Ecology and Economic Impact of the Invasive Brown Marmorated Stink Bug (Hemiptera: Pentatomidae; Halyomorpha halys) in the Utah Agricultural Landscape

Zachary R. Schumm
Utah State University

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ECOLOGY AND ECONOMIC IMPACT OF THE INVASIVE BROWN MARMORATED
STINK BUG (HEMIPTERA: PENTATOMIDAE; Halyomorpha halys) IN
THE UTAH AGRICULTURAL LANDSCAPE

by

Zachary R. Schumm

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

Diane G. Alston, Ph.D.                  Lori R. Spears, Ph.D.
Major Professor                      Committee Member

John Stevens, Ph.D.                  Kezia Manlove, Ph.D.
Committee Member                   Committee Member

Richard S. Inouye, Ph.D
Vice Provost for Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2020
ABSTRACT

Ecology and Economic Impact of the Invasive Brown Marmorated Stink Bug
(Hemiptera: Pentatomidae; Halyomorpha halys) in the
Utah Agricultural Landscape

by

Zachary R. Schumm, Master of Science
Utah State University, 2020

Major Professor: Dr. Diane G. Alston
Department: Biology

Brown marmorated stink bug (Halyomorpha halys Stål) (BMSB) is an invasive, economically important crop and nuisance pest native to eastern Asia that invaded the U.S. in the late 1990’s. Given this insect’s wide host range of nearly 200 native and cultivated plants, and its reduced susceptibility to management with insecticides, it can be a challenging and expensive pest to suppress. BMSB was first detected in Utah in 2012, and is of concern to Utah’s specialty fruit and row crop producers. Utah’s specialty crop production landscapes typically consist of small-scale fields surrounded by suburban development. Additionally, Utah’s high elevation (>1,200 m), arid climate with hot summers and cold winters is unique compared to other regions with BMSB invasions. Therefore, I undertook the exploration of how BMSB behavior,
ecology, and impact to an important tree fruit crop in Utah may differ from other regions of the U.S.

In Chapter II, I quantified the impact of BMSB nymph and adult feeding to tart cherry (*Prunus cerasus* Linnaeus), a processed fruit crop not yet studied in regards to BMSB susceptibility. I found that tart cherry is susceptible to yield loss due to abscission if BMSB feeding occurs between petal fall of flowers and pit hardening of fruits. In Chapter III, I monitored and quantified the behavior of BMSB in the Utah specialty crop landscape, explored location preferences within agricultural sites, and compared efficacy of several monitoring methods appropriate to crop management application. I found that, unlike other regions of the U.S., BMSB does not concentrate around field edges, and that pyramid-style traps baited with pheromone lures tend to be the most effective sampling method for the relatively lower population densities experienced in Utah to-date. Finally, in Chapter IV, I discuss parasitoid wasps that are biological control agents of BMSB and other stink bugs. I provide a unique observation of male-guarding behavior of a stink bug egg mass in a typical sib-mating system where only females have been documented to exhibit egg-guarding behavior. Additionally, in Chapter V, I include an extension fact sheet published over the course of these studies that aims to inform growers and the public on how to best recognize, monitor, and manage this pest in Utah.
PUBLIC ABSTRACT

Ecology and Economic Impact of the Invasive Brown Marmorated Stink Bug
(Hemiptera: Pentatomidae; Halyomorpha halys) in the
Utah Agricultural Landscape

Zachary R. Schumm

The brown marmorated stink bug (BMSB) is a major insect pest that causes economic loss to a diversity of U.S. fruit and vegetable crops, and invades homes and human structures, causing nuisance issues for homeowners. This destructive insect causes millions of dollars of crop damage annually, and is difficult to manage due to its resistance to some common insecticides. BMSB is a relatively new pest to Utah, and its biology and ecology is not well known in the high elevation, arid Intermountain West region. In Chapter II, I explored the potential impact of BMSB to tart cherry, an unstudied crop in regards to BMSB susceptibility. I determined that tart cherry fruits may abort if fed on by BMSB from the flower petal-fall through fruit pit-hardening stages, causing severe economic loss. In Chapter III, I evaluated several commercially available stink bug traps baited with pheromone lures in diverse specialty crop habitats to assess BMSB location preferences and attraction to traps. These results will guide BMSB monitoring and management decision-making. I found that Utah specialty crop fields are often small enough in size that BMSB invades the entire site and does not concentrate around field borders as in other U.S. regions. Additionally, I determined that pyramid-style traps were more effective in attracting BMSB under low densities as experienced in Utah to-date. Lastly, in Chapters IV and V, I discuss findings and results of surveys for
parasitoid wasps that attack and kill developing BMSB eggs, and share extension materials aimed to inform growers and the public about biological control agents of this pest in the Utah agricultural landscape.
First and foremost, I would like to thank my advisors, Dr. Diane Alston, and Dr. Lori Spears, for their incredible support, mentoring, and assistance that they provided over the course of my program. Their continuous aid has made me a better scientist, critical thinker, and individual. In addition, I thank my committee members, Dr. John Stevens and Dr. Kezia Manlove, for growing my background in statistics, and making me way more interested in mathematics and learning a new language than I ever thought was possible. You have all challenged me, helped me develop as a professional, and supported me greater than any committee I could have ever asked for. I will never forget the time, effort, and assistance you have provided me.

Additionally, my work would never be possible without my incredible technicians, who deserve to be called out by name and given a year supply of Taco Time: Hanna Kirkland, Kate Richardson, Erin Berdahl, Stephanie Hall, Lily Bourett, Chelise Dever, James Withers, Ben Steadman, Ryan West, Loren Linford, and Yota Mizuno. You should all know that your hard work and dedication to my research endeavors will never be forgotten. I cannot stress enough that I would not have completed half of what I did without your assistance. Thank you for all of the incredible times in the field, the millions of laughs, and for keeping my spirits up when something went wrong or when it felt like my research was doomed. It has been amazing watching you all develop as scientists and learn from one another. I have learned so much from you all.

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so incredibly thoughtful, kind, knowledgeable, and supportive over these last few years. From day one, you have done nothing but encourage my success, and have always been there to offer scientific and life support (and shrimp). Thank you for sharing so much of your life with me in the lab and in the field. I am a better person today than I was when I arrived, in part because of you (and again, shrimp).

Finally, I thank my parents, my family, and my friends from around the country. You have all propelled me through this journey from day one, and supported me every step of the way. To those that I left back east, I can’t thank you enough for your support, even though I could only visit a few times. I miss you all dearly.

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CHAPTER I

INTRODUCTION: ECOLOGY AND ECONOMIC IMPACT OF THE INVASIVE BROWN MARMORATED STINK BUG (HEMIPTERA: PENTATOMIDAE; *Halyomorpha halys*) IN THE UTAH AGRICULTURAL LANDSCAPE

**BMSB Origin and Distribution**

Brown marmorated stink bug *Halyomorpha halys* (Stål) (BMSB) is an invasive agricultural and nuisance pest native to China, Japan, Korea, and Taiwan (Hoebeke and Carter 2003; Lee et al. 2013). In North America, it was first discovered in Allentown, Pennsylvania in 1996 but was misidentified as the native brown stink bug, *Euschistus servus* (Say) until 2001. BMSB is now found in 44 U.S. states and four Canadian provinces, with pest status ranging from detections to severe agricultural and nuisance issues (Stopbmsb.org; Figure 1-1). In addition to North America, BMSB has invaded Italy, Switzerland, France, Greece, and Hungary (Cesari et al. 2014; Vetek et al. 2014; Haye et al. 2015; Valentin et al. 2017). Ecological niche modeling by Zhu et al. (2012) predicts that BMSB can establish in much of the U.S., including the mid-Atlantic, Midwest, Pacific Northwest, and Intermountain West.

In Utah, BMSB is more likely to establish in the northern valleys that receive greater precipitation and have cooler temperatures than the southern deserts; current populations are primarily established in this region. BMSB was first detected in Utah in 2012 in Salt Lake City and agricultural crop damage was first detected in 2017 in popcorn, apple, and peach. Since 2017, feeding damage has also been found in tomato and squash. To-date, homeowners have primarily reported nuisance issues, with
periodical reports of BMSB injury to home gardens and commercial fruit and vegetable production areas. BMSB has become established in five Utah counties (Box Elder, Weber, Davis, Salt Lake, and Utah) and has been detected in Cache, Carbon, and Kane counties, with highest populations in Davis, Salt Lake and Utah counties. The single report of BMSB in Kane County is presumed to be assisted by humans, as the climate and resource availability for BMSB survival in southern Utah is considered less optimal and limited.

**BMSB Identification and Life Cycle**

Adult BMSB are shield-shaped, measure 12-17 mm in length, and are marbled brown in color (Hoebeke and Carter 2003). They have white stripes on the antennae unlike native stink bugs in the U.S. with similar coloration (Rice et al. 2014). Male BMSB can be distinguished from females based upon the morphology of the last abdominal sternite. For males, the terminal sternite is excavated and appears as a fork or “U” shape, whereas females do not have this excavation (i.e., the terminal abdominal sternite is continuously round) (Figure 1-2). Males also tend to be slightly smaller than females, especially in wild populations. Egg clusters are usually composed of 28 eggs and are light green in color prior to hatch. Nymphs vary in color as they age, beginning as orange and black first instars that measure about 2.5 mm in length. Upon reaching the second instar, nymphs begin to turn grey / black and grow to about 13 mm in length as fifth instars (Rice et al. 2014; Spears et al. 2018) (Figure 1-3). The complete development from egg to adult requires 538 degree days with a minimum and maximum developmental threshold of 14.14°C and 35.76°C, respectively (Nielsen et al. 2008a).
In the U.S., BMSB has one to two generations per year (Nielsen and Hamilton 2009; Bakken et al. 2015; Nielsen et al. 2016); whereas it can produce up to six generations per year in eastern Asia (Hoffmann 1931). BMSB enters reproductive diapause in fall; termination occurs in spring once a critical photoperiod of 12.7-13.5 hours has been reached (designated as a ‘biofix’ to break reproductive diapause in the spring) (Nielsen et al. 2016, 2017). This critical photoperiod in Utah occurs in approximately mid-late April depending on location. Egg-laying by overwintered adults (F₀) commences in late May to early June, and new summer generation adults (F₁) are expected to appear in late June to early August depending on geographic location (Spears et al. 2018). Furthermore, preliminary data from Utah suggests that F₁ adults lay eggs in mid-August, and F₂ nymphs emerge and become mobile in late August, indicating that under optimal conditions, a partial F₂ adult generation may be possible (M. C. Holthouse; unpublished data). Overwintering adults seek shelter within and under natural and artificial structures. In the spring, approximately 148 degree days is required for overwintering-emerging adults (F₀) to reach reproductive maturity and onset of oviposition (Nielsen et al. 2008a).

**BMSB Overwintering and Nuisance Issues**

BMSB adults overwinter in congregations in sheltered structures, such as sheds, houses, and attics. When entering and leaving structures, BMSB can be found in the hundreds to thousands, causing nuisance concerns for humans in areas with established BMSB populations (Inkley 2012). Although BMSB prefer to overwinter in artificial structures, they have been shown to overwinter in natural landscapes within protective
structures, including cracks and crevices in trees with thick bark such as oak (*Quercus* spp.) and locust (*Robinia* spp.) (Lee et al. 2014a). In the mid-Atlantic region of the U.S., BMSB prefer to overwinter in large, dead, standing trees over downed trees or leaf litter (Lee et al. 2014a). However, some native stink bugs can be found overwintering in leaf litter, leaving the possibility open for BMSB to utilize this habitat in some regions. Due to non-abundance of preferred natural overwintering habitats found in other U.S. regions (e.g., large forest stands and associated leaf litter), the ability of BMSB to overwinter in natural landscapes of Utah has not been proven.

