. 2014b).

Black light traps attracting foraging *H. halys* adults can be used to document season-long, landscape-level populations (Nielsen et al. 2013). Brown marmorated stink bug response to light-based stimuli is affected by intensity and wavelength under both laboratory and field conditions, with adults most attracted to white, blue, and black (UV) stimuli (Leskey et al. 2014). During summer months, large aggregations of adults have been observed at outdoor dusk-to-dawn light sources. Nymphs have never been documented responding to light-based stimuli.

**Fig. 5.** Second instar brown marmorated stink bugs. (Photo by Ian Grettenberger.)

**Fig. 6.** Third instar brown marmorated stink bug. (Photo by Ian Grettenberger.)

## Ecology

**Chemical Ecology.** Brown marmorated stink bug males produce a recently identified two-component aggregation pheromone, (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol and (3*S*,6*S*,7*R*,10*R*)-10,11-epoxy-1-bisabolen-3-ol (Khrimian et al. 2014, Zhang et al. 2013; U.S. patent WO2013090703 A1). Aggregation pheromones differ from sex pheromones in a few important ways. First, aggregation pheromones tend to elicit responses from all mobile life stages, presumably identifying a resource such as a host plant, mate, or overwintering site. Secondly, aggregation pheromones tend to bring respondents to an area, but unlike sex pheromones with which responders will generally attempt to locate the exact point source of the stimulus, responders to aggregation pheromones will be attracted to and may be arrested by stimuli several meters away from the stimulus source. In the mid-Atlantic region, sensitivity to the aggregation pheromone deployed in traps coincides with initial dispersal from overwintering sites and peak population densities are typically detected from late July to late September. Brown marmorated stink bugs also respond to the kairo-

**Fig. 7.** Fourth instar brown marmorated stink bug. (Photo by Ian Grettenberger.)

**Fig. 8.** Fifth instar brown marmorated stink bug. (Photo by Ian Grettenberger.)

mone 2,4,6, E,E,Z methyl decatrienoate, the aggregation pheromone of *Plautia stali* Scott (Heteroptera: Pentatomidae), which was used for many of the initial pheromone trials in the United States, though this stimulus is only attractive beginning in early August (Aldrich et al. 2009, Nielsen et al. 2011, Leskey et al. 2012a). The 2,4,6, E,E,Z methyl decatrienoate pheromone also has proven to be a strong synergist for the aggregation pheromone of *H. halys*, increasing sensitivity of baited traps season-long (Weber et al. 2014).

**Host Plants.** Brown marmorated stink bug has >100 reported host plants (Bergmann et al. 2013). It is common in woodlots and is widely considered an arboreal species. Host plants such as *A. altissima*, *Paulownia tomentosa* (Thunberg) Steudel, *Acer* spp., and *Fraxinus* spp. appear important for supporting populations, particularly during initial invasions into a region (Nielsen and Hamilton 2009b). The ability to disperse among host plants seems important for development and survival of *H. halys*, which can complete development exclusively on *A. altissima* and *P. tomentosa*; however, despite often inflicting heavy late-season injury, *H. halys* survivorship on apple (*Malus domestica* Borkh) is low (Funayama 2002, 2004). Many economically important crop species are hosts for *H. halys* including peach, apple, filbert nut (*Corylus avellana* L.), pear (*Pyrus communis* L.), wheat (*Triticum aestivum* L.), grapes (*Vitis* spp.), small fruit, field corn (*Zea mays* L.), soybean (*Glycine max* L. Merrill), sorghum (*Sorghum bicolor* L.), and many vegetable crops such as sweet corn, tomato (*Solanum lycopersicum* L.), pepper, okra (*Abelmoschus esculentus* (L.) Moench), and eggplant (*Solanum melongena* L.). On these plant species, *H. halys* prefers to feed upon reproductive structures. In soybean, for instance, they do not colonize the crop in large numbers until the R3 stage and peak population abundance occurs at R5 when the pods begin to fill (Nielsen et al. 2011). Brown marmorated stink bugs appear to move readily among crops and crop phenology may drive its movement.

**Invasion Ecology.** The close association of *H. halys* with humans can distress some residents (Inkley 2012), but it also can prompt volunteer citizen scientists to help track pest invasions. Many universities, such as Rutgers, Penn State, and Oregon State University have developed websites with varying levels of verification to track citizen reports of *H. halys*. In some instances, reports to these databases have become the first sightings in a state.

Lights can attract *H. halys* adults as they disperse across the landscape (see Biology). In New Jersey, a network of black light traps located at farms throughout the state has been used to track the spread of *H. halys.* These traps attract males and females equally well and their captures can detect movement of early dispersers into tree fruit, an event coinciding with sexual maturation of female bugs. Data from this statewide network of traps indicated a 75% annual population increase from 2004 to 2011, which equated to an annual invasion of 2.8 farms (Nielsen et al. 2013). These findings illustrate the scale of the *H. halys* invasion and emphasize that the bug is an efficient disperser. Further analyses of data from this network suggests that landscape features in New Jersey may be associated with *H. halys* population hotspots (Wallner et al. 2014). Early in the invasion, there was a strong association of *H. halys* population abundance with urban environments. Railroads and wetlands appear to facilitate population spread and populations eventually settle in agricultural regions (Wallner et al. 2014). This analysis supports the hypothesis that the agriculture–urban interface may drive populations, with urban settings providing overwintering habitat and increased overwintering survival, while agricultural crops provide resources for development and population increase (see Hufbauer et al. 2013).

## Host Plant Species, Economic Damage, and Sampling or Scouting Procedure

**Vegetables.** Brown marmorated stink bug can cause significant injury to a wide range of vegetable crop species when bugs insert their feeding stylets into plant fruiting bodies, which are often the marketable portion of the crop. Feeding injury to beans (*Phaseolus* spp.) may result in scarred, faded sunken areas, and deformed pods (Fig. 9); similar pod injury can occur when the bugs feed upon okra. Injury to fleshy fruit, like tomatoes and peppers, will produce white spongy areas on the skin (Figs. 10 and 11) and internal tissue damage (Fig. 12). Along with reduced quality of marketable produce, feeding injury to vegetables may reduce fruit set and subsequent yield by causing abortion of flower buds and young fruiting bodies. In addition to direct damage, the feeding stylets of *H. halys* can also transmit pathogenic bacteria or yeasts, such as *Eremothecium coryli*, which can cause fruit rot (Fig. 13). Under heavy infestations, losses >50% due to *H. halys* damage have been common. Among vegetables, sweet corn, okra, and pepper appear to be highly preferred host plant species for adult colonization and reproduction (Kuhar et al. 2012f). Eggplant and green bean (*Phaseolus vulgaris* L.) are also suitable for oviposition and nymphal development. Tomato appears to be less suitable for *H. halys* reproduction, but can suffer severe fruit damage, particularly in late August. Brown marmorated stink bugs will also feed on other vegetable species such as asparagus (*Asparagus officinalis* L.), cucur-

**Fig. 9.** Brown marmorated stink bug damage on lima bean pods (*Phaseolus lunatus* L.). (Photo by Thomas Kuhar, Virginia Polytechnic Institute and State University.)

