Biological Control 97 (2016) 120–130

Contents lists available at ScienceDirect

Biological Control

journal homepage: www.elsevier.com/locate/ybcon

Frequency, efficiency, and physical characteristics of predation by generalist predators of brown marmorated stink bug (Hemiptera: Pentatomidae) eggs

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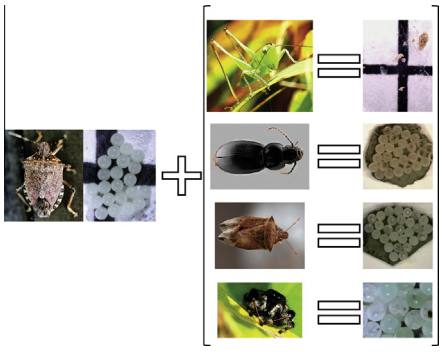
HIGHLIGHTS

- The native natural enemy community of *Halyomorpha halys* in the US is not well-documented.
- We systematically categorized damage to and main predators of *H. halys* egg masses.
- Egg damage consisted of complete or incomplete chewing, and stylet or punctured sucking.
- The main predators were Tettigoniidae, Carabidae, Gryllidae, and to a lesser extent, Salticidae.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 December 2015
Revised 8 March 2016
Accepted 10 March 2016
Available online 11 March 2016

Keywords:
Biological control
Halyomorpha halys
Integrated pest management
Handling behavior
Sentinel egg masses

ABSTRACT

The native generalist predator community of *Halyomorpha halys*, an invasive species in the United States and Europe, has not been well defined to date. The aims of the current study were to determine whether generalist predators that are commonly found in mid-Atlantic orchards and vegetable crops are capable of feeding on *H. halys* eggs and, if so, to systematically characterize the appearance of feeding damage in order to link it to sentinel egg mass surveys. Over 25 field-collected and commercially available arthropod predator taxa, including adults and immatures, were evaluated as potential predators of *H. halys* eggs in laboratory trials, and a photographic library of egg mass damage was developed. In addition, over 400 sentinel egg masses were deployed in tree fruit and vegetable crops, and direct observations were made of predator taxa in situ. We found that the most frequent and efficient predators of *H. halys* eggs were katydids and ground beetles, and to a lesser extent earwigs, jumping spiders, and crickets. Egg damage for each taxon studied was ascribed to one of four egg damage syndromes: complete chewing, incomplete chewing, stylet sucking, and punctured sucking. The first two are caused by predators with chewing mouthparts and are differentiated by the presence of irregular chorion debris left behind in the case of incomplete chewing compared with nothing left behind or an entire segment of the egg mass completely removed for complete chewing. The latter two are caused by predators with piercing/sucking mouthparts or chelicerae and are separable by the presence of a feeding sheath for stylet sucking compared to a simple hole or slit in otherwise hollowed eggs for punctured sucking via chelicerae. Complete and incomplete chewing were the two feeding syndromes most frequently documented in the field and with the greatest number of eggs consumed per egg mass. Taxa evaluated in laboratory trials were reliably found

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http://dx.doi.org/10.1016/j.biocontrol.2016.03.008
1049-9644/Published by Elsevier Inc.

in tree fruit and vegetable crops. Overall, our work contributes to the identification of key egg mass predators of *H. halys* in specialty crop agroecosytems.

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1. Introduction

Increasingly, generalist predators have been recognized as an important regulator of arthropod herbivores (e.g. Riechert and Lockley, 1984; Riechert and Bishop, 1990; Jones, 1995; Symondson et al., 2002; Messelink et al., 2010). For example, 75% of studies that examined biological control by a generalist predator found reduced pest numbers in the presence of the predator (Symondson et al., 2002). Predators play an even larger role in the biological control of invasive species that may lack specialist predators in their introduced range (Chang and Kareiva, 1999). However, it is often difficult to link mortality to specific predator groups.

The brown marmorated stink bug, *Halyomorpha halys* (Stål), is an invasive (Hoebeke and Carter, 2003), highly polyphagous agricultural pest in the US (Leskey et al., 2012a), Europe, and elsewhere (Lee, 2015). *Halyomorpha halys* feeds on more than 150 different plants (www.stopbmsb.org), with all major vegetable and fruit crops susceptible (Kuhar et al., 2012; Leskey et al., 2012b). Conventional *H. halys* management in the U.S. relies on high dosage applications of broad spectrum insecticides (Leskey and Hamilton, 2011; Leskey et al., 2012b), a tactic that can disrupt effective biological control and integrated pest management programs aimed at controlling other pests. Since the introduction of *H. halys*, insecticide use has increased by up to 4-fold in some crops (Leskey et al., 2012b). Currently, conventional management practices for *H. halys* are not economically or ecologically sustainable for vegetable and fruit crops.