### BMSB Host Plants and Damage Symptoms

BMSB is highly polyphagous and known to utilize nearly 200 host plants in the U.S. ([https://www.stopbmsb.org/where-is-bmsb/host-plants/](https://www.stopbmsb.org/where-is-bmsb/host-plants/)), with over 60 plants documented as hosts of BMSB in Utah ([https://utahpests.usu.edu/caps/bmsb-host-plants](https://utahpests.usu.edu/caps/bmsb-host-plants)). BMSB females prefer to lay their eggs on the underside of host leaves, where first instar nymphs will emerge and begin feeding on stems, leaves, flowers, fruits, and nuts.

Primary agricultural hosts of concern in the U.S. are apple, peach, cherry (sweet and tart), corn (field and sweet), tomato, pepper, and soybean. BMSB is an edge-driven pest, and prefers to feed and reproduce near field borders (Basnet 2015). Additionally, crop damage may be more severe on field borders that are adjacent to woodlots, likely due to the easy transition between trees and food resources in the agricultural site (Hoebeke and Carter 2003; Nielsen and Hamilton 2009; Martinson et al. 2013; Rice et al. 2017b). Tree hosts that are known to harbor high populations of BMSB include empress tree (*Paulownia tomentosa* Sieb. & Zucc.), tree of heaven (*Ailanthus altissima* Mill.), and
catalpa (*Catalpa* spp.), which have large leaves, abundant fruiting structures, and ample surface area for egg-laying.

BMSB uses its proboscis (stylet) to penetrate host plant structures. Feeding damage to fruits can cause scarring, corking, gummosis, and deformity or cat-facing. In addition, feeding through the stylets can transmit bacteria which can lead to fruit rot (Rice et al. 2014). Complete abortion of fruit development can also occur if BMSB feeds on young plant stages, such as flowers or early fruit (Rice et al. 2014) (Figure 1-4). Furthermore, BMSB damage can require 1-2 weeks to become evident after feeding occurs (Spears et al. 2018) (Figure 1-5).

In Utah, a number of specialty crops may be at risk as a result of BMSB invasion. The largest fruit and vegetable commodities in Utah include corn, peach, and apple; all are hosts of BMSB. In addition, Utah is the second largest tart cherry producing state in the U.S., but has yet to be studied in regards to BMSB damage and susceptibility. Sweet cherry, a close relative of tart cherry, has exhibited reduced quality and yield, and increased susceptibility to fungal infections if fed on by BMSB (Moore et al. 2019). However, tart cherry differs from sweet cherry in that it is a processed crop utilized in dried, frozen, canned, and juiced products versus fresh market sales. Thus, exploring tart cherry susceptibility to BMSB and its impact on yield and quality as a processed product will provide useful insights to monitoring and management strategies for tart cherry production throughout the U.S.
Effective monitoring for BMSB in agricultural and ornamental landscapes has been shown to include several trap types baited with aggregation pheromone, beat sheet sampling, and light trapping (Leskey et al. 2012a; Joseph et al. 2013; Nielsen et al. 2013; Weber et al. 2014; Morrison et al. 2015; Rice et al. 2018; Spears et al. 2018). Beat sheet sampling involves use of a square canvas sheet mounted flat on two wooden poles in an “x” shape, and a wooden pole or stick to gently beat and agitate vegetation above the sheet. BMSB have a natural behavior to fall from host plants when disturbed, known as thanatosis or death-feigning. It is notably important to sample as much of the vegetation as possible, as BMSB is known to move to the upper canopy of trees; therefore, visual inspection of fruits that are out of reach for sampling should be conducted (Quinn et al. 2019).

For less labor-intensive surveys, the best monitoring methods are commercially available stink bug traps. Two trap types are currently recommended: a ~1.22 m tall black pyramid trap sold by AgBio Inc. (Westminster, CO), and a dual-panel, clear sticky trap sold by Trécé, Inc. (Adair, OK) (Figure 1-6). Traps are baited with an artificial mimic of a BMSB aggregation pheromone, along with a synergist, to attract BMSB season-long (Figure 1-6, right). This two-part aggregation pheromone [(3S,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol and (3R,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol)] (Khrimian et al. 2014; Zhang et al. 2016; U.S. patent # 9,451,771) can attract all mobile life stages of BMSB (second instar – adult), although it is more effective at attracting adults, especially in the late season when BMSB naturally begin to aggregate for overwintering diapause.
(Khrimian et al. 2008; Morrison et al. 2015). The added synergist (methyl [E,E,Z]-2,4,6-decatrienoate) is placed alongside the aggregation pheromone to increase attraction throughout the entire monitoring period (mid-spring to late fall).

To match the collection container height on pyramid traps, the suggested mounting of a clear sticky panel traps is effectuated ~1.2 m above the ground, and should be attached to a wooden ground stake with a binder clip and staples / thumb tacks (Acebes-Doria et al. 2018). It is recommended that traps of either style be placed near crop field borders, as strong edge effects on BMSB colonization of crop fields have been observed, especially if adjacent to a wooded boundary (Joseph et al. 2014; Blaauw et al. 2016; Rice et al. 2017b). If multiple traps are to be used in the same orchard, individual traps should be placed at least 5 m apart to prevent interference among pheromone lure plumes (Kirkpatrick et al. 2019).

Each trap type has its individual benefits. Pyramid traps are beneficial for their tree trunk mimicking properties, which may stimulate more BMSB attraction (Leskey et al. 2012a). Sticky panel traps, however, are more cost-effective, and BMSB captures, while generally lower, show the same general trends season-long as the more expensive pyramid trap. Therefore, sticky panel traps are now the recommended trap for BMSB monitoring to support management decisions (Acebes-Doria et al. 2019). Further studies suggest that BMSB are attracted to light sources, and adding a light stimulus to traps may create a positive synergistic effect on BMSB attraction (Leskey et al. 2015; Rice et al. 2017a).
Management of BMSB

BMSB adults have a strong dispersal capacity. Adults can fly more than 117 km based on flight-mill studies; however, most fly less than 5 km in a single day with longer flight trends for foraging (summer generation) versus overwintering adults (Lee and Leskey 2015; Wiman et al. 2015). Regardless, BMSB are mobile and can easily exploit a wide range of habitats to search for feeding and egg-laying hosts in relatively short periods of time. Their high capacity for dispersal and wide host range make them a landscape-level pest, contributing to difficulty in management in agricultural and ornamental landscapes.

Management thresholds have been developed for pyramid and sticky panel traps in apple orchards, with a threshold of 10 adults cumulatively per trap (Short et al. 2017). Research is ongoing to identify thresholds in other cropping systems.

Chemical Management.

The use of commercial insecticides for control of BMSB has been useful but is not economically sustainable in the long-term. In commercial production areas, the primary reason for the lack of insecticide effectiveness is BMSB’s resistance to many common insecticide classes (e.g., pyrethroid and neonicotinoid) which can result in initial knockdown, but allows for recovery of BMSB (Nielsen et al. 2008b; Leskey et al. 2012b; Lee et al. 2013). Most of the insecticides with efficacy against BMSB are broad-spectrum, meaning that they are non-selective in protecting natural enemies and other non-target arthropods (Wilson et al. 2018). One such chemical class, the
organophosphates, has a more restricted use than other insecticides due to the passage of the 1996 Food Quality Protection Act, which banned “harm-causing” compounds (Leskey et al. 2012b). Therefore, high frequency application of synthetic insecticides without heavy restrictions are preferred to suppress BMSB populations, and are best applied when feeding populations are highest to save on management costs (Short et al. 2017).

In private home gardens and small-scale production systems, BMSB suppression is especially challenging because of the diversity of host plants and reduced registrations of insecticide products. Some of the best home garden options include neem oil, essential oils, insecticidal soap, and capsaicin which result in moderate nymph mortality (> 60%), but only low adult mortality (< 30%) (Bergmann and Raupp 2014). In smaller gardens, visual inspection of plants, physical removal, and barriers to plant infestation (e.g., netting and row covers) may be most effective in protecting crop yield. In organic systems, control is limited to cultural practices (Leskey and Nielsen 2018) and organic certified insecticides (Lee et al. 2014b).

BMSB populations are typically highest on field edges; therefore, border sprays of insecticides (treating the row or several rows of plants on the field border) can be effective in reducing BMSB populations. In addition, two alternate-row-middle sprays, where insecticides are applied to alternate sides of the tree, with seven day intervals between sprays, have been shown to help reduce pressure on natural enemies and delay pesticide resistance (Blaauw et al. 2015; Short et al. 2017; Leskey and Nielsen 2018).
Biological Control Management.

Due to the high cost of insecticide management options, including disruption of integrated pest management programs (Kuhar et al. 2016; Wilson et al. 2018), suppression of BMSB has shifted to biological control (Dieckhoff et al. 2017). Very few BMSB adult predators have been observed in the U.S., but some opportunistic predators include mantises (Mantodea), spiders (Araneae), and assassin bugs (Hemiptera: Reduviidae). However, arthropods that attack the egg stage are considered to be the most promising biological control agents. Both egg predators and parasitoids can be found throughout the U.S., searching for and terminating BMSB nymphal development at the natal site. While egg predators (sucking and chewing mouthparts) can quickly consume eggs, their relative effectiveness tends to be low, with only 4.5 – 10% of eggs preyed upon in the wild (Ogburn et al. 2016). The most common egg predators include Orthopterans (true crickets and katydids), Dermapterans (earwigs), Salticids (jumping spiders), and Carabids (ground beetles) (Rice et al. 2014; Morrison et al. 2016; Pote and Nielsen 2017).

Egg parasitoid wasps are the primary natural enemies of native stink bugs in the Nearctic (Koppel et al. 2009; Tillman 2016). Three families of parasitoid wasps have been found stinging BMSB eggs in the U.S.: Scelionidae, Eupelmidae, and Encyrtidae (Abram et al. 2017). The only species that have been able to sting, complete development, and emerge from BMSB eggs are *Anastatus reduvii* (Howard), *A. mirabilis* (Walsh & Riley), *A. persalli* Ashmead (Hymenoptera: Eupelmidae), *Trissolcus brochymenae* (Ashmead), *T. euschisti* (Ashmead), *T. hullensis* (Harrington), and

Impacts of native parasitoid wasps on BMSB egg masses have been highly variable among habitats (Jones et al. 2014; Cornelius et al. 2016a-b; Herlihy et al. 2016; Ogburn et al. 2016). Although parasitism rates are variable, wasps have not been shown to be highly effective at reducing BMSB populations in any region, which consistently result in lower than 14% BMSB egg mortality, and less than 5% of parasitized eggs producing a viable parasitoid wasp (Cornelius et al. 2016a-b; Dieckhoff et al. 2017; M. C. Holthouse, unpublished data). However, egg mortality rates due to unknown factors (i.e., not confirmed to be caused by parasitism) in field assays were as high as 58%, and may be attributed to parasitoid wasps (Cornelius et al. 2016b). Therefore, more investigation on the effectiveness of native natural enemies on BMSB egg mortality is needed.

Due to the overall low and variable efficacy of native parasitoids across North America, the focus has shifted to a specific classical biological control agent, the samurai wasp, *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae), which is native to eastern Asia (Figure 1-7). Parasitism rates of *T. japonicus* for BMSB eggs in China have been as high as 70%, making it a hopeful candidate for release in the U.S. (Yang et al. 2009).

The samurai wasp has been held in U.S. quarantine facilities since 2007 to complete host-range testing for documentation of its effectiveness and safety as a biological control agent (Rice et al. 2014; Talamas et al. 2015). However, in 2014, an adventive samurai wasp was located in Beltsville, Maryland (Talamas et al. 2015; Herlihy et al. 2016). Since then, the wasp has been found in the wild in twelve other
states, for a total of thirteen states (Maryland, Virginia, West Virginia, Delaware, New Jersey, New York, Pennsylvania, Ohio, Michigan, Oregon, Washington, California, and Utah) and Washington, D.C.; its populations in some of these areas have been shown to be on the rise.