**Fig. 10.** Damage on tomato resulting from brown marmorated stink bug feeding. (Photo by Thomas Kuhar.)

**Fig. 11.** Brown marmorated feeding damage on bell pepper. (Photo by Peter Shearer, Oregon State University.)

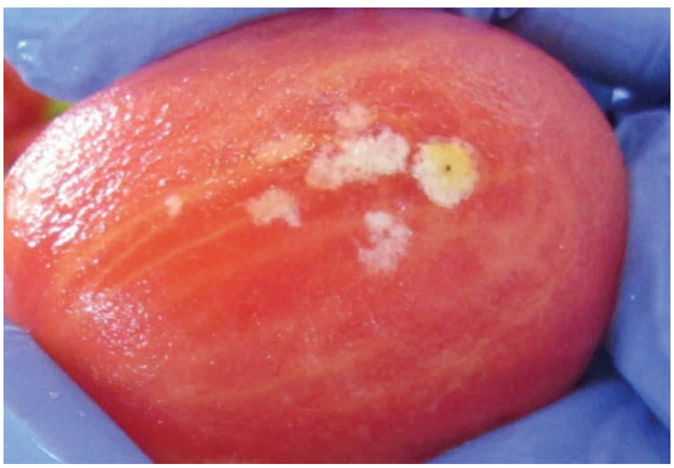

**Fig. 12.** Peeled tomato revealing corky tissue formation caused by brown marmorated stink bug feeding. (Photo by Shelby Fleischer, Penn State University.)

**Fig. 13.** Indirect damage (bacterial rot) on tomato caused by brown marmorated stink bug. (Photo by Doug Inkley, National Wildlife Federation.)

**Fig. 14.** Brown marmorated stink bug damage on apple. (Photo by Tracy Leskey, Agricultural Research Service, United States Department of Agriculture.)

bits, or brassicas, but to a lesser degree and depending on their proximity to more preferred vegetables.

In the mid-Atlantic region, *H. halys* attacks the majority of vegetable crops present from late July to October (Kuhar et al. 2012a). In mixed vegetable plantings, or on small farms with diverse crops, over the growing season *H. halys* adults and nymphs often move significantly among crops, depending upon the relative attractiveness of each crop. Vegetable crops nearest overwintering shelters or directly bordering wooded areas are at the highest risk of *H. halys* attack. Late in the season, vegetables bordering a more attractive host plant such as soybeans may suffer less *H. halys* damage than those that do not.

**Fruit.** In Asia, *H. halys* is an occasional outbreak pest of tree fruit (Lee et al. 2013a). Damage to apples (Fig. 14) and pears in the United States first appeared in Allentown, PA, and Pittstown, NJ, in 2006 (Nielsen and Hamilton 2009a). In orchards where it establishes, *H. halys* quickly becomes the predominant stink bug species and, unlike native stink bug species, is a season-long pest of tree fruit (Nielsen and Hamilton 2009a, Leskey et al. 2012a). In particular, *H. halys* heavily attacks peaches, nectarines (*Prunus persica* (L.) Batsch), apples, and Asian pears (*Pryrus pyrifolia* Nakai).

In the mid-Atlantic United States in 2008–2009, increasing *H. halys* populations caused late-season damage to fruit crops (Leskey and Hamilton 2010a), but *H. halys* was not a widely recognized pest until late in the 2010 season. Damage from *H. halys* feeding during the 2010 outbreak resulted in US$37 million in losses to mid-Atlantic

**Fig. 15.** Damage from brown marmorated stink bug on immature peach. (Photo by Tracy Leskey.)

apples alone (American/Western Fruit Grower 2011) with some stone fruit growers losing >90% of their crop (Leskey and Hamilton 2010b).

Feeding injury from *H. halys* to stone fruit, principally peaches (Fig. 15) and nectarines, causes depressed or sunken areas that may become cat-faced as fruit develops. On pome fruit, including apples and pears, feeding results in indented depressions on the surface and corky spots in the flesh of fruit. Feeding may also cause fruiting structures to abort prematurely (Nielsen and Hamilton 2009a). Increases in targeted insecticide applications, particularly postbloom, has mitigated *H. halys* damage in orchard crops (Leskey et al. 2012a). Residual activity of most insecticides on fruit and foliage against *H. halys* is very short, necessitating narrower application intervals of broad-spectrum materials to maintain fresher residues (Lee et al. 2012, Leskey 2012c). Increased reliance on chemical control has increased secondary pest outbreaks that are typically controlled by natural enemies (Leskey et al. 2012c).

Brown marmorated stink bug has the potential to feed and reproduce in small fruit crops such as blueberries (*Vaccinium* spp.), raspberries (*Rubus idaeus* L.), grapes, and blackberries (*Rubus* spp.; Leskey and Hamilton 2010b); however, little is known about its economic impact in these crops. Studies are underway in the United States to determine its potential impact, spatial distribution, and seasonal abundance in small fruit crops. In the northeastern United States, blueberry growers first found *H. halys* during the late-season in 2010 and many growers in New Jersey have since reported it in and around structures and houses. Contamination risks are a great concern for blueberry growers who mechanically harvest and then sell their berries to processors or ship them to other countries and regions within the United States. During 2011–2012, *H. halys* population abundance in New Jersey blueberry farms remained low and did not require control measures.

In caneberries (raspberries and blackberries), stink bug species cause two types of injury. In early season, *H. halys* feeding may cause death of buds, though this apparent damage needs to be further explored. In late season, *H. halys* attacks mature berries, inserting their stylets between drupelets, and possibly feeding on the receptacle; this feeding causes discoloration and collapse of individual drupelets. Droppings produced by feeding stink bugs can add an unpleasant taste to berries. No damage by *H. halys* has been observed in cranberries.

In wine grapes, *H. halys* establishment raised concern about stink bugs tainting grape juice. Some preliminary data indicate that the taint does not survive fermentation and bottling, while others indicate it may (Mohekar et al. 2014, Tomasino et al. 2014). Brown marmorated stink bug uses grapevines as reproductive hosts, and both nymphs and adults feed upon grape clusters (Pfeiffer et al. 2012). This feeding results in necrosis and deformation at the feeding site, and many bugs may be seen on individual clusters. Action thresholds need to be determined.

**Field Crops.** The main field crop species colonized thus far by *H. halys* are corn and soybeans. There is some evidence that stink bug populations can accumulate in fields of wheat, cotton (*Gossypium hirsutum* L.), hops (*Humulus lupulus* L.), sorghum, and possibly sunflower (*Helianthus annuus* L.). This latter crop is relatively scarce in the mid-Atlantic region where stink bugs are currently so abundant, but the host plant species is being explored as a trap crop for *H. halys* in vegetable production, so it seems reasonable to suspect that large fields of sunflower would be attractive to *H. halys*. Thus far, *H. halys* nymphs have mainly been discovered in corn and soybeans, suggesting these crops are attractive to adult bugs and suitable for oviposition and nymphal development. Based on population abundance at different times of the season, it seems that *H. halys* colonizes corn fields when ears are developing (July), and later in the year bug populations develop in soybean fields when pods form and seeds are filling (August and September). This knowledge can increase the efficiency of scouting by allowing scouts to focus only on those fields in susceptible growth stages. Further, given that *H. halys* populations are worse in crop fields adjacent to woods (see below), it appears that wooded areas are sources of bugs, but research has yet to explore the movement of bugs among habitats or how this movement might be exploited for management.