There is a high level of interest among growers in alternative management strategies for *H. halys* (Working Group Priorities, 2015). Control of *H. halys* offers the promise of long-term regulation of the populations of this invasive species, while minimizing insecticide input into agroecosystems (Messing and Wright, 2006). It is important to consider the phenology of *H. halys* in determining which life stages may be vulnerable to attack by natural enemies. *Halyomorpha halys* completes two full generations in some mid-Atlantic states (e.g., West Virginia), with F_1 eggs initially appearing in agricultural systems in mid- to late-May and F_2 eggs by late June to early July (Leskey et al., 2012c). Eggs of *H. halys* deposited in agroecosystems develop in 5–6 d (Lee et al., 2013; Nielsen et al., 2008), during which they are vulnerable to attack by natural enemies. Eggs are likely more vulnerable to generalist predator attack than other life stages, because other *H. halys* life stages are highly mobile (Lee and Leskey, 2015; Lee et al., 2014).

Native stink bug species in the US experience high egg parasitism and predation (e.g. Jones, 1995; Tillman, 2010, 2011; Yeargan, 1979). Important genera of parasitoids include *Trissolcus* spp., *Telenomus* spp., and *Ooencyrtus* spp, and individuals may parasitize up to 100% of the eggs in an egg mass (Tillman, 2010; Ehler, 2002; Koppel et al., 2009). In a laboratory evaluation of over 25 potential arthropod predators of *Nezara viridula* (L.) eggs, only five species fed, including Chrysopidae and *Geocoris* spp. (Ehler, 2002). The same study found that Coccinellidae, Reduviidae, Nabidae, and Araneae were frequent predators of nymphal *Nezara viridula*. Additionally, predation rates ranged from 2.3 to 22.2% for eggs of *Euschistus servus* (Say) and *Podisus maculiventris* (Say) when surveyed in field and vegetable crops in Virginia (Koppel et al., 2009), but can be significantly higher for certain pentatomids in corn (Tillman, 2010, 2011).

In its native range in Asia, *H. halys* experiences top-down pressure from its native natural enemies, including 14 species of parasitic Hymenoptera that attack the egg stage and predators in the families Anthocoridae, Asilidae, Canidae, Pentatomidae, Reduviidae and Thomisidae that attack various life stages (Lee et al., 2013). To some degree, all three stages of *H. halys* (i.e., eggs, nymphs and adults) are vulnerable to generalist predators. Jones (2013) found that the wheel bug, *Arilus cristatus* (Hemiptera: Reduviidae), was the most efficient predator of *H. halys* adults and nymphs. The same study found very low rates of predation in the laboratory by *Orius insidiosis* (Hemiptera: Anthocoridae), *Hippodamia convergens* (Coleoptera: Coccinellidae), and *Harmonia axyridis* (Coleoptera: Coccinellidae) on first instar *H. halys* nymphs. Based on field surveys, Rice et al. (2014) reported that predators in the families Araneae, Coccinellidae, Forficulidae, Anthocoridae, Geocoridae, Reduviidae, Mantidae, and Chrysopidae attack *H. halys* in North America. To date, specific information on potential *H. halys* egg predators in US agroecosystems has not been widely reported. Three predators commonly found in Canadian agroecosystems, *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae), *Coleomegilla maculata* (De Geer) (Coccinellidae), and *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae), were shown to attack *H. halys* eggs in the laboratory (Abram et al., 2015). Another stink bug predator, the predatory digger wasp, *Astata occidentalis* (Hymenoptera: Sphecidae), is attracted to methyl (*E,E,Z*)-2,4,6-decatrienoate as a host-finding kairomone (Cottrell et al., 2014). This compound, in combination with the recently identified *H. halys* aggregation pheromone (Khrimian et al., 2014), is used to monitor *H. halys* through the growing season in the United States (Leskey et al. (2015a,b); Morrison et al., 2015a).

Recently, sentinel *H. halys* egg masses generated in the laboratory have been deployed in coordinated trials throughout the mid-Atlantic states to monitor parasitism and predation by native natural enemies. Lacking a viable seriological technique for detecting predation by specific taxa, egg predation has been typically characterized as "chewing" or "piercing/sucking" based on visual observations. However, during the course of these surveys, widespread and frequent unexplained loss and damage to egg masses have been commonly reported (Dieckhoff, 2014). In cases where eggs were completely removed, they have typically been reported as "lost" (e.g. see Koppel et al., 2009), potentially deflating estimates of predation rates and assessment of control by natural enemies in the field. Whether this pattern is due to predation or abiotic factors (e.g. abrasion with neighboring leaves, and ablation by wind or rain) is unknown, as it is unclear whether predators are able to remove egg masses from sentinel cards.

The aim of our study was to conclusively establish which generalist predators potentially found in or near mid-Atlantic orchards and vegetable crops are capable of feeding on *H. halys* eggs and to systematically characterize the appearance of feeding damage to eggs attacked by specific native predator taxa. We exposed 11,800 *H. halys* eggs to generalist predators in 25 families in controlled laboratory trials and catalogued the resulting physical damage to the eggs via pre- and post-exposure microscopic photography. We also monitored research apple and peach orchards through beat sampling and vegetable crops on an organic farm through visual sampling to confirm the presence of our laboratory-tested predators in agroecosystems. Finally, we also deployed sentinel egg masses in orchard and field crop systems using a predator