These discoveries have allowed for its rearing and, in some states, redistribution to assist with the biological control of BMSB (Beers et al. 2019; Lowenstein et al. 2019). As of 2020, post-release sampling in some areas indicate little to no effectiveness; however, these studies are still in the early stages (Bergh et al. 2019). Surveying for parasitoids in the western U.S. is still in its infancy, including in Utah. Detection and testing the efficacy of *T. japonicus* in an Intermountain West environment with cold winters and arid, hot summers will support filling knowledge gaps in current research on this potentially efficacious biological control agent for BMSB.

**Research and Extension Objectives**

This thesis describes the results of field and lab investigation into BMSB ecology and economic damage potential in agricultural systems in northern Utah. More specifically, my research objectives were to 1) determine the economic damage potential of BMSB on tart cherry in Utah (Chapter II), 2) determine the seasonal and spatial dispersal of BMSB in Utah agricultural habitats using pheromone-baited traps and visual plant inspections (Chapter III), 3) determine the survivability of BMSB in different overwintering habitats of northern Utah (Appendix C), and 4) determine the presence and effectiveness of natural enemies of BMSB in Utah’s agricultural landscapes (Appendix D). In addition, chapter IV relays a novel and interesting observation in *Trissolcus*
euschisti, a native parasitoid of stink bug eggs that occurred over the course of these studies. I complete the current story of biological control of BMSB in Utah with the discovery of the samurai wasp, a non-native, naturally introduced, effective parasitoid of BMSB that will hopefully combat this invasive pest throughout the region (Appendix E). In addition, an in-depth manuscript on the surveys conducted to discover samurai wasp and other native BMSB parasitoids can be seen in Appendix F. A broad view of the ecology of BMSB in northern Utah will assist future researchers, extension practitioners, growers, and the general public in managing this pest as populations continue to spread and establish.

During my studies, I made several accomplishments in extension to reach diverse audiences and share research and information related to BMSB biology, ecology, and management in Utah. I include several extension publications (fact sheets and Utah Pests newsletters) produced as a part of my thesis project (Chapter V, Appendix G, Appendix H). In my Curriculum Vitae (Appendix I), I provide an overview of my extension impacts (presentations given, posters presented, etc.).
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Figure 1-1. The current distribution and status of BMSB in North America as of March 2020 (https://www.stopbmsb.org/where-is-bmsb/state-by-state/).
Figure 1-2. Female (left) and male (right) BMSB. Males have claspers on the terminal abdominal segment, while the female’s terminal segment is smooth and rounded. Photo by Ian Grettenberger, University of California, Davis.

Figure 1-3. BMSB nymphal instar and adult life stages.
Figure 1-4. Tart cherry fruits injured by BMSB show external damage (red fruits) and those that abscised (failed to develop) due to BMSB feeding, leaving only pits attached to stems.
Figure 1-5. Internal corking damage to apple (left) and external cat-facing damage to peach (right). Apple photo by Chris Bergh, Virginia Polytechnic Institute and State University; Peach photo by Utah State University Extension.
Figure 1-6. Black pyramid trap (AgBio Inc, Westminster, CO) (left) and Pherocon® dual-panel sticky trap (Trécé Inc., Adair, OK) (right). Both traps are baited with Trécé Pherocon® BMSB dual lure.
Figure 1-7. Samurai wasp, *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae), a highly effective biological control agent for brown marmorated stink bug.
CHAPTER II

IMPACT OF BROWN MARMORATED STINK BUG (HEMIPTERA: PENTATOMIDAE) FEEDING ON TART CHERRY (ROSALES: ROSACEAE) QUALITY AND YIELD IN UTAH

ABSTRACT

Brown marmorated stink bug (Halyomorpha halys Stål) (BMSB) is an invasive and economically important agricultural and ornamental insect pest now established in 46 U.S. states. It was first detected in Utah in 2012, and began causing agricultural damage in 2017. Tart cherry (Prunus cerasus Linnaeus) is a major processed agricultural commodity in Utah; yet, its susceptibility to BMSB is unstudied. Limb cages with six BMSB adults, nymphs or no BMSB were established in a randomized complete block design in a tart cherry orchard to determine feeding impact on different fruit developmental stages. After one week of feeding, half of the fruits in each cage were removed to assess feeding intensity, and the remainder left through maturity to assess marketability and quality. Feeding by adults and nymphs between petal fall and fruit pit hardening, even at feeding pressures as low as 1.7 – 4.0 feeding sites per fruit, caused 100% abscission of fruits, significantly reducing marketability as compared to the control treatment. For fruits that escaped abscission and matured, few quality differences were detected among treatments, indicating that BMSB feeding caused minimal detectable quality loss to this processed tree fruit crop. We conclude that tart cherries are at risk of abscission with short-term BMSB feeding between petal fall and pit hardening when
overwintered adults or F₁ nymphs are present in orchards, and suggest that longer-term feeding may be necessary to cause quality and yield reductions after pit hardening.

**KEYWORDS**

BMSB, Feeding Damage, *Prunus cerasus*, Yield, Quality

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2 Coauthored by Diane G. Alston, Lori R. Spears, and Kezia Manlove
Introduction

Brown marmorated stink bug (*Halyomorpha halys* Stål) (BMSB) is an invasive agricultural and nuisance pest native to China, Japan, Korea, and Taiwan (Hoebek and Carter 2003; Lee et al. 2013). Since its introduction to the U.S. in the 1990’s, BMSB has become a severe pest in tree fruit, nut, vegetable, and field crops (Nielsen and Hamilton 2009; Leskey and Hamilton 2010; Leskey and Hamilton 2012; Kuhar et al. 2012; Rice et al. 2014). BMSB is known to feed on over 100 plant hosts, including both vegetative and reproductive plant structures, such as stems, leaves, fruiting bodies, and seed pods (Bergmann et al. 2013; Haye et al. 2015; Wiman et al. 2015). Feeding damage can range from localized wilting and necrosis, to abscission or deformation of fruiting bodies, resulting in fruit quality and/or yield loss (Strong 1970; Tingey and Pillimer 1977; Hori 2000). If feeding occurs early in fruit development, then abscission, or premature abortion, of fruits is more probable (Nielsen and Hamilton 2009; Rice et al. 2014). Late season feeding can result in several outcomes including discoloration, necrosis, deformation at feeding sites, and cat-facing (extensive deformation) of fruits, all of which can impact crop marketability (Pfeiffer et al. 2012; Rice et al. 2014). Additionally, when BMSB pierce plant structures with their stylet, secondary infections caused by yeast may occur, resulting in additional damage and crop loss (Mitchell 2004).

Studies to characterize BMSB damage to some vegetable and fruit crops have found high vulnerability among pepper, sweet corn, and okra, with losses exceeding 50% due to scarring, sunken lesions, and fruit deformation (Kuhar et al. 2012; Rice et al. 2014). Orchard fruits are often attacked season-long by BMSB, placing them at greater
risk to crop loss (Nielsen and Hamilton 2009; Leskey et al. 2012). Injury to apple can be severe, with losses exceeding 90% during periods of high BMSB infestations (Leskey and Hamilton 2010). Stone fruits, such as peach and nectarine are susceptible to cat-facing and premature fruit abortion (Nielsen and Hamilton 2009). Additionally, sweet cherries targeted by BMSB may exhibit reduced fruit weight, lower marketability, and increased susceptibility to fungal infections (Moore et al. 2019). Few studies have assessed susceptibility of other stone fruit and berry crops, or have determined the impact of BMSB on processed fruit crops.

Utah is the second largest producer of tart cherry (*Prunus cerasus* Linnaeus) in the U.S., with an average annual production of 17,899 metric tons on 1,287 hectares, and a utilized value of production over $14.5 million (from 2013-2017; UDAF 2018). As BMSB continues to spread and establish in tart cherry producing states, such as Utah and Michigan, a better understanding of the susceptibility of tart cherry to BMSB feeding is needed. BMSB was first detected in Utah in 2012, and agricultural damage was first reported in 2017 (Holthouse et al. 2017). It is established in the highly urbanized areas of northern Utah, and its populations continue to expand. Northern Utah is unique compared to other geographic areas where BMSB has invaded due to its comparatively high elevation (>1,200 meters), aridity, hot summers, and cold winters (NOAA NECI 2019). Agricultural production areas in northern Utah are often adjacent to or surrounded by urban/suburban development. BMSB will typically feed on host plants adjacent to overwintering sites inside human structures after spring emergence (Rice et al. 2014). Therefore, the close proximity between agricultural production and overwintering areas
may facilitate higher BMSB impacts to Utah specialty crop production, particularly in the early season shortly after termination of overwintering diapause.

The objective of this study was to examine the impact of BMSB adult and nymph feeding on early to mature developmental stages of tart cherry (‘Montmorency’) in regards to quality and yield. Tart cherry is a processed crop, utilized for dried, frozen, canned, and juiced products; therefore, damage thresholds and economic impacts will likely differ from those of fresh-consumed fruit crops. An economic assessment of the potential impact of BMSB infestation on tart cherry will offer monitoring and management support to Utah growers and other tart cherry-producing regions to better manage economic loss as BMSB continues to increase its distribution in the U.S.

**Materials and Methods**

**Experimental Design.**

Experiments were conducted at the Utah State University Horticultural Research Farm in Kaysville, UT (N 41° 1’ 20.88”, W 111° 56’ 5.544”). In 2018, beginning at the bud stage of tart cherry (April 18), cylindrical sleeve cages (30 x 80 cm; open at both ends), made of white no-see-um mesh (Mosquito Curtains, Alpharetta, GA), were placed over the terminal end of 12 limbs on 12 individual trees in an orchard row of tart cherry; the base secured with a zip tie. Branches were selected to include a similar number of buds at approximately breast height, and were not exposed to direct sunlight. Selected branches were checked for other arthropods, which were removed prior to introducing treatments. All fruit buds inside the cage were counted, and replicates of six BMSB adults or nymphs (second to third instar), or no bugs (control), were added to cages in a
randomized complete block design (see BMSB sources below). The terminal end of each cage was sealed with a twist of the cloth and zip tie. BMSB remained in cages for one week to allow for feeding, and then removed, along with half of the fruit bud structures with stems still attached (selected evenly along the bagged section of limb). Cages were then resealed to allow for development of remaining fruit structures. This procedure was repeated for the petal fall (May 3), first blush (May 24), pit hardening (June 14), and mature fruit stages (July 9).

In 2019, using knowledge of negative effects of BMSB feeding on early fruit developmental stages from 2018, the experimental design was expanded to include a total of nine fruit developmental stages: petal fall (May 21), mid green (May 28), late green (June 4), first blush (June 11), pit hardening (June 18), half red (June 25), full red (July 2), near mature (July 9), and mature (July 16) fruit stages.

**BMSB Sources.**

BMSB were acquired from wild and colony-reared populations at Utah State University, and supplemented in 2019 with individuals from the New Jersey Department of Agriculture colony. The colony was fed a combination of organic store-bought apple, pepper, carrot, and string beans; and maintained at 23°C, 60% RH, and 16:8 light/dark photoperiod. Due to low availability of wild BMSB for early-season tart cherry bud stages, primarily colony-reared insects were used; whereas, mid and late-season cages included a mixture of colony-raised and wild BMSB. BMSB were not starved before initiation of experiments.
Feeding Injury.

Fruit transported to the laboratory following one week of exposure to BMSB in field cages were placed into a 500 ml glass beaker containing acid fuchsin stain (250 ml 95% Ethanol, 250 ml acetic acid, 1 g acid fuchsin powder) for 5 seconds, air-dried, and then observed under a dissecting microscope at 10× magnification to count the number of BMSB feeding sites (presence of a stylet sheath or a hole penetrating the fruit).

Fruit Abscission and Marketability.