*Field Corn.* Brown marmorated stink bug populations are highest in field corn during ear formation, specifically during the milk (R3 growth stage) and dough (R4) stages. The bugs appear to feed primarily on developing kernels by piercing the husk, and the resulting damage discolors and shrink individual kernels (Fig. 16). Some evidence from Pennsylvania suggests that feeding by *H. halys* on late-stage, vegetative corn plants can abort ear production, but more research is needed to explore this potential phenomenon. Populations of bugs on corn plants, particularly in field edges, can often exceed three bugs per ear, but in some fields, it is not uncommon to find as


**Fig. 16.** Damage to field corn by brown marmorated stink bug, which feed through the husk on individual kernel. (Photo by Galen Dively, University of Maryland.)

**Fig. 17.** Brown marmorated stink bug nymphs feeding on an ear of corn. (Photo by Ronald Hoover, Penn State University.)

**Fig. 18.** "Stay-green" syndrome caused by brown marmorated stink bug feeding on the edge of a soybean field near Lancaster, PA. (Photo by Jeff Graybill, Penn State Extension.)

many as 20 bugs on some ears (Fig. 17). Brown marmorated stink bug population in field corn is typically highest within 12 m of field edges and decrease significantly toward the centers of fields. The highest population densities tend to be in corn fields adjacent to wooded areas, but significant populations can also occur in fields in proximity to alfalfa (*Medicago sativa* L.) and sorghum fields, and even buildings; fields with the fewest bugs tend to be adjacent to open areas (D. V., unpublished data).

Research from 2012 suggests that adult infestations occurring at the R3 growth stage caused significantly lower yields compared with infestations at R4. For a similar experiment conducted in 2011, the trend was in the same direction yet analyses did not reveal a significant yield reduction between the timing of infestations. In both years, *H. halys* feeding affected grain quality, with infestations occurring at growth stage R2 (blister stage) and R3 resulting in the greatest number of damaged kernels per ear (Cissel, unpublished data). Additional research needs to evaluate the impact of *H. halys* feeding on yield when sustained infestations occur during the entire grain fill period. Because feeding damage by the brown stink bug was correlated with increased aflatoxin levels in corn (Ni et al. 2011), the influence of *H. halys* feeding damage on aflatoxin development should also be explored. While economic thresholds for field corn are still being developed, it must be acknowledged that effectively treating infested corn fields can be challenging because of the height of mid- to late-season corn plants and the amount of foliage between the top of the plant and the ear (Reisig 2011).

*Soybean.* Brown marmorated stink bug populations tend to invade soybean fields during the R4 (fully elongated pods) to R6 (fully developed seed) plant growth stages. Before these stages, bug populations can be found but numbers tend to be lower. Brown marmorated

**Fig. 19.** Flattened soybean pods caused by brown marmorated stink bug feeding directly on seeds through the pod. (Photo by Jeff Graybill.)

stink bug tends to feed on developing seeds directly through the pod. As with field corn, *H. halys* populations typically remain on field edges, especially those bordering wooded areas, corn fields, and

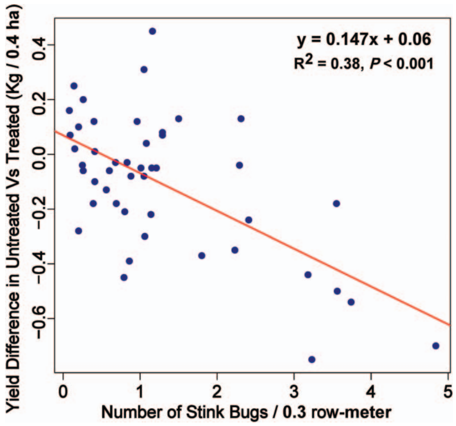


**Fig. 20.** Relationship between brown marmorated stink bug density and yield difference in treated and untreated soybean zones.

buildings, while low infestations tend to be in field edges bordering open areas (D. V., unpublished data). Field edge-only insecticide applications have been promoted to growers and repeat posttreatment field visits have verified that these treatments can be effective in managing infestations. In late summer and early autumn, *H. halys* populations on the edges of soybean fields often leave a signature because their feeding often causes a "stay green" syndrome in which attacked plants exhibit significantly delayed senescence relative to uninfested portions of the field. Thus, in the mid-Atlantic region in September and October it is not uncommon to find yellowing fields with bright green edges (Fig. 18). It should be noted, however, that other factors (e.g., plant pathogens and nutrient stress) can cause similar "stay-green" effects, but there is an obvious abundance of green edges in areas with large *H. halys* populations. Brown marmorated stink bug feeding on developing seeds during the R5 growth stage causes the greatest crop injury, resulting in shriveled seeds and flatten pods (Fig. 19), damage similar to that caused by native stink bug species. Recent field cage-based research on the influence of *H. halys* on soybean yield showed that a density of four stink bugs per 0.3 m of row decreased seed quality (Owens et al. 2013). This study did not detect a significant relationship between *H. halys* densities and yield loss (Owens et al. 2013). However, an ongoing field study in the mid-Atlantic region comparing yields of pyrethroid-treated and untreated R4 stage plots indicated that one *H. halys* per 0.3 m of row resulted in a loss of 375 g per ha or 2.2 bushels per acre (Fig. 20); (G. D., unpublished data). Brown marmorated stink bug feeding on R6 or R7 stage soybeans appears less likely to cause yield loss, but can decrease soybean quality, which can influence the value of the grain. When completed, these additional studies will increase our understanding of the exact relationship between *H. halys* densities and yield loss. Further, a field cage study showed that feeding injury caused by *H. halys* is similar to that caused by native stink bug species, indicating that all stink bug species can be combined for determining the economic threshold for a field. Peak abundance of native stink bugs occurs at similar reproductive stages in soybean (Herbert and Toews 2012). While still under development, tentative economic thresholds are one to two *H. halys* per row foot, or five stink bugs per 15 sweeps of a net. We recommend scouting field edges during R4–R6 and making field edge-only treatments if populations exceed tentative thresholds. Several insecticides provide control, and a single field edge-only treatment can be effective, if applied at the right time.

*Wheat.* We have seen populations of adult *H. halys* develop in the milk and soft dough stages of wheat fields (J. W., unpublished data). Given the apparent preference of *H. halys* for developing seeds of other grains, it seems likely that bugs are feeding on developing seeds, though this, and any influence of their feeding on yield and any associated economic thresholds, remains to be established. Research on native stink bugs indicates that the most susceptible stages of wheat development are the milk and soft dough stages (Viator et al. 1983). This coincides with the stage of the wheat fields when *H. halys* adults have been observed in wheat (J. W., unpublished data). In the absence of a more preferred host species, wheat may be attractive to *H. halys*, though more studies are needed to determine if *H. halys* poses a significant risk. Similar to soybean and field corn, we observed higher densities of *H. halys* in wheat field edges bordering wooded areas.