When fruits remaining inside sleeve cages reached maturity (July 16 in 2018; July 25 in 2019), they were removed and assessed for abscission and marketability. Fruits that did not develop, or absced (the fruit pit without flesh attached to the stem), were counted. In 2018, fruit marketability was determined with a visual assessment (i.e., fruits were deemed unmarketable if any damaged, deeply scarred, or rotting tissue was present). In 2019, an additional marketability assessment was conducted using a TOMRA® laser sorting machine (TOMRA®, Asker, Norway) at the Payson Fruit Growers, Inc. processing plant in Payson, UT. All fruits were run through the laser and unmarketable fruits were ejected based on laser detection of decay or discolored flesh that would deem a tart cherry unfit for processing.

Fruit Quality.

Quality measurements were collected on all fruits that did not abscise and reached maturity, including mass (g), diameter (mm), and sugar content (% brix) using an analytical balance, manual calipers, and a refractometer (Atago ATC-1, Tokyo, Japan), respectively.
**Statistical Analyses.**

Generalized linear mixed effects models and analysis of variance (ANOVA) were used to compare fruit injury (mean number of BMSB feeding sites per structure) (Poisson distribution), fruit marketability (binomial distribution), fruit abscission (binomial distribution), and quality among treatments (normal distribution). Data met distributional requirements, and were not transformed. Models were run separately for each response variable at each fruit stage, and for each year; no adjustments for multiple hypothesis testing were required. Following significant results, pairwise comparisons were used to differentiate treatments. Models and post-hoc comparisons were performed using the `glmer`, `aov`, `emmeans`, and `TukeyHSD` functions in the `lme4` and `stats` packages distributed with base R Version 1.2, run using RStudio for Mac (R Core Team 2017). Significance for all tests was set at $\alpha \leq 0.05$. Figures were made in the `ggplot2` package version 3.2.1 in the Tidyverse Environment for RStudio (Wickham 2016; Wickham et al. 2019).

**Results**

**Feeding Injury.**

Treatments resulted in significant differences in the mean number of BMSB feeding sites per tart cherry fruiting structure in both years. Mean number of feeding sites ranged from 0 to 1.0 sites per fruit in the control treatment, 0.5 sites per bud to 13.3 sites per mature fruit in the nymph treatment, and 0.4 sites per bud to 37.8 sites per mature fruit in the adult treatment. Notably, feeding sites were found uniformly on fruiting structures and were seldom found on stems.
In 2018, feeding intensity differed significantly among treatments at all fruit development stages (Table 2-1). Fruits exposed to adult or nymph BMSB exhibited significantly more feeding sites per fruiting structure than were present on structures in the control at all fruit stages; exposure to adults additionally resulted in more feeding sites per structure than exposure to nymphs at all stages except the bud stage (Figure 2-1a).

In 2019, feeding intensity differed significantly among treatments at all fruit development stages (Table 2-1). Exposure to adults and nymphs resulted in significantly more feeding sites per fruit compared with the control treatment in all developmental stages. Adult exposure additionally resulted in more feeding sites per fruit than nymph exposure at all stages except the petal fall stage, where effects from nymphal feeding were greater than adult feeding (Figure 2-1b).

**Fruit Abscission and Marketability.**

Overall, 3% of control fruits (SD = 0.07), 22% of nymph-fed fruits (SD = 0.34), and 31% of adult-fed fruits abscised (SD = 0.45) across 2018 and 2019. Fruit abscission did not occur in the bud, petal fall, and mature fruit stages in 2018, or in the near mature and mature fruit stages in 2019, regardless of treatment.

In 2018, the proportion of abscised fruits did not differ significantly among treatments in any fruit stage (Table 2-1). However, exposure to either adults or nymphs resulted in 100% fruit abscission in the first blush stage, whereas no control fruits abscised. This biologically significant difference was not detectable in the statistical
models due to complete separation in outcomes among the treatments, and lack of within-treatment variability (Figure 2-2a).

In 2019, the proportion of abscised fruits differed significantly among treatments in all stages from petal fall to first blush (Table 2-1). In the petal fall stage, exposure to adults resulted in a higher proportion of abscised fruits than the control treatment (Figure 2-2b). Adult and nymph exposure resulted in a higher proportion of abscised fruits than the control treatment from mid green to first blush, with adult exposure additionally resulting in more abscission than nymphal exposure. Although this is biologically significant, it was not picked up by the model in the mid green and late green stages because 100% of adult-fed fruits abscised (Figure 2-2b).

Overall, 71% of control fruits (SD = 0.18), 51% of nymph-fed fruits (SD = 0.29), and 47% of adult-fed fruits were deemed marketable (SD = 0.34) as determined by visual assessments in 2018 and the laser sorter in 2019.

Adult and nymph BMSB feeding was associated with significant differences in marketability of fruits in both years. In 2018, only the pit hardening stage experienced a difference in marketability among treatments as determined by visual assessments (Table 2-1). In this stage, adult-fed fruits were significantly more marketable than nymph-fed fruits. However, in the first blush stage, both adult and nymphal feeding reduced marketability of fruits by 100% compared to the control treatment, in which 35% of fruits were marketable (Figure 2-3a). Again, the model was unable to pick up these key biologically significant differences due to complete separation.

In 2019, there were significant differences in marketability among treatments in every fruit stage from petal fall to first blush, and additionally in the near mature and
mature stages as determined by the laser sorting machine (Table 2-1). In the petal fall stage, adult-fed fruits were significantly less marketable than control fruits (Figure 2-3b). Furthermore, adult and nymph-fed fruits were less marketable than control fruits in the mid green, late green, and first blush stages. The model could not pick up the biologically significant effect of adult feeding on marketability in the mid and late green stages because 0% of adult-fed fruits were marketable. Additionally, nymph-fed fruits were less marketable than adult-fed and control fruits in the near mature stage. While the model also suggested a significant difference in marketability in the mature fruit stage in 2019, follow-up pairwise comparisons did not reveal significant differences between any two treatments (Figure 2-3b).

**Fruit Quality.**

In 2018, there was a significant sugar content difference among treatments in the pit hardening stage, but no other quality differences were detected in any other fruit stage (Table 2-2). Pairwise comparisons revealed that adult and nymph treatments resulted in significantly lower sugar content (15.7% and 14.6% brix, respectively) compared to control fruits (17.6% brix). In 2018, during the first blush stage, no fruits from the adult or nymph treatments developed to maturity (Figures 2-2a and 2-3a). In 2019, there were no significant differences in fruit quality metrics (mass, diameter, and sugar content) among treatments in any fruit stage (Table 2-2).
Discussion

Our study provides the first in-depth analysis of the potential impacts of BMSB feeding on tart cherry. We determined that tart cherry fruits are highly susceptible to yield loss if BMSB feeding occurs from petal fall to pit hardening. During these early season stages, the trees are allocating energy to fruit ovary production and protection, and will allocate energy to fruit swelling and ripening after the pits harden. These results are supported by other studies that report fruit abortion to peach and apple if feeding occurs during early fruit developmental stages (Nielsen and Hamilton 2009; Rice et al. 2014). More concerning for tart cherry production, however, is that low levels of BMSB feeding pressure can cause fruit abortion. For example, nymphal feeding for the mid and late green stages in 2019 was less than 1.0 site per fruit; however, nymph-feeding still caused high rates of abscission and significantly lower marketability than control treatments for these fruit stages (84% and 44% abscission, respectively). Interestingly, as fruits developed, i.e., increased in size and pits hardened, nymph-fed fruit marketability substantially increased in 2019.

We included peach (‘Suncrest’) in our original experiment; however, due to spring freeze damage to peach flowers in 2018 and reduced availability of BMSB in 2019, only limited replication of selected peach developmental stages was included in our study. The peach data suggest, however, that fruit abscission in peach occurs less often than in tart cherry if feeding occurs between first blush and pit hardening of fruits (Z. Schumm, unpublished data). We postulate that lower abscission in peach is due to greater fruit size. In stone fruits, the development and hardening of pits and seeds are a precursor
to expansion of the fruit exocarp (flesh) (Zavalloni et al. 2006). Furthermore, damage to young, developing fruit ovaries is known to increase abscission and negatively impact fruit set (Sawicki et al. 2015; Chang-Qui et al. 2018).

During our study, the mean distance from the fruit skin to the pit during stages prior to pit hardening was less than 3.2 mm, whereas once the pit hardened this distance increased substantially to 4.5 mm and reached ~ 11 mm by fruit maturity. Therefore, a plausible reason that BMSB adults caused more abscission of tart cherry fruits than second and third instar nymphs may be due to stylet length and their ability to penetrate into the developing ovaries, potentially feeding through the exocarp and into the endocarp (pit) and seed while the pit is soft. Reduced stylet length in second and third instar nymphs, and an inability to reach developing pits and seeds during feeding may explain why nymph-fed fruits were generally more marketable when exposed to BMSB between petal fall and pit hardening. Additionally, it may explain why marketability of fruits with nymph feeding increased as fruits increased slightly in size as they reached the pit hardening stage. Further research should be conducted to test this hypothesis and to determine other plausible explanations such as differing feeding strategies by adults and nymphs. We do however note that we seldom found feeding sites on cherry stems, indicating that BMSB adults and nymphs prefer fruiting structures over stems.

Our study addressed impacts to tart cherry fruit yield and quality from relatively short-term BMSB feeding, one week. Longer-term feeding is known to cause severe damage in several other *Prunus* fruit crops (Leskey et al. 2012; Rice et. al 2014), including tart cherry observed during other Utah studies where over two weeks of BMSB feeding resulted in severe tissue damage and dry, shriveled fruits (C. Holthouse,
unpublished data). Overall, we suggest that short-term feeding by adults and nymphs can cause severe yield loss via fruit abscission if feeding occurs from petal fall to fruit pit hardening. Interestingly, in contrast, we seldom found quality effects from BMSB feeding in late-season fruit stages that received the highest feeding pressure (1.8 – 13.3 nymph feeding sites per fruit and 5.2 – 37.8 adult feeding sites per fruit). Additionally, the single significant quality difference seen in sugar content during this study could have been due to chance alone based on an alpha value of 0.05 and 39 separate quality analyses being conducted (Table 2). This suggests that long-term feeding (more than one week) under substantial feeding pressure may be needed to induce quality loss in tart cherry fruit due to it being a processed versus fruit market product. Our results for tart cherry support those for other tree fruit crops, that early-season injury by BMSB can result in economically significant fruit yield loss (Anthon et al. 2007; Nielsen and Hamilton 2009; Rice et al. 2014).

In sweet cherry fruits, early season feeding by stink bug pests is known to cause cat-facing and dimpling of fruits, and late season feeding can cause discoloration of the flesh surrounding the pit (Anthon et al. 2007). Additionally, BMSB feeding is known to lower quality and marketability of sweet cherry (Moore et al. 2019). While our results for tart cherry found different early season feeding outcomes than for sweet cherry (fruit abscission versus cat-facing), the processed nature of tart cherry alters fruit quality standards as compared to fresh market sweet cherry fruits. We found only minor reductions in quality for tart cherry fruits fed on mid and late season when BMSB populations are likely at their highest levels in commercial orchards. We importantly note that the laser sorter did not reject many fully-formed fruits, even when visible external
tissue damage was present. Therefore, our results support the hypothesis that although BMSB feeding to tart cherry fruits induces visual quality reduction, the fruits are still readily marketable for processing, including dried, juiced, canned and frozen products. Importantly, some control fruits also experienced slight visual quality reduction, which resulted in overall marketability to be lower in 2018 when only visual checks were used to confirm marketability.

The first in-depth look into the potential impacts of BMSB injury to tart cherry fruits suggests high susceptibility to abscission and yield loss when feeding occurs between petal fall and pit hardening when trees are investing energy into the development of seeds and pits of fruits. For growers, this suggests that monitoring and management, while beneficial season-long, is critical during pre-pit hardening stages of fruit development. We do not anticipate high populations of BMSB to be in the agricultural landscape in the early season, particularly nymphs that do not emerge until overwintering adults oviposit at the end of May. However, BMSB is active in the Utah agricultural landscape from petal fall until maturity of tart cherries (Z. Schumm, unpublished data).

From this study, the primary concern for growers appears to be yield loss caused by overwintering adults. Additional studies are necessary to test the impact of long-term late-season feeding to the quality of processed tart cherry fruits. In addition, more thought should be given to compensatory vs. additive fruit impacts (e.g., in order prevent marketability or quality reduction in later season fruit stages, the fruit must first escape all feeding impacts from early season stages). Comparing BMSB and tart cherry phenology alongside feeding impacts at individual fruit stages will be imperative when determining additive effects of long-term BMSB feeding.
Overall, we suggest that while BMSB abundance is likely low in tart cherry cropping systems during the stages most vulnerable to yield loss, monitoring is still important given that even low levels of feeding can cause fruit abscission. A full understanding of the impact of BMSB feeding to all developmental stages of tart cherry and associated quality loss for this processed stone fruit crop is pivotal to development of best management practices for this highly destructive invasive insect pest.

Acknowledgments

We thank Mark Cody Holthouse, Erin Berdahl, Lily Bourett, Stephanie Hall, Hanna Kirkland, Kate Richardson, Loren Linford, Ben Steadman, Ryan West, and James Withers for their assistance with field and lab research. In addition, we thank Payson Fruit Growers, Inc., for use of their TOMRA® laser sorter, the New Jersey Department of Agriculture for supplying additional BMSB, and John Stevens and Susan Durham for statistical support. Funding was provided by the National Institute of Food and Agriculture, U.S. Department of Agriculture, Specialty Crop Research Initiative under award number 2016-51181-25409; USDA Specialty Crop Block Grant to Utah Department of Agriculture and Food; and Utah State University Extension. This research was supported by the Utah Agricultural Experiment Station, Utah State University, and approved as journal paper number 9301.
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http://treefruit.wsu.edu/crop-protection/opm/stink-bugs/

http://www.stopbmsb.org/where-is-bmsb/host-plants/#host_plants_table


10.1093/besa/23.4.277


Table 2-1. Generalized linear mixed model results for tart cherry feeding intensity, marketability, and abscission at each developmental stage in 2018 and 2019. Bolded numbers indicate significant differences among treatments ($p < 0.05$). Asterisks indicate a lack of variability within treatments.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fruit Stage</th>
<th>Feeding Intensity</th>
<th></th>
<th></th>
<th>Abscission</th>
<th></th>
<th></th>
<th>Marketability</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F$</td>
<td>$df$</td>
<td>$p$</td>
<td>$F$</td>
<td>$df$</td>
<td>$p$</td>
<td>$F$</td>
<td>$df$</td>
</tr>
<tr>
<td>2018</td>
<td>Bud</td>
<td>6.06</td>
<td>2</td>
<td>&lt;0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.37</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Petal Fall</td>
<td>208.36</td>
<td>2</td>
<td>&lt;0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.37</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>First Blush</td>
<td>18.76</td>
<td>2</td>
<td>&lt;0.01</td>
<td>0*</td>
<td>2</td>
<td>1*</td>
<td>0*</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Pit Hardening</td>
<td>92.57</td>
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<td>&lt;0.01</td>
<td>1.09</td>
<td>2</td>
<td>0.33</td>
<td>4.93</td>
<td>2</td>
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<tr>
<td></td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>2.70</td>
<td>2</td>
</tr>
<tr>
<td>2019</td>
<td>Petal Fall</td>
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<td>2</td>
<td>&lt;0.01</td>
<td>5.92</td>
<td>2</td>
<td>&lt;0.01</td>
<td>3.58</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mid Green</td>
<td>70.06</td>
<td>2</td>
<td>&lt;0.01</td>
<td>11.92</td>
<td>2</td>
<td>&lt;0.01</td>
<td>19.24</td>
<td>2</td>
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<tr>
<td></td>
<td>Late Green</td>
<td>145.50</td>
<td>2</td>
<td>&lt;0.01</td>
<td>8.23</td>
<td>2</td>
<td>&lt;0.01</td>
<td>10.26</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>First Blush</td>
<td>76.28</td>
<td>2</td>
<td>&lt;0.01</td>
<td>12.75</td>
<td>2</td>
<td>&lt;0.01</td>
<td>25.50</td>
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<tr>
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<td>Pit Hardening</td>
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<td>2</td>
<td>&lt;0.01</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0.99</td>
<td>2</td>
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<tr>
<td></td>
<td>Half Red</td>
<td>159.49</td>
<td>2</td>
<td>&lt;0.01</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0.53</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Full Red</td>
<td>139.45</td>
<td>2</td>
<td>&lt;0.01</td>
<td>0</td>
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<td>1</td>
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<tr>
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<td>393.56</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>7.55</td>
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</tr>
<tr>
<td></td>
<td>Mature</td>
<td>231.95</td>
<td>2</td>
<td>&lt;0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.35</td>
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</table>
Table 2-2. ANOVA results for tart cherry fruit quality, including mass, diameter, and sugar content (% brix) at each developmental stage in 2018 and 2019. Bolded numbers indicate significant differences among treatments for the indicated metric and developmental stage ($p < 0.05$).

<table>
<thead>
<tr>
<th>Year</th>
<th>Fruit Stage</th>
<th>Mass</th>
<th></th>
<th></th>
<th>Diameter</th>
<th></th>
<th></th>
<th>(% Brix)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F$</td>
<td>df</td>
<td>$p$</td>
<td>$F$</td>
<td>df</td>
<td>$p$</td>
<td>$F$</td>
<td>df</td>
</tr>
<tr>
<td>2018</td>
<td>Bud</td>
<td>0.70</td>
<td>2,5</td>
<td>0.54</td>
<td>0.93</td>
<td>2,5</td>
<td>0.45</td>
<td>1.03</td>
<td>2,5</td>
</tr>
<tr>
<td></td>
<td>Petal Fall</td>
<td>0.54</td>
<td>2,2</td>
<td>0.65</td>
<td>0.14</td>
<td>2,2</td>
<td>0.88</td>
<td>3.56</td>
<td>2,2</td>
</tr>
<tr>
<td></td>
<td>First Blush</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pit Hardening</td>
<td>3.39</td>
<td>2,6</td>
<td>0.10</td>
<td>0.34</td>
<td>2,6</td>
<td>0.73</td>
<td>16.02</td>
<td>2,6</td>
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<tr>
<td></td>
<td>Mature</td>
<td>0.71</td>
<td>2,6</td>
<td>0.53</td>
<td>0.77</td>
<td>2,6</td>
<td>0.51</td>
<td>0.84</td>
<td>2,7</td>
</tr>
<tr>
<td>2019</td>
<td>Petal Fall</td>
<td>0.79</td>
<td>2,6</td>
<td>0.50</td>
<td>1.59</td>
<td>2,6</td>
<td>0.28</td>
<td>1.02</td>
<td>2,6</td>
</tr>
<tr>
<td></td>
<td>Mid Green</td>
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<td>1,1</td>
<td>0.38</td>
<td>15.98</td>
<td>1,1</td>
<td>0.15</td>
<td>0.12</td>
<td>1,1</td>
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<td></td>
<td>Late Green</td>
<td>0.42</td>
<td>1,3</td>
<td>0.56</td>
<td>&lt;0.01</td>
<td>1,3</td>
<td>0.98</td>
<td>0.00</td>
<td>1,3</td>
</tr>
<tr>
<td></td>
<td>First Blush</td>
<td>6.56</td>
<td>2,3</td>
<td>0.08</td>
<td>1.89</td>
<td>2,3</td>
<td>0.29</td>
<td>1.92</td>
<td>2,3</td>
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<tr>
<td></td>
<td>Pit Hardening</td>
<td>0.36</td>
<td>2,6</td>
<td>0.71</td>
<td>0.23</td>
<td>2,6</td>
<td>0.80</td>
<td>0.25</td>
<td>2,6</td>
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<tr>
<td></td>
<td>Half Red</td>
<td>0.86</td>
<td>2,6</td>
<td>0.47</td>
<td>1.02</td>
<td>2,6</td>
<td>0.42</td>
<td>0.74</td>
<td>2,6</td>
</tr>
<tr>
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<td>Full Red</td>
<td>1.31</td>
<td>2,6</td>
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<td>1.68</td>
<td>2,6</td>
<td>0.26</td>
<td>2.33</td>
<td>2,6</td>
</tr>
<tr>
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<td>Near Mature</td>
<td>2.00</td>
<td>2,6</td>
<td>0.22</td>
<td>1.83</td>
<td>2,6</td>
<td>0.24</td>
<td>0.34</td>
<td>2,6</td>
</tr>
<tr>
<td></td>
<td>Mature</td>
<td>&lt;0.01</td>
<td>2,6</td>
<td>0.99</td>
<td>0.04</td>
<td>2,6</td>
<td>0.96</td>
<td>0.29</td>
<td>2,6</td>
</tr>
</tbody>
</table>
Figures

Figure 2-1. Mean number of feeding sites (± SE) per fruiting structure for each tart cherry developmental stage in 2018 (a) and 2019 (b) (five and nine developmental stages were tested in respective years). Different letters indicate significant differences in means among treatments (Tukey HSD; \( p < 0.05 \)). Asterisks indicate a lack of variability within treatment(s).
Figure 2-2. The mean proportion of fruits that abscised or did not develop (± SE) for each treatment and fruit stage in 2018 (a) and 2019 (b). BMSB, especially adults, caused high rates of abscission between petal fall and pit hardening fruit stages in both years. Different letters indicate significant differences in means among treatments (Tukey HSD; $p < 0.05$). Asterisks indicate a lack of variability within treatment(s).
Figure 2-3. Proportion of fruits remaining that were marketable (± SE) at harvest for each tart cherry developmental stage in 2018 (a) and 2019 (b). Different letters indicate significant differences in means among treatments (Tukey HSD; *p* < 0.05). Asterisks indicate a lack of variability within treatment(s).
CHAPTER III

COLONIZATION BEHAVIOR OF BROWN MARMORATED STINK BUG

(Halyomorpha halys STÅL) IN THE UTAH AGRICULTURAL LANDSCAPE¹

Abstract

Brown marmorated stink bug (Halyomorpha halys Stål) is a polyphagous, invasive insect of economic concern to agricultural production in North America. BMSB was first discovered in Utah in 2012; crop damage was first reported in 2017. We propose that northern Utah’s high elevation agricultural regions (> 1,200 m), arid climate, and small-scale production fields surrounded by suburban development may invoke differences in BMSB behaviors and effectiveness of monitoring protocols as compared to other regions with BMSB invasions. To evaluate these potential differences, we sampled BMSB along transects with pyramid traps, sticky panel traps, and visual plant inspections at nine orchard and community garden site-years (< 2.5 ha). Sampling was conducted in four locations within sites; exterior, border, border-interior, and center; and in early, mid, and late seasonal periods. Results did not support a BMSB preference for field site borders as found in other regions of the U.S. Pyramid traps attracted significantly more BMSB than sticky panel traps throughout the growing season, and more BMSB than visual plant inspections in the mid and late season. Visual monitoring may be a cost-effective BMSB detection strategy when conducted near pheromone-baited traps in the early season. Therefore, we suggest that pyramid traps and visual plant inspection,
especially in combination, may provide optimal monitoring and detection of BMSB in
the Utah agricultural landscape where populations are relatively low. Additionally,
border-focused management strategies may be less effective in Utah compared to regions
with higher BMSB infestations, larger field sizes, and adjacent agricultural or natural
landscapes.