**Ornamental Plants in the Eastern United States.** *Host Plant Breadth.* Before its arrival in the United States, *H. halys* was known to feed on a wide variety of woody ornamental plants in Asia (Hoebeke and Carter 2003). This included both gymnosperms such as *Cryptomeria* (Funayama 2005) and angiosperms such as *Malus* (Funayama 2004) and *Paulownia* (Hiruki 1999). In one of the earliest accounts of host use in the United States, 50 woody tree and shrub species were identified as hosts for *H. halys* (Bernon 2004). This list was broadened and researchers noted marked temporal changes in patterns of host use as *H. halys* moved among woody plants in various stages of development (Nielsen and Hamilton 2009b). In general, they detected correlations between the abundance of *H. halys* nymphs and the presence of maturing pods and fruit. Of the nine woody trees and shrubs studied, all supported populations of *H. halys* (Nielsen and Hamilton 2009b). The most current compilation of hosts in the United States includes >120 species of woody trees and shrubs and at least three herbaceous perennials growing in protected culture and as wild hosts in the invaded range (Bergmann et al. 2013). This list will continue to expand. Ongoing surveys at three commercial ornamental plant nurseries in central Maryland between 2011 and 2012 revealed that *H. halys* used 174 of the 200 cultivars of woody trees and shrubs as hosts (E. B., unpublished data). Plants with the greatest abundances of *H. halys* in protected culture and on wild hosts included cultivars in the genera *Acer*, *Ailanthus*, *Catalpa*, *Cercis*, *Ilex*, *Magnolia*, *Malus*, *Mimosa*, *Morus*, *Paulownia*, *Platanus*, *Prunus*, and *Syringa* (Bergmann et al. 2013, E. B., unpublished data). Hosts include those used solely for feeding and those which also used for feeding and oviposition.

*Direct and Indirect Damage.* In Japan, *H. halys* is a pest on cedar and cypress farms (Funayama 2005) and is reported to injure various shade

**Fig. 21.** Brown marmorated stink bugs feed through the bark of ornamental trees releasing sap that stains the tree attracting ants and stinging Hymenoptera. (Photo by Michael Raupp, University of Maryland.)

trees (Hoebeke and Carter 2003). In China, *H. halys* damage ornamental plants such as *Hibiscus*, *Celosia*, and *Paulownia* (Hoebeke and Carter 2003). In the mid-Atlantic United States in 2010, the population abundance of *H. halys* grew enormously. With this population explosion, *H. halys* became an important pest and economic threat to ornamental woody and herbaceous plants in commercial nurseries and landscapes via direct (Leskey et al. 2012b) and potential indirect feeding damage (Hoebeke and Carter 2003). By midsummer 2010, direct feeding damage by *H. halys* was first noted in Maryland as disfigured fruits and wilted foliage of *Malus*, *Crateagus*, and *Amelanchier* (Leskey et al. 2012b). Brown marmorated stink bug feeding on foliage can result in stippling damage, which then progresses to a brown and scab-like appearance (Hoebeke and Carter 2003). In August of 2010, *H. halys* became very abundant in Maryland and West Virginia nurseries and landscapes on trunks of trees such as *Platanus*, *Acer*, and *Ulmus*. Brown marmorated stink bugs demonstrate a unique habit of feeding through the bark (Fig. 21), a behavior not reported for this species and is unusual for stink bugs in general (Panizzi 1997, Martinson et al. 2013). The resulting injury included copious sap flow, fluxes, and discolored bark at feeding sites. Several species of native ants and wasps fed on these exudates, which had high sugar concentrations; thus, it appears that bark feeding by *H. halys* facilitate native Hymenoptera by creating a novel feeding niche (Martinson et al. 2013). Bark feeding has since been observed on several additional host species (E. B., unpublished data). Wilting and death of herbaceous perennials due to heavy feeding damage by *H. halys* has been reported on a small number of species (Leskey et al. 2012b).

In addition to direct damage from feeding, *H. halys* may also cause indirect damage. In Asia, *H. halys* is a vector of witches' broom disease, which can greatly alter growth patterns of afflicted plants (Bak et al. 1993, Hiruki 1999, Yu and Zhang 2009). The disease–vector potential of *H. halys* has raised concerns, but to date has not been reported on ornamental plants in the United States.

*Sampling and Monitoring.* Ornamental environments consist of a diversity of plant species of varying shapes and sizes, which makes standardized sampling somewhat challenging. The most common methods of quantifying *H. halys* activity on ornamentals has been the use of standardized beat sampling methods (Nielsen and Hamilton 2009b) and timed visual counts (E. B., unpublished data). These sampling methods allow for comparison of *H. halys* densities among plant species and changes in densities over time.

## Biological Control

In Asia, several natural enemies of *H. halys* have been identified including arthropod predators, dipteran parasitoids, and hymenopteran egg parasitoids (Qiu 2007, Qiu et al. 2007, Leskey et al. 2012b, Leskey et al. 2013). Predators found in Asia attack all life stages of *H. halys*, while parasitoids use adult and egg stages as hosts. The highest levels of parasitism reported in Asia ranged from 63 to 85% for hymenopteran egg parasitoids in the genera *Trissolcus* (Zhang et al. 1993, Qiu 2007, Qiu et al. 2007, Yang et al. 2009, Talamas et al. 2013) and *Anastatus* (Hou et al. 2009). Pathogens may also contribute to *H. halys* mortality, including *Ophiocordyceps nutans* (Hypocreales: Phiocordycipitaceae) (Sasaki et al. 2012) and an intestinal virus of *P. stali* (Hemiptera: Pentatomidae) (Nakashima et al. 1998).

In North America, field surveys conducted primarily in the eastern United States have identified several natural enemies associated with *H. halys* (Biddinger et al. 2012). Chewing and sucking predators of *H. halys* eggs, nymphs, and adults have been identified in the following families: Anthocoridae, Asilidae, Chrysopidae, Coccinellidae, Crabronidae, Forficulidae, Geocoridae, Mantidae, Melyridae, and Reduviidae. In addition, spiders have been observed feeding on all life stages of *H. halys* (Kawanda and Kitamura 1992, Lan-fen 2010, Leskey et al. 2012b). Mortality of *H. halys* eggs owing to predation and other unknown causes reached 40–70% in corn and soybean plots in Pennsylvania, Maryland, and New Jersey, averaged 23% in ornamental nurseries surveyed in Maryland, and predators alone caused ≈25% egg mortality in Pennsylvania orchards (Biddinger et al. 2012, C.R.R.H., D.J.B., and P.M.S., unpublished data). Coccinellidae (particularly *Harmonia axyridis* Pallas) and Forficulidae (earwigs) are the primary predators in orchard systems surveyed in Pennsylvania (Biddinger et al. 2012, D.J.B., unpublished data). In addition, late *H. halys* instars composed the majority (95%) of nest provisioning by sand wasps (Crabronidae) in 40 nests surveyed in Pennsylvania, New Jersey, and Maryland (D.J.B., unpublished data).