Keywords

Border effects, Trapping, Landscape-level effects, Suburban-agriculture Interface

1 Coauthored by Diane G. Alston and Lori R. Spears
INTRODUCTION

Brown marmorated stink bug (*Halyomorpha halys* Stål) (BMSB) is an economically important invasive agricultural and nuisance pest introduced to the U.S. from eastern Asia in the mid 1990’s (Hoebeke and Carter 2003; Leskey and Nielsen 2018). As of 2020, it occurs in 44 U.S. states, varying in degree of impact from detection to severe agricultural and nuisance problems. Most of the severe agricultural issues are present in the eastern U.S.; however, populations and agricultural concerns are growing in the west, with Oregon, moving into the severe agricultural damage category in 2020 (Hahn et al. 2016, stopBMSB.org). BMSB is highly polyphagous; it uses nearly 200 host plants including numerous fruit, vegetable, and row crops of agricultural importance (Nielsen and Hamilton 2009; Leskey and Hamilton 2010; Leskey et al. 2012; Kuhar et al. 2012; Rice et al. 2014; Leskey and Nielsen 2018). Its robust host range, coupled with its propensity for long-distance dispersal, elevate the concerns for its continued spread and establishment throughout North America (Wiman et al. 2014; Lee and Leskey 2015).

To monitor BMSB, a two part aggregation pheromone [(3S,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol and (3R,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol)] with a synergist [methyl (E,E,Z)-2,4,6-decatrienoate] is effective in attracting nymphs and adults throughout the duration of BMSB activity (mid-spring to late fall) (Zhang et al. 2013; Khrimian et al. 2014; Weber et al. 2014). Commonly, BMSB captures in pheromone-baited traps increase during the fall when BMSB adults aggregate in preparation for overwintering diapause (Akotsen-Mensah et al. 2018). Both pyramid style and dual sticky panel traps baited with the dual lure are reliable monitoring tools for
BMSB in the agricultural landscape (Leskey et al. 2012; Morrison et al. 2015; Rice et al. 2018). A national-scale study showed that although pyramid traps often capture more BMSB, sticky panel traps accurately track populations with less cost and greater convenience; therefore, sticky panel traps are now recommended as the standard for season-long management decision-making in the U.S. (Acebes-Doria et al. 2019).

BMSB was first detected in Utah in 2012, and agricultural damage was first confirmed in 2017. As of 2019, damage has been documented in peach, popcorn, sweet corn, squash, and tomato. Additionally, observations suggest that tart cherry, a valuable agricultural commodity in Utah, may be highly susceptible to BMSB (Z. Schumm, unpublished data; Chapter II). While no severe economic damage has been documented in Utah, concerns about economic harm from BMSB are on the rise. Utah, as compared to other invaded states, experiences hot and dry summers, cold winters, and agricultural field sites are located at elevations greater than 1,200 m (NOAA NECI 2019).

Additionally, specialty crops tend to be grown in smaller fields (0.1 – 1.9 ha) typically surrounded by urbanized landscapes, increasing their accessibility to overwintered BMSB adults dispersing from human structures in the spring (Lee and Leskey, 2015; USDA NASS, 2017).

Studies have documented strong field edge effects on BMSB colonization of crops, with resulting increased damage in peach and apple orchard borders (Joseph et al. 2014; Blaauw et al. 2016). Furthermore, BMSB abundance and damage has been positively correlated with proximity to woodlots, likely due to availability of diverse resources to support BMSB overwintering and survival (Hoebekke and Carter 2003; Nielsen and Hamilton 2009; Martinson et al. 2013; Rice et al. 2017). Due to the presence
of urbanized landscapes instead of wooded habitats in proximity to Utah’s agricultural sites, and the relatively small-scale of specialty crop fields, we hypothesize that BMSB dispersal and colonization behaviors may vary from other infested regions of the U.S. Specifically, we hypothesize that there will be minimal field edge concentration of BMSB in the Utah agricultural landscape due to their ability to invade the interiors or centers of small field sites with normal dispersal behavior.

Additionally, because Utah BMSB populations are relatively low in the agricultural landscape since its recent introduction, even with high-intensity sampling (Acebes-Doria et al. 2019), we postulate that sticky panel traps may not yet offer successful monitoring of BMSB. Therefore, we predict that pyramid traps may be more useful until population size increases to a tipping-point level, yet to be determined. Here, we explore the effectiveness of three common BMSB sampling methods (pyramid traps, sticky panel traps, and visual plant inspections) at different sample locations within diverse agricultural sites throughout northern Utah. We aim to provide Utah growers with the most useful monitoring tools and strategies to best manage this destructive pest.

METHODS

Field Site Description.

Six small-scale community gardens and commercial orchards (0.25-2.5 ha) in areas with documented BMSB populations were selected for study in 2018 and 2019. Study field sites were adjacent to or surrounded by suburban communities with residential housing. Orchards were composed of peach, apple, pear, and tart cherry trees;
community gardens included a wide variety of vegetable and fruit crops. Field sites, individual years in which each field site was sampled, and associated host plants are reported in Table 1.

Experimental Design.

*Orchards.* Two trap types were utilized: ~1.2 m tall ground-deployed pyramid traps with black bases and yellow entry cones (AgBio Inc., Westminster, CO) and clear dual sticky panel traps (Trécé Inc., Adair, OK) attached to a wooden stake and positioned ~1.2 m above the ground. Sticky panel traps were replaced every three wk or in cases of trap damage or debris accumulation. BMSB dual pheromone lures were secured to traps using twist ties, and were replaced after 12 weeks of use. Lures were positioned either hanging underneath container entry cones (pyramid traps) or to the tops of wooden stakes (sticky panel traps) using twist ties. In 2018, traps were located along a transect running through each field site at 5 m outside the edge (hereafter referred to as “exterior”), 5 m inside the border (“border”), and 5 m away from the center (“center”) on both sides of the transect within a field site (Figure 3-1). At each sample location, one pyramid trap and one sticky panel trap (trap pair) were placed on opposite sides of the transect line (trap positions randomly assigned), and were separated by 10 m to prevent pheromone lure plumes from overlapping (Kirkpatrick et al. 2019). Sticky panel trap faces were oriented perpendicular to the tree rows. In 2019, a fourth trap location was selected 10 m from the border location into the field site interior (“border-interior”) (Figure 3-1).

*Community Gardens.* Transect design in the community garden field sites was similar to that in orchards. However, due to limitations in garden sizes (<0.5 ha), the
distance between paired traps and trap locations was reduced to 5 m, which still offered adequate separation to prevent pheromone plume overlap.

Sampling.

Once per week from mid-May to late October, the number of BMSB adults and nymphs caught in traps was counted, and all BMSB removed. Adults were distinguished by sex and nymphs categorized into 1st to 3rd instar or 4th to 5th instar (Rice et al. 2014; see Analyses for description of data combination before analysis). All plant material within 1 m of each trap was visually inspected for BMSB for 2 min using beating sheets (fruit trees) or physical inspection of vegetation (vegetable and ground cover plants). Live BMSB captured from visual inspections were collected and removed. Due to different collection methods for trapping vs. visual inspection catch (one week of bug accumulation in traps vs. two minutes of visual inspections surrounding each trap per week), plus summary of data for analysis (see analysis methods), visual inspections cannot be directly compared to trapping catch. However, these methods still offer insight into relative effectiveness of different sampling methods.

Analyses.

To account for a large number of zero data, all BMSB adult and nymph counts (sexes and life stages) were combined for each sample type per wk. Additionally, BMSB counts were compiled into early (May 15 – Jul 5), mid (Jul 6 – Aug 31), and late (Sep 1 – Oct 25) seasonal periods. Due to continued over-dispersion of data, BMSB counts were combined for replicate transect locations in each site (e.g., combined BMSB catch in pyramid traps at the border is the sum of the pyramid trap catch at the border on both
ends of the transect in a field site). Due to data summarization, the BMSB total for pyramid and sticky traps for each trap location within a site is the sum of two values, while the total for visual inspections is the sum of four values. All data were transformed to log (x) +1 prior to analysis to meet normality assumptions.

A three-way repeated measures ANOVA was used to test the null hypothesis that there were no significant differences in BMSB detection (counts) among sample location on a transect, sample type, and seasonal period. Pairwise comparisons were used to examine significant main effects in more detail. All analyses were performed using the anova function in the rstatix package distributed with base R version 1.2, and were run using R Studio for Mac (R Core Team 2017). Figures were plotted using the ggplot2 package version 3.2.1 for RStudio (Wickham 2016; Wickham et al. 2019). Significance for ANOVAs was set at $\alpha \leq 0.05$. A Bonferroni adjustment was used in cases of multiple hypothesis testing.

RESULTS

Across both years and all field sites, a total of 1,739 BMSB (adults and nymphs) were captured, with more captures in pyramid (961) than sticky panel traps (266) or in visual inspections (512). Pyramid traps resulted in more captures than sticky traps in all nine site-years, and more than visual inspections in eight out of nine site-years. Sticky panel traps only outperformed visual inspections in one site-year (Table 3-1).

The three-way repeated measures ANOVA results found no significant three-way interaction among sample location, sample type, and seasonal period ($F_{12, 252} = 0.29$, $p = 0.99$). However, a significant two-way interaction between sample type and seasonal
period ($F_{4,252} = 2.433, p = 0.05$) demonstrated that although more BMSB were detected in pyramid traps than sticky traps throughout the season, pyramid traps only detected more BMSB than visual inspections in the mid and late season (Figure 3-2).

Additionally, there was a significant main effect of sample location ($F_{3,284} = 3.35, p = 0.02$). Pairwise comparisons revealed that field border and border-interior locations had significantly more BMSB detection than did field exterior locations (Tukey HSD test; $p < 0.05$) (Figure 3-3). For trap locations that existed within the growing area of agricultural commodities (i.e., border, border interior, and center locations), there were no differences in BMSB detection.

**DISCUSSION**

Our study provides comparison of the effectiveness of three monitoring techniques for BMSB, and whether they differ among locations within small specialty crop fields, in representative specialty crop production sites in northern Utah. Under low BMSB population densities currently found in Utah ($< 1$ BMSB captured per trap per wk) (Acebes-Doria et al. 2019), our results confirm that pyramid traps provided greater detection of BMSB than sticky panel traps in the early, mid, and late season. Visual inspections performed similarly to pyramid traps in the early season, but detected fewer BMSB in the mid and late season. Visual inspections were conducted for 2 min per wk, whereas traps provided cumulative BMSB counts for an entire week. Although not directly comparable methods, the results provide insights into the value of visual inspections when used in combination with pheromone-baited traps to aid detection of BMSB early in the season when plant biomass is less and BMSB densities are low.
Although sticky panel traps detected BMSB throughout the season, the densities were very low season-long while pyramid trap detections increased. Therefore, in regions with low BMSB density such as Utah, the efficacy of sticky traps is too low to provide adequate detection alerts for pest management decisions and does not track population increases in the later season (Acebes-Doria et al. 2019). We recommend that regions with low BMSB density can best track populations with pyramid traps, and reliable early season detection can occur with either pyramid traps, visual inspections, or both in tandem. If visual inspections are to be conducted without a pheromone-baited trap placed nearby, pheromone lures should still be placed near or in sampled host plants (Akotsen-Mensah et al. 2018).

BMSB colonization and establishment in locations 5 or 10 m outside of specialty crop fields was less than border and border interior locations within fields. These results suggest that field exterior locations may be inhospitable to BMSB due to a lack of acceptable host plants. In addition, we did not observe a preference of BMSB for field borders as has been observed in other studies (Hoebke and Carter 2003; Nielsen and Hamilton 2009; Martinson et al. 2013; Joseph et al. 2014; Blaauw et al. 2016). In contrast to other trap efficacy and BMSB dispersal studies, the specialty crop fields in this study were surrounded by suburban and urban landscapes that included residential and commercial properties with ornamental vegetation. Additionally, field size in this study ranged from 0.25 to 2.5 ha, less than in other studies. Therefore, the consistent preference of BMSB for border locations as observed in other regions was diminished in our study with field sizes < 2.5 ha. Notably, BMSB has been shown to disperse as far as 70 m
within agricultural sites, which exceeds or nearly equals the distance to the center of the smaller fields that were utilized for this study (Kirkpatrick et al. 2019).