A wide-spread survey of parasitoids using sentinel (e.g., laboratory reared) egg masses found telenomine platygastrids to be the predominant parasitoids emerging from *H. halys* eggs in the mid-Atlantic United States and Oregon (Table 1). Rates of parasitism recorded

**Table 1. North American natural enemies of *Halyomorpha halys* reported from field surveys (D.J.B., C.R.R.H., A.L.J., T.P.K., P.M.S., N.G.W., and J. W., unpublished data)**

| Order | Family (subfamily if known) | Species | *H. halys* life stages attacked | Locality |
|---|---|---|---|---|
| Araneae | Arachnida | | Eggs, nymphs, adults | Maryland, Oregon, Pennsylvania |
| Coleoptera | Coccinellidae | *Harmonia axyridis* | Eggs | Pennsylvania |
| Dermaptera | Forficulidae | | Eggs | Pennsylvania |
| Diptera | Tachinidae | *Trichopoda pennipes* | Adult, late instars | Pennsylvania |
| Hemiptera | Anthocoridae | *Orius* sp. | Eggs | Maryland |
| | Geocoridae | *Geocoris* sp. | Eggs, nymphs | Maryland, Oregon, Pennsylvania |
| | Reduviidae | *Arilus cristatus* | Eggs, nymphs, adults | Maryland, Oregon, Pennsylvania |
| Hymenoptera | Crabronidae | *Astata* unicolor | Adults, late instars | Pennsylvania |
| | | *Astata* bicolor | Late instars | Oregon |
| | | *Bicyrtes quadrafaciata* | Late instars | Pennsylvania |
| | Encyrtidae | *Ooencyrtus* sp. | Eggs | Delaware, Maryland |
| | Eupelmidae | *Anastatus mirabilis* | Eggs | Delaware, Maryland |
| | | *Anastatus pearsalli* | Eggs | Delaware, Maryland, Pennsylvania |
| | | *Anastatus reduvii* | Eggs | Delaware, Maryland, Delaware |
| | Platygastridae (Scelioninae) | *Gryon obesum* | Eggs | Maryland |
| | Platygastridae (Telenominae) | *Telenomus podisi* | Eggs | Maryland, Pennsylvania |
| | | *Telenomus utahensis* | Eggs | Virginia |
| | | *Trissolcus brochymenae* | Eggs | Delaware, Maryland, Virginia |
| | | *Trissolcus edessae* | Eggs | Delaware, Maryland, Virginia |
| | | *Trissolcus euschisti* | Eggs | Delaware, Maryland, Oregon |
| | | *Trissolcus thyantae* | Eggs | Virginia |
| | | *Trissolcus utahensis* | Eggs | Oregon |
| Mantodea | Mantidae | *Tenodera sinensis* | Nymphs, adults | Maryland |
| Neuroptera | Chrysopidae | Unidentified larvae | Eggs, early nymphs | Maryland, Oregon, Pennsylvania |

during these surveys were low (<1% to 11%) and highly variable between locations and years. In addition, a tachinid fly, *Trichopoda pennipes* F. (Diptera: Tachinidae), parasitized *H. halys* adults. Parasitism rates for *T. pennipes* averaged 1–5% (up to 20% in some locations) but emergence rates were negligible (D.J.B. and K.A.H., unpublished data). In apple orchards in Pennsylvania, *Telenomus podisi* Ashmed was the most common species found to attack *H. halys* egg masses (D.J.B., unpublished data). In 2012, parasitism of naturally occurring egg masses in Maryland nurseries averaged 31% (P.M.S. and A.L.J., unpublished data). Notably, species of parasitoids frequently found emerging from *H. halys* eggs in field crop and vegetable systems were absent or rarely detected in ornamental nurseries. Conversely, the most common parasitoids found during egg surveys in ornamental nurseries were either absent or rare in field crop and vegetable plots (C.R.R.H., P.M.S., and A.L.J., unpublished data). Thus, predators and parasitoids inflicting mortality on *H. halys* eggs appear to be highly variable depending on the ecosystem (Leskey et al. 2012b, 2013), which suggests the local composition of host plant species and landscape features may influence the species composition of indigenous natural enemies associated with *H. halys*.

Based upon their success suppressing *H. halys* populations in Asia, several *Trissolcus* species are currently being evaluated in the United States quarantine facilities as potential agents for field releases. In field crop systems, experiments are being conducted to determine the potential use of insectary plants to enhance the effectiveness of the local natural enemy fauna in managing *H. halys* and indigenous stink bug species. Ultimately, classical biological control using parasitoids native to Asia and conservation biological control to enhance the effectiveness of introduced and indigenous natural enemies may provide the most promising long-term solutions for landscape-level reduction of *H. halys* populations (Leskey et al. 2012b).

## Chemical Control

Since the widespread outbreak of *H. halys* in the mid-Atlantic United States in 2010, chemical control has been the most widely used strategy for managing its damage to crops. Tree fruit growers in this region increased the number of insecticide applications, in some cases nearly fourfold from 2010 to 2011 and have reduced the interval between sprays to maintain residues (Leskey et al. 2012a).

Numerous methods have been used to demonstrate the relative effectiveness of a broad range of insecticides against *H. halys* adults and nymphs, including treated glass surfaces (Nielsen et al. 2008b, Lee et al. 2012, Leskey et al. 2012c), direct-contact topical applications (G. K., unpublished data), bean dip feeding bioassays (Kuhar et al. 2012e), and field efficacy trials (Kuhar et al. 2012a,b,c,d; Krawczyk et al. 2012; Leskey et al. 2014). Active ingredients that have been most effective include several pyrethroids (bifenthrin, permethrin, fenpropathrin, and beta-cyfluthrin), neonicotinoids (dinotefuran, clothianidin, and thiamethoxam,), carbamates (methomyl and oxamyl), the organophosphate acephate, and the organochlorine endosulfan. Unfortunately, these insecticides are generally broad-spectrum in their activity; they can be hard on natural enemy populations and quite disruptive to integrated pest management programs (Leskey et al. 2012a).

To return to an integrated approach to managing all pests in the crops affected by *H. halys*, growers require a more sustainable strategy for chemical control that combines efficient use of insecticides with a better understanding of its biology and behavior. In fruiting vegetables such as pepper and tomato, neonicotinoids like dinotefuran can be applied as a soil drench or via drip chemigation and have been shown to provide control of *H. halys* up to 14 d after treatment (T. K., unpublished data). This application strategy minimizes the use of foliar-applied insecticides and does not flare pyrethroid-resistant aphid populations (Kuhar et al. 2012a). In soybeans, a single field edge-only treatment can be effective if timed correctly (D. H., J. W. and G. D., unpublished data). This strategy also reduces the amount of insecticides applied and provides a reservoir for natural enemies in the center of the field. Tree fruits are vulnerable to *H. halys* feeding injury through the fruiting period, with some stone fruit (e.g., peaches) being particularly susceptible from the early stages of fruit development onward. Given the long time between fruit set and maturity of many tree fruit crops, especially late season apple and peach varieties, growers have been forced to use certain insecticides in the postbloom period, such as pyrethroids, that had not been used previously. This has resulted in increased incidences of secondary pest outbreaks, especially woolly apple aphid and scale insect species. An assessment of the distribution of *H. halys* injury to late-season apple varieties at harvest revealed that, in general, fruit on trees border rows adjacent to woodlands suffered more injury than those in the orchard interior (C. B., unpublished data). Further, fruit from the top of trees received more injury than lower scaffolds in the canopy. These observations suggest possible benefits from more aggressive *H. halys* management at orchard-block perimeters and adequate covering tree tops with sprays.

Developing novel insecticides that target stink bugs with less impact on beneficial insects would significantly advance grower capabilities of combating *H. halys*, and of course fit better into integrated pest management programs. If chemical control is truly needed for a given situation, entomologists and crop consultants should recommend use of effective selective chemical tools over more disruptive, broad-spectrum insecticides. Frequent rotation of insecticide classes should minimize potential insecticide resistance.

Future studies may explore an "attract and kill" strategy for managing *H. halys* on select plants at field or orchard borders baited with lures designed to attract and aggregate them in spatially precise locations. By only treating these plants or rows with insecticide, the overall amount of material applied against *H. halys* would be reduced.

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## References Cited

Aldrich, J. R., A. Khrimian, X. Chen, and M. J. Camp. 2009. Semiochemically based monitoring of the invasion of the brown marmorated stink bug and unexpected attraction of the native green stink bug (Heteroptera: Pentatomidae) in Maryland. Fla. Entomol. 92: 483–491.

American/Western Fruit Grower. 2011. Brown marmorated stink bug causes $37 million in losses to mid-Atlantic apple growers. (http://www.growingproduce.com/article/21057/brown-marmorated-stink-bug-causes-37-million-in-losses-to-mid-atlantic-apple-growers) (accessed 9 August 2013).

Arnold, K. 2009. Halyomorpha halys (Stål, 1855), eine für die europäische Fauna neu nachgewiesene Wanzenart (Insecta: Heteroptera: Pentatomidae: Cappaeini). Mitteilungen des Thüringer Entomologenverbandes 16: 19.

Bak, W. C., W. H. Yeo, and Y. J. La. 1993. Little-leaf symptom development in the periwinkle infected with Paulownia witches'- broom mycoplasma-like organism by the yellow-brown stink bug, Halyomorpha halys Stål (*H. mista* Uhler). Korean J. Plant Pathol. 9: 236–238.

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. 2013. Host plants of the brown marmorated stink bug in the U.S. (http://www.stopbmsb.org/where-is-bmsb/host-plants/#host_plants_table) (accessed 15 September 2013).

Bernon, G. 2004. Biology of *Halyomorpha halys*, the brown marmorated stink bug (BMSB). U.S. Dep. Agric. APHIS CPHST, 17. Final Report - U.S. Dep. Agric. APHIS CPHST 2004 T3P01.

Biddinger, D., J. Tooker, A. Surcica, and G. Krawzyk. 2012. Survey of native biocontrol agents of the brown marmorated stink bug in Pennsylvania fruit orchards and adjacent habitat. Pa. Fruit News 42: 47–54.

Callot, H., and C. Brua. 2013. Halyomorpha halys (Stål, 1855), la punaise diabolique, nouvelle espèce pour la faune de France (Heteroptera Pentatomidae). L'Entomologiste 69: 69–71.

EPPO. 2013. European and Mediterranean Plant Protection Organization Reporting Service No 5. Pest & Diseases, pp. 10–11.

Fogain, R., and S. Graff. 2011. First records of the invasive pest, Halyomorpha halys (Hemiptera: Pentatomidae), in Ontario and Quebec. J. Entomol. Soc. Ont. 142: 45–48.

Funayama, K. 2002. Oviposition and development of *Halyomorpha halys* (Stål) and *Homalogonia obtuse* (Walker) in apple trees. Japn. J. Appl. Entomol. Zool. 46: 1–6.

Funayama, K. 2004. Importance of apple fruits as food for the brown-marmorated stink bug, Halyomorpha halys (Stål) (Heteroptera: Pentatomidae). Appl. Entomol. Zool. 39: 617–623.

Funayama, K. 2005. Does the brown-marmorated stink bug, Halyomorpha halys (Stål) (Heteroptera: Pentatomidae) reproduce by feeding on the cones of Japanese cedar, *Cryptomeria japonica* D. Don? Japn. J. Appl. Entomol. Zool. 49: 265–268.

Gariepy, T. D., T. Haye, and J. Zhang. 2014. Occurrence, genetic diversity, and potential pathways of entry of *Halyomorpha halys* in newly-invaded areas of Canada and Switzerland. J. Pest Sci. 87: 17–28.

Hamilton, G. C. 2009. Brown marmorated stink bug. Am. Entomol. 55: 19–20.

Harris, A. C. 2010. *Halyomorpha halys* (Hemiptera: Pentatomidae) and *Protaetia brevitarsis* (Coleoptera: Scarabeidae: Cetoniinanae) intercepted in Dunedin. The Weta 40: 42–44.

Haye, T., and D. Wyniger. 2013. Die marmorierte baumwanze, *Halyomorpha halys.* Wirtspflanzen. (http://www.halyomorphahalys.com/aktuelle-verbreitung skarts-current-distrabution.html).

Heckmann, R. 2012. Erster nachweis von *Halyomorpha halys* (Stål, 1855) (Heteroptera: Pentatomidae) für Deutschland. Heteropteron 36: 17–18.

Hiruki, C. 1999. Paulownia witches'-broom disease important in East Asia. Acta Hortic. 496: 63–68.

Herbert, J. J., and M. D. Toews. 2012. Seasonal abundance and population structure of brown marmorated stink bug (Hemiptera: Pentatomidae) in farmscapes containing corn, cotton, peanut, and soybean. Ann. Entomol. Soc. Am. 104: 909–918.

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

Hoffmann, W. E. 1931. A pentatomid pest of growing beans in South China. Peking Nat. Hist. Bull. 5: 25–26.

Hou, Z., H. Liang, Q. Chen, Y. Hu, and H. Tian. 2009. Application of *Anastatus* sp. Against *Halyomorpha halys.* For. Pest Dis. 4: 39, 40: 43.

Hufbauer, R. A., A. Rutschmann, B. Serrate, H. V. de Conchard, and B. Facon. 2013. Role of propagule pressure in colonization success: disentangling the relative importance ofdemographic, genetic and habitat effects. J. Evol. Biol. 26: 1691–1699.

Inkley, D. B. 2012. Characteristics of home invasion by the brown marmorated stink bug (Hemiptera: Pentatomidae). J. Entomol. Sci. 47: 125–130.

Kawada, H., and C. Kitamura. 1983. The reproductive behavior of the brown marmorated stink bug, halyomorpha mista Uhler (Heteriotera: Pentatomidae): observation of mating behavior and multiple copulation. Appl. Entomol. Zool. 18: 234–242.

Kawada, H., and C. Kitamura. 1992. The tachinid fly, *Bogosia sp.* (Diptera: Tachinidae), as a parasitoid of the brown marmorated stink bug, *Halyomorpha mista* Uhler (Heteroptera: Pentatomidae). Japn. J. Environ. Entomol. Zool. 4: 65–70.

Khrimian, A., A. Zhang, D. C. Weber, H.-Y. Ho, J. R. Aldrich, K. E. Vermillion, M. A. Siegler, S. Shirali, F. Guzman, and T. C. Leskey. 2014. Stereoisomeric libraries of 1,10-bisaboladien-3-ols and 10,11-epoxy-1-bisabolen-3-ols for semiochemical discovery. Aggregation pheromone of brown marmorated stink bug, *Halyomorpha halys* (Stål). Proc. Natl. Acad. Sci. 77: 1708–1717.