Interestingly, specialty crop producer cooperators for this study did not report BMSB damage to their crops, even during periods of high BMSB abundance. Likewise, no definitive BMSB-attributed damage was observed on fruits or vegetables throughout the duration of the study. Coupled with the climate factors that may already limit BMSB abundance in the Intermountain West (e.g., high elevation, shorter duration growing seasons, cold winters, and low humidity), the lack of woodlot edges, and the ability of BMSB to diffuse populations over the entirety of small agricultural fields alters the target of population suppression on field borders as recommended in other regions of the U.S.

Our study suggests that pyramid traps are much more effective than sticky panel traps at detecting and monitoring BMSB in this low-density region, and that BMSB does not colonize specific locations within small fields (< 2.5 ha). Regions with low BMSB density and small agricultural sites may benefit from monitoring using pyramid traps, and should not focus sampling solely on field edges as is traditionally done in high density regions. BMSB continues to invade and establish in northern Utah. Furthermore, populations will likely fluctuate with the recent natural introduction of samurai wasp (*Trissolcus japonicus* Ashmead), a promising, non-native biological control agent of BMSB (Zhang et al. 2017; Milnes et al. 2019; Holthouse et al. 2019). Therefore, we recommend continued monitoring to best prevent economic impacts in the future. Growers should utilize pyramid traps for season-long monitoring, or implement visual plant inspections in tandem with a dual pheromone lure or baited pyramid trap if detection is the primary goal. While severe economic crop loss due to BMSB has not yet
been documented in Utah, continued monitoring will be pivotal to managing this destructive pest as it continues to spread and establish.

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Table 3-1. Total BMSB catch by sample method for each orchard or community garden site and year.

<table>
<thead>
<tr>
<th>Site #</th>
<th>Hosts</th>
<th>Year</th>
<th>Total BMSB per sample type</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pyramid</td>
<td>Sticky</td>
<td>Visual</td>
<td></td>
</tr>
<tr>
<td>Orchards*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Peach</td>
<td>2018</td>
<td>83</td>
<td>12</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>269</td>
<td>76</td>
<td>198</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Apple / pear / peach</td>
<td>2018</td>
<td>51</td>
<td>6</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>58</td>
<td>19</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Tart cherry</td>
<td>2019</td>
<td>64</td>
<td>24</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Gardens†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mixed veg.</td>
<td>2018</td>
<td>54</td>
<td>12</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Mixed fruit / berry / veg.</td>
<td>2018</td>
<td>95</td>
<td>47</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2019</td>
<td>166</td>
<td>26</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Mixed veg.</td>
<td>2019</td>
<td>121</td>
<td>44</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>961</td>
<td>266</td>
<td>512</td>
<td></td>
</tr>
</tbody>
</table>

GPS Coordinates
* Site 1: 41.1861, -112.0403; Site 2: 40.3473, -111.7143; Site 3: 41.0201, -111.9300
† Site 4: 41.0272, -111.9322; Site 5: 40.7522, -111.8734; Site 6: 40.6357, -111.8639
Figure 3-1. An example of experimental design setup for orchards. Stars indicate pyramid traps and circles indicate sticky panel traps. Dark gray-shaded traps indicate border-interior traps that were only used in 2019. Trap locations within a site (exterior, A; border, B; border-interior, C; and center, D) were separated by at least 10 m. Traps in each trap pair were randomized and at least 5 m from the transect line.
Figure 3-2. Combined mean number of BMSB adults and nymphs (± SE) for three sample types (pyramid trap, sticky trap, and visual inspection) in early (May 15 – Jul 5), mid (Jul 6 – Aug 31), and late (Sep 1 – Oct 25) season of 2018 and 2019. Capital and lowercase letters represent significant differences among individual sample methods among seasonal periods, and among different sample methods within individual seasonal periods, respectively (p < 0.025). Data are presented as non-transformed.
Figure 3-3. Mean (± SE) number of BMSB collected at four sample locations within field sites (exterior, border, border-interior, and center) in 2018 and 2019. Different letters indicate significant differences between sample location (Tukey HSD; $p < 0.05$). Data are presented as non-transformed.
CHAPTER IV

NON-SIB MALE GUARDING BEHAVIOR OBSERVED IN *Trissolcus euschisti* (HYMENOPTERA: SCELIONIDAE)

Abstract

Wasps in the genus *Trissolcus* (Hymenoptera: Scelionidae) are obligate parasitoids of stink bugs and typically undergo sib-mating behavior. There is little documentation on how these wasps outbreed and spread genetic material. We discovered a new method for avoidance of inbreeding depression in *T. euschisti* (Ahmead), a parasitoid wasp observed attacking eggs of the green stink bug egg (*Chinavia hilaris* Say) in Utah. During field surveys for *Trissolcus japonicus* (Ashmead), an exotic biological control agent of the invasive brown marmorated stink bug (BMSB, *Halyomorpha halys* Stål), we discovered a non-sib male *T. euschisti* guarding an egg mass with no parasitoid emergence where a female previously deposited her eggs, effectively guarding pre-emergent females from sib-males that would typically wait near the natal site to mate with their sisters. This finding may implicate that outbreeding is more prevalent than once thought in sib-mating systems, and that when releasing *T. japonicus* for the biological control of BMSB, it may be important to release multiple strains to lower the potential of inbreeding depression.
Keywords

Sib-mating, Egg Guarding, Scelionidae, Endogamy Inbreeding Depression, Biological Control

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1 We thank the Science Matters team and the permission editors for allowing the reprinting of this publication in this thesis

2 Coauthored by Diane G. Alston, Lori R. Spears, and Mark C. Holthouse
Introduction

Wasps in the genus *Trissolcus* (Order Hymenoptera: Family Scelionidae) are obligate egg parasitoids of insects in the superfamily Pentatomoidea (Order Heteroptera), particularly stink bugs (Heteroptera: Pentatomidae)[1]. *Trissolcus* wasps have been the focus of biological control efforts for the economically important invasive brown marmorated stink bug (BMSB, *Halyomorpha halys* Stål) in North America and Europe. Research has shown that chemical control programs lack effectiveness and sustainability[2]; therefore, there is strong interest in identifying effective biological control agents.

Host eggs utilized by parasitoids are vulnerable to competitors (such as egg predators and other parasitoids) when naturally laid; therefore, female parasitoids, including those in the genus *Trissolcus*, will often stay with their brood to guard them from challengers[3][4][5][6][7]. In studied representatives of *Trissolcus*, once development of progeny is nearly complete, the parent female will depart. Males will emerge from eggs in near unison and then competitively mate with sibling females when they emerge up to three days later[8][9][10].

Sib-mating is commonplace in the parasitoid family Scelionidae[11], which leads to inbreeding and may consequently result in fitness decline[12]. Numerous animal taxa have evolved behavioral strategies for avoiding inbreeding risks. In vertebrates, due to selective breeding and mate-choice, sib-mating rarely occurs except in instances of accident or error, leading to more prevalent outbreeding[13]. However, sib-mating species
(primarily plants and insects) have developed other strategies to prevent inbreeding depression. Loch and Walter\textsuperscript{[11]} postulate that outbreeding in \textit{Trissolcus} may occur if males and/or females can locate and/or attract the opposite sex after leaving the natal site. In addition, females may be able to locate parasitized host eggs and mate with unrelated males as they emerge from host eggs. Finally, males may be able to locate host eggs parasitized by unrelated females and compete with emerging males for access to the later-emerging females.

Evidence for mating after leaving the natal site is provided by Loch and Walter\textsuperscript{[8]}, where the outbreeding potential of \textit{Trissolcus basilis} (Wollaston), an egg parasitoid of southern green stink bug (\textit{Nezara viridula} Linnaeus) was explored. They found that a single, newly emerged male dominated the natal site by guarding the eggs and chasing and behaving aggressively toward subordinate males. As many as 18\% of females, however, dispersed from their natal egg mass to mate with subordinate males outside of the guarded arena. In addition, 25\% of females were mated more than once by dominant and/or subordinate males near or away from their natal egg mass, and 13\% of females departed the natal site and surrounding area without mating at all, leaving as virgins. Female dispersal from their natal site and polyandry are documented mechanisms for outbreeding in a typically inbreeding species. Non-sib mating at the natal site, another mechanism for outbreeding, has been suggested\textsuperscript{[11]} but has not heretofore been documented for parasitoid wasps in the genus \textit{Trissolcus}.
Objective

We herein describe what we believe to be the first documented observation of non-sib male guarding behavior in a *Trissolcus* wasp. Guarding behavior in this genus is documented to occur by ovipositing females (to protect their offspring from competitors), and by dominant sib-males that will guard their sisters’ eggs until emergence to mate with them. There are few documented ways in which these sib-mating parasitoids spread genetic material to prevent inbreeding depression, and we implicate the possibility of non-sib male guarding to contribute to genetic robustness.

Results and Discussion

Of the 13 eggs in the egg mass, a single male parasitoid emerged six days after collection. During the two observation periods that included the single emerged male, the original marked male was guarding the eggs, aggressively chasing away the emerged male. Nine female wasps emerged between the last hourly check on Day 6 and the first hourly check on Day 10. The three remaining un-emerged eggs had the chorion chewed open with fully developed female wasps nearing emergence. The marked male was aggressively guarding the un-emerged wasps from the previously emerged wasps, regardless of the approaching wasp’s sex (Supp. video accessible in Appendix A). Active guarding of the un-emerged wasps by the marked male occurred over the entire eight-hour observation period, indicating that the marked male was both dominant at the natal site and likely waiting to mate with the un-emerged females. We suspect that the marked male had already mated with many or all of the emerged females in this manner (mated
upon emergence); however, mating would have occurred between the last observation on Day 6 and first observation on Day 10; hence no mating was observed between the marked male and any female. The three un-emerged wasps were unable to complete emergence and expired, at which time the observations were terminated. All wasps (i.e., the marked male, emerged male and females, and un-emerged females) were later identified as *T. euschisti*.

The observation of a non-sib male guarding a stink bug egg mass from emerging males and competing females has been suggested as a potential method for outbreeding\[1\] but remained undocumented. Given that males emerge from eggs within a mass in near unison and the first male emergence occurred six days after egg collection, it is likely that the male present at collection sought out the egg mass as a non-sib *T. euschisti*. This observation is additionally supported by the darkening of the eggs that occurred after collection, which typically occurs around seven days after parasitism\[14\]. Egg darkening post-collection indicates that parasitoids were still developing in the host eggs while the marked male was already present.

There is evolutionary pressure to avoid inbreeding depression in many fauna. For example, in larger animals, there is evidence for sex-biased dispersal, in which one sex disperses a greater distance than the other\[15\][16]. Kin-detection can also prevent inbreeding, in which individuals recognize their kin using different visual, olfactory, or auditory cues to prevent sib-mating\[17\][18]\[19\]. In primarily sib-mating systems, other mechanisms to avoid inbreeding depression must be in place\[18\][11]. In the case of *Trissolcus* wasps, while females can mate with unrelated males after departing the
natal site, outbreeding may also occur via egg guarding by non-sib males as we propose here. To confirm, this mechanism requires support from other studies, and could give new light to inbreeding depression avoidance in sib-mating systems.

**Limitations**

The documentation of the single observation herein was discovered during field surveys for a separate study. While we did observe guarding behavior of the non-sib-male at the natal site for a short period, the wasps and egg mass were collected to prevent the original wasps from departing. Further, although mating was not directly observed, it is presumed to have occurred shortly after female emergence based on normal mating behavior of other males in the genus *Trissolcus*\(^8\). This observation should lead to further studies to more thoroughly evaluate this potential mechanism.