Kiritani, K. 2007. The impact of global warming and land-use change on the pest status of rice and fruit bugs (Heteroptera) in Japan. Glob. Change Biol. 13: 1586–1595.

Krawczyk, G., T. R. Enyeart, and L. A. Hull. 2012. Understanding biology and behavior of brown marmorated stink bug as a basis for development of management programs in fruit orchards. Pa. Fruit News 92: 22–27.

Kuhar, T. P., H. Doughty, K. Kamminga, A. Wallingford, C. Philips, and J. Aigner. 2012a. Evaluation of insecticides for the control of brown marmorated stink bug in bell peppers in Virginia experiment 1, 2011. Arthropod Manag. Tests 37: E37. doi:10.4182/amt.2012.E37.

Kuhar, T. P., H. Doughty, K. Kamminga, A. Wallingford, C. Philips, and J. Aigner. 2012b. Evaluation of insecticides for the control of brown marmorated stink bug in bell peppers in Virginia experiment 2, 2011. Arthropod Manag. Tests 37: E38. doi: 10.4182/amt. 2012.E38.

Kuhar, T. P., H. Doughty, K. Kamminga, A. Wallingford, C. Philips, and J. Aigner. 2012c. Evaluation of insecticides for the control of brown marmorated stink bug in bell peppers in Virginia experiment 3, 2011. Arthropod Manag. Tests 37: E39. doi:10.4182/amt.2012.E39.

Kuhar, T. P., H. Doughty, K. Kamminga, A. Wallingford, C. Philips, and J. Aigner. 2012d. Evaluation of insecticides for the control of brown marmorated stink bug in bell peppers in Virginia experiment 4, 2011. Arthropod Manag. Tests 37: E40. doi:10.4182/amt.2012.E40.

Kuhar, T. P., H. Doughty, K. Kamminga, and L. Lilliston. 2012e. Evaluation of insecticides using bean dip bioassay for control of brown marmorated stink bug, 2011. Arthropod Manag. Tests 37: doi: 10.4182/amt.2012.E41.

Kuhar, T., K. Kamminga, J. Whalen, G. P. Dively, G. Brust, C.R.R. Hooks, G. Hamilton, and D. Herbert. 2012f. The pest potential of brown marmorated stink bug on vegetable crops. Plant Health Progress doi:10.1094/PHP-2012-0523-01-BR.

Lan-fen, Q.I.U. 2010. Natural enemy species of *Halyomorpha halys* and control effects of the parasitoids species in Beijing. Northern Hort. 9: 72.

Lee, D. H., S. E. Wright, and T. C. Leskey. 2012. Impact of insecticide residue exposure on the invasive pest, Halyomorpha halys (Hemiptera: Pentatomidae): analysis of adult mobility. J. Econ. Entomol. 106: 150–158.

Lee, D. H., B. D. Short, S. V. Joseph, J. C. Bergh, and T. C. Leskey. 2013a. 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., S. E. Wright, G. Boiteau, C. Vincent, and T. C. Leskey. 2013b. Effectiveness of glue for harmonic radar tag attachment on *Halyomorpha halys* (Hemiptera: Pentatomidae) and their impact on adult survivorship and mobility. Environ. Entomol. 42: 515–523.

Lee, D. H., A. L. Nielsen, and T. C. Leskey. 2014a. Dispersal capacity and behavior of nymphal stages of *Halyomorpha halys* (Hemiptera: Pentatomidae) evaluated under laboratory and field conditions. J. Insect Behav. doi: 10.1007/s10905-014-9456-2.

Lee, D. H., J. P. Cullum, J. L. Anderson, J. L. Daugherty, L. M. Beckett, and T. C. Leskey. 2014b. 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 G. C. Hamilton. 2010a. Brown marmorated stink bug working group meeting. (http://projects.ipmcenters.org/Northeastern/FundedProjects/ReportFiles/Pship20 10/Pship2010-Leskey-Progress Report-237195.pdf) (accessed 9 August 2013).

Leskey, T. C., and G. C. Hamilton. 2010b. Brown marmorated stink bug working group meeting. (http://projects.ipmcenters.org/Northeastern/FundedProjects/ReportFiles/Pship20 10/Pship2010-Leskey-Progress Report-237195-Meeting-2010_11_17.pdf) (accessed 9 August 2013).

Leskey T. C., and G. C. Hamilton. 2012. Brown Marmorated Stink Bug Working Group Meeting. (http://www.northeastipm.org/neipm/assets/File/BMSB-Working-Group-Meeting-Report-Nov-2012.pdf) (accessed 12 August 2013).

Leskey T. C., and G. C. Hamilton. 2013. Brown Marmorated Stink Bug Working Group Meeting. (http://www.northeastipm.org/neipm/assets/File/BMSB-Working-Group-Meeting-Report-Dec-2014.pdf).

Leskey, T. C., G. C. Hamilton, D. J. Biddinger, M. L. Buffington, C. Dieckhoff, G. P. Dively, H. Fraser, T. Gariepy, C. Hedstrom, D. A. Herbert, et al. 2014. Datasheet for *Halyomorpha halys* (Stål), (Hemiptera: Pentatomidae). *In* Crop Protection Compendium. CAB International, Wallingford, United Kingdom.

Leskey, T. C., B. D. Short, B. R. Butler, and S. E. Wright. 2012a. 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: 535062, doi:10.1155/2012/535062.

Leskey, T. C., G. C. Hamilton, A. L. Nielsen, D. F. Polk, C. Rodriguez-Saona, J. C. Bergh, D. A. Herbert, T. P. Kuhar, D. Pfeiffer, G. P. Dively, et al. 2012b. Pest status of the brown marmorated stink bug, *Halyomorpha halys* in the USA. Outlooks Pest Manag. 23: 218–226. doi:10.1564/23oct07.

Leskey, T. C., D. H. Lee, B. D. Short, and S. E. Wright. 2012c. Impact of insecticides on the invasive *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae): analysis on the insecticide lethality. J. Econ. Entomol. 105: 1726–1735.

Leskey, T. C., B. D. Short and D. H. Lee. 2013. Efficacy of insecticide residues on adult *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) mortality and injury in apple and peach orchards. Pest Manag. Sci. 70: 1097–1104. doi:10.1002/ps. 3653.

Martinson, H. M., M. J. Raupp, and P. M. Shrewsbury. 2013. Invasive stink bug wounds trees, liberates sugars, and facilitates native Hymenoptera. Ann. Entomol. Soc. Am. 106: 47–52. doi: http://dx.doi.org/10.1603/AN12088.

Mohekar, P., N. G. Wiman, J. Osborne, C. H. Hedstrom, V. M. Walton, and E. Tomasino. 2014. Postharvest impact of brown marmorated stink bug in wine. 88th Annual Orchard Pest and Disease Management Conference, 9 January, Portland, OR.

Mueller, G., I. L. Luescher, and M. Schmidt. 2011. New data on the incidence of household arthropod pests and new invasive pests in Zurich (Switzerland), pp. 99–104. *In* W. H. Robinson, A. E. De Carvalho Campos (eds.), Proceedings of the Seventh International Conference on Urban Pests. Instituto Biologico, Sao Paulo, Brazil.

Nakashima, N., J. Sasaki, K. Tsuda, C. Yasunaga, and H. Noda. 1998. Properties of a new picorna-like virus of the brown-winged green bug, *Plautia stali.* J. Invertebr. Pathol. 71: 151–158.

Ni, X., J. P. Wilson, G. D. Buntin, B. Guo, M. D. Krawkowsky, R. D. Lee, T. E. Cottrell, B. T. Scully, A. Huffaker, and E. A. Schmelz. 2011. Spatial patterns of aflatoxin levels in relation to ear-feeding insect damage in preharvest corn. Toxins 3: 920–931.

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

Nielsen, A. L., and G. C. Hamilton. 2009b. Life history of the invasive species *Halyomorpha halys* (Hemiptera: Pentatomidae) in Northeastern United States. Ann. Entomol. Soc. Am. 102: 608–616.

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

Nielsen, A. L., P. W. Shearer, and G. C. Hamilton. 2008b. Toxicity of insecticides to *Halyomorpha halys* (Hemiptera: Pentatomidae) using glass-vial bioassays. J. Econ. Entomol. 101: 1439–1442.

Nielsen, A. L., G. C. Hamilton, and P. W. Shearer. 2011. Seasonal phenology and monitoring of the non-native *Halyomorpha halys* (Hemiptera: Pentatomidae) in soybean. Environ. Entomol. 40: 231–238.

Nielsen, A. L., K. Holmstrom, G. C. Hamilton, J. Cambridge, and J. Ingerson-Mahar. 2013. Use of black light traps to monitor the abundance and spread of the brown marmorated stink bug. J. Econ. Entomol. 106: 1495–1502.

Owens, D. R., D. A. Herbert, Jr., G. P. Dively, D. D. Reisig, and T. P. Kuhar. 2013. Does feeding by *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) reduce soybean seed quality and yield? J. Econ. Entomol. 106: 1317–1323.

Panizzi, A. R. 1997. Wild hosts of pentatomids: ecological significance and role in their pest status on crops. Annual Rev. Entomol. 42: 99–122.

Pfeiffer, D. G., T. C. Leskey, and H. J. Burrack. 2012. Threatening the harvest: The threat from three invasive insects in late season vineyards, pp. 449–474. *In* N. J. Bostanian, C. Vincent, R. Isaacs (eds.), Arthropod Management Vineyards. Springer, New York, NY.

Qiu, L. F. 2007. Studies on biology of the brown-marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), an important pest for pome trees in China and its biological control. Ph.D. dissertation, Chinese Academy of Forestry, Beijing, China.

Qiu, L. F. 2010. Natural enemy species of *Halyomorpha halys* and control effects of the parasitoids species in Beijing. Northern Hortic. 9: 72.

Qiu, L. F., Z. Yang, and W. Tao. 2007. Biology and population dynamics of *Trissolcus halyomorphae.* Scientia Silvae Sinicae. 43: 62–65.

Reisig, D. D. 2011. Insecticidal management and movement of the brown stink bug, Euschistus servus, in corn. J. Insect Sci. 11: 1–12.

Sasaki, F., T. Miyamoto, A. Yamamoto, Y. Tamai, and T. Yajima. 2012. Relationship between intraspecific variations and host insects of *Ophiocordyceps nutans* collected in Japan. Mycoscience 53: 85–91.

Sauer, C. 2012. Die marmorierte baumwanze tritt neu im Deutschschweizer Gemüsebau auf.gemüsebau info 28/12. Extension Gemüsebau, Forschungsanstalt Agroscope Changins Wädenswil.

Talamas, E. J., M. Buffington, and K. Hoelmer. 2013. New synonymy of *Trissolcus halyomorphae* Yang. J. Hymenoptera Res. 33: 113–117.

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.

Tomasino, E., N. G. Wiman, J. Osborne, C. H. Hedstrom, and V. M. Walton. 2014. Impact of brown marmorated stink bug on Pinot noir wine quality. 64th American Society for Enology and Viticulture National Conference, 24 June Monterey, CA.

Viator, H. P., A. Pantoja, and C. M. Smith. 1983. Damage to wheat seed quality and yield by the rice stink bug and southern green stink bug (Hemiptera: Pentatomidae). J. Econ. Entomol. 76: 1410–1413.

Walker, K. 2009. Brown marmorated stink bug (*Halyomorpha halys*). (http://www.padil.gov.au) (accessed 25 November 2011).

Wallner A. M., G. C. Hamilton, A. L. Nielsen, N. Hahn, E. Green, and C. R. Rodriguez-Saona. 2014. Landscape factors facilitating the invasive dynamics and distribution of the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), after arrival in the United States. PLoS ONE 9: e95691.

Weber, D. W., T. C. Leskey, G. J. Cabrera Walsh, and A. Khrimian. 2014. Synergy of aggregation pheromone with methyl decatrienoate in attraction of brown marmorated stink bug. J. Econ. Entomol. 107: 1061–1081.

Wermelinger, B., D. Wyniger, and B. Forster. 2008. First records of an invasive bug in Europe: *Halyomorpha halys* Stål (Heteroptera: Pentatomidae), a new pest on woody ornamentals and fruit trees? Mitteilungen-Schweizerische Entomologische Gesellschaft 81: 1–8.

Wiman, N. G., V. M. Walton, P. W. Shearer, S. I. Rondon, and J. C. Lee. 2014. Factors affecting flight capacity of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). J. Pest Sci. doi:10.1007/s10340-014-0582-6.

Wyniger, D., and P. Kment. 2010. Key for the separation of *Halyomorpha halys* (Stål) from similar-appearing pentatomids (Insecta: Heteroptera: Pentatomidae) occurring in Central Europe, with new Swiss records. Mitteilungen der Schweizerischen Entomologischen Gesellschaft 83: 261–270.

Xu, J., D. M. Foneseca, 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.

Yanagi, T., and Y. Hagihara. 1980. Ecology of the brown marmorated stink bug. Plant Prot. 34: 315–326.

Yang, Z. Q., Y. X. Yao, L. F. Qiu, and Z. X. Li. 2009. A new species of *Trissolcus* (Hymenoptera: Scelionidae) parasitizing eggs of *Halyomorpha halys* (Heteroptera: Pentatomidae) in China with comments on its biology. Ann. Proc. Entomol. Soc. Am. 102: 39–47.

Yu, G., and J. Zhang. 2009. The brown-marmorated stink bug, *Halyomorpha halys* (Heteroptera: Pentatomidae) in P. R. China. *In* Y. Wu and X.-Y. Wang (eds.), "International workshop on biological control of invasive species of forests", 20–25 September 2007, Beijing, China.

Zhang, C. T., X. Y. Yao, L. F. Qiu, and Z. F. Li. 1993. A study on the biological characteristics of *Halyomorpha picus* and *Erthesina fullo.* For. Res. 6: 271–275.

Zhang, A., A. Khrimian, J. R. Aldrich, T. C. Leskey, and D. C. Weber. 2013. Compositions and methods to attract the brown marmorated stink bug (BMSB) *Halyomorpha halys.* US Patent WO2013090703 A1.

Zhu, G., W. Bu, Y. Gao, and G. Liu. 2012. Potential geographic distribution of brown marmorated stink bug invasion (*Halyomorpha halys*). PLoS ONE 7: e31246.