**Alternative Explanations**

While the entire host apple tree was surveyed for egg masses, it is possible that the guarding male emerged from a nearby, unseen egg mass parasitized by the same parent and/or sought to mate with the female that originally parasitized the egg mass or other passing females. However, these alternative explanations neither describe nor detract from the uniqueness of the guarding behavior of the male observed in this study.

**Conjectures**

Additional field and lab observations are needed. Specifically, closer attention should be paid to the area surrounding field-collected egg masses to maximize the
likelihood of repeated documentation, and to better understand and document the frequency of this behavior. Collaborators throughout the world working on biological control of brown marmorated stink bug are often equipped with colonies of *Trissolcus spp.* that would support such field and lab experimentation.

**Methods**

Weekly from late May to mid-October, 2018, we conducted surveys for naturally-laid stink bug egg masses on the underside of leaves in diverse cropping systems in northern Utah. On June 19, a green stink bug (*Chinavia hilaris* Say) egg mass containing 13 eggs was discovered on an apple tree leaf in Salt Lake City, Utah (N 40° 45’ 8.297” W 111° 52’ 25.281”). At the time of detection, a male parasitoid wasp was guarding the egg mass (defined as walking or standing on top of host eggs and using aggressive behaviors to chase away competitors), and two female parasitoid wasps were also present. The guarding male appeared to be preventing female access to the eggs via aggression. After observing the guarding behavior for one minute, the egg mass and three adult wasps were collected into a 47 mm clear, capped petri dish (Fisherbrand, Pittsburgh PA) and transported to the lab for observation and analysis. The decision to collect the egg mass after one minute was based on concern that prolonged observation could have resulted in further disturbance of the natal site and departure of parasitoids.

In the lab and on the day of collection, the petri dish was chilled for ten minutes at 4.4°C to slow wasp movement, and the dorsal thorax of the guarding male was marked with a dot of yellow acrylic paint to differentiate it from other males emerging from the egg mass (Figure 4-1, Supp. Video). The female parasitoids were vouchered in ethanol
and identified. The marked male was left in place for observation. The egg mass was reared at 27°C, 16:8 hr light / dark cycle, and checked hourly from 8:00 – 16:00 for nine days to document parasitoid emergence.

With the initial male remaining on the egg mass, darkening egg coloration was first noted on Day 3, indicating the likelihood of previous parasitism, and new adult wasps emerged on the sixth and tenth day after collection (June 25 and 29, 2018, respectively). The petri dish was placed under a microscope camera (Leica EZ4D, Wetzlar, Germany) to observe wasp behavior: 2 ten-minute observations at 10:00 and 14:00 on Day 6 (one new wasp emerged) and 9 ten-minute observations on Day 10 conducted each hour from 8:00 – 16:00 (9 new wasps emerged). Observations were captured on video using Leica Acquire Software. All parasitoid wasps were vouchered after observations and identified using the key to Nearctic *Trissolcus*.[20]

**Acknowledgements**

We thank Lily Bourett, Hanna Kirkland, Kate Richardson, Ryan West, and Ben Steadman for field and lab assistance, Elijah Talamas for species confirmations, and Wasatch Gardens for access to the study site.

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Figure 4-1. The original male *Trissolcus* wasp with yellow acrylic paint marking on the thorax (indicated by an arrow; dorsal view available in supplementary video accessible in Appendix A), exhibiting guarding behavior over green stink bug eggs (dark color indicates previous parasitism) without emergence holes from additional parasitoid wasps.
CHAPTER V
PARASITOID WASPS OF THE INVASIVE BROWN MARMORATED STINK BUG IN UTAH (UTAH EXTENSION FACT SHEET)¹

¹Coauthored by Mark C. Holthouse, Diane G. Alston, Lori R. Spears, and Yota Mizuno

Introduction

The brown marmorated stink bug (BMSB, Halyomorpha halys Stål) is an invasive agricultural and nuisance pest native to eastern Asia. It was first confirmed in the U.S. in Allentown, PA, in 1996 and has since spread to 44 U.S. states, many of which have now experienced economic crop damage from this pest (Fig. 5-1). In Utah, BMSB is now established in five counties (Box Elder, Weber, Davis, Salt Lake and Utah), and has been detected in Cache and Kane counties. While crop damage to peach, apple, squash, and popcorn has been identified, it is currently causing mostly nuisance problems due to overwintering bugs on and inside human structures.

Adult BMSB are marbled brown and black, camouflaging well with woody vegetation. To separate this stink bug from native look-alikes, notice the characteristic white bands on their antennae. Native species do not have this feature. BMSB also has smooth shoulders and a black/white pattern on the edge of the abdomen (Fig. 5-2).

BMSB is a successful invasive for many reasons: it is polyphagous (feeds on many plant types), highly mobile, has few natural enemies, and adults have a tough exoskeleton that is covered in a waxy, water-repellent cuticle that helps protect them
from pesticide applications. Biological control, through the use of egg parasitoids, is the most suitable option for long-term management of BMSB.

**General Parasitoid Information**

There are at least two families of stink bug parasitoids in Utah, Eupelmidae and Scelionidae. These are small, typically black wasps that may be mistaken for small gnats or ants. They will fly in search of stink bug egg masses. Once they find the eggs, they will sting them, depositing one of their own eggs into the stink bug egg. The wasp egg will hatch, and the larva wasp will feed and develop within the stink bug egg, effectively killing the host. The adult wasp will emerge a couple of weeks later.

The Eupelmids attacking BMSB are all generalist parasitoids, meaning that they sting the eggs of a wide variety of insects. Native parasitoids in this group are moderately successful at stinging and developing inside BMSB eggs, but are unlikely to control BMSB populations due to their generalist nature.

The second family, Scelionidae, includes some stink bug specialists, meaning they only sting stink bug eggs. Specialists are more promising as a control agent for BMSB. Although many of the native Scelionid species will sting BMSB eggs, some will not develop into an adult and emerge. Those that can complete development within BMSB eggs have the potential to be more effective control agents.

Stink bug eggs are usually bright in color (Fig. 5-3) and take 5 to 7 days to develop and hatch. Eggs will develop a triangular egg “burster” shortly before stink bugs emerge from the egg (Fig. 5-4). However, if parasitized by a wasp, the eggs will turn dark
brown or black after about a week. As the wasps develop, the eggs will continue to darken until the adult wasps emerge about 14 days later (Fig. 5-3).

There is usually a skewed sex ratio in emerging wasps. In a typical stink bug egg mass that consists of 14-28 eggs, one to three wasps will be male, and the rest will be female. Male wasps will emerge first and wait for the females to emerge. Once mated, the females fly off in search of new egg masses to sting.

Parasitoid Wasp Families in Utah

**Eupelmidae – Generalist Egg Parasitoids**

Eupelmids are small (3-5 mm), slender wasps that are generalist egg parasitoids. One genus, *Anastatus*, will parasitize BMSB, as well as other stink bugs and insects. They can resemble ants at first glance. Females often have a white band or white triangles on the wings. There are three species of *Anastatus* known to attack BMSB in Utah (Table 5-1). When seen on a stink bug egg mass, a general rule is that these wasps are much larger than an individual egg (Fig. 5-5).

Females are typically larger than males, and under direct light can exhibit brown, green, or blue iridescence. Males are typically all black, smaller (< 4 mm), and lack wing patterns, making males indistinguishable to species without a microscope.

**Scelionidae – Specialist Egg Parasitoids**

Scelionids are very small (1-2 mm), but often robust wasps that are specialists on different insect groups (Fig. 5-7). One genus within this family, *Trissolcus*, only stings stink bug eggs. The wasps attacking BMSB can only be identified to species by using
microscopes, as they are entirely black, small, and lack wing patterns or other characteristics to separate them with the naked eye. However, they can be generally identified in the field to family or genus using the tool that they are as small as or smaller than a stink bug egg (Fig. 5-8). There are at least two genera of stink bug parasitoids in the family Scelionidae in Utah (Trissolcus and Telenomus), with at least eight different species between these two genera (Table 5-1).

Surveys are ongoing for other species of parasitoid wasps in Utah, particularly Trissolcus japonicus (samurai wasp) (Fig. 5-9). This wasp is native to eastern Asia, the native range of BMSB. In its native range, BMSB causes minimal economic damage, presumably due to effective biological control by the samurai wasp.

Samurai wasp was collected in China and is undergoing host range-testing in U.S. quarantine facilities to assess non-target effects for release in the U.S. However, samurai wasp has arrived on its own to the U.S. It has been found in 12 states as of January 2019 (Maryland, Pennsylvania, New Jersey, New York, Delaware, Oregon, Ohio, Virginia, West Virginia, Michigan, California, and Washington).

If samurai wasp is found in Utah, it can be reared and redistributed throughout the state to contribute to biological control of BMSB. Until samurai wasp is located in Utah, its release is prohibited.

Samurai wasp is more likely to be found in areas where BMSB are abundant (urban areas of Salt Lake and Utah valleys). However, it could be found in any location with established BMSB populations, making widespread surveys highly valuable.
Surveying for Parasitoids

Methods used to survey for stink bug parasitoids include physical placement of stink bug egg masses on host plants in the field, finding naturally-laid stink bug egg masses laid directly on host plants, and deployment of yellow sticky cards.

**Physical Egg Mass Placements:**

Lab-reared stink bug eggs are attached to small squares of cardstock paper. These cards are then clipped to the underside of leaves on common hosts of stink bugs in Utah (fruit trees, vegetables, and ornamental trees such as northern catalpa [*Catalpa speciosa*]) (Fig. 5-10). Cards are left for 3 to 4 days to attract parasitoids. When collecting cards, parasitoids guarding the eggs are also collected to further assess their efficacy in stinging and developing in eggs.

**Finding Naturally-laid Egg Masses:**

Stink bug egg masses can be found on the underside of leaves, on the fruiting structures, and occasionally on the stems of host plants (Fig. 5-11). Just as with deployed egg masses, parasitoids guarding the egg masses are collected to assess efficacy in killing and developing in stink bug eggs.

**Yellow Sticky Cards:**

Yellow sticky cards attract various insects. Cards are deployed for two weeks on the trunks and branches of ornamental and agricultural host plants, after which the wasps are removed from the card and identified (Fig. 5-12). When placed in areas with high parasitoid wasp diversity, cards are an effective tool for monitoring wasp diversity and
density. While cards are effective at locating parasitoid wasps, information regarding the wasp’s behavior on BMSB eggs, or their effectiveness at stinging, killing, and sustaining populations within them cannot be determined.

If You See a Parasitoid Wasp:

If you see a parasitoid on an egg mass, be mindful that it is beneficial for your garden/crops, as the wasps are potentially killing the stink bugs that would normally emerge and begin eating your plants. You can choose to either leave the stink bug eggs and parasitoids on the plant (preferred), or chase off the parasitoid, remove the stink bug eggs from the plant, and freeze or destroy them before they hatch.

It is possible that if the parasitoid wasps are left on the egg masses, then you may end up with more wasps, and consequently fewer stink bugs negatively impacting your plants. Parasitoids that are known to attack BMSB eggs in Utah can be seen in Figure 5-13. Locations of current surveys in Utah and associated genera compositions can be seen in Figure 5-14.

Report Parasitoid Wasps

Reports of stink bug egg masses with parasitoid wasps on them are valuable to protect all Utah communities and property owners, and could help find new wasp species that may assist with biological control of BMSB. USU Extension has created a Report an Invasive Pest in Utah website to report a finding, upload a photo, and find contact information for submitting a specimen for identification. Collect the egg mass and wasp in a bag or sealable container for specimen submission.
References


Stopbmsb.org. A comprehensive website on BMSB identification, management, and new research.
Table 5-1. Parasitoid wasp species found in Utah as of April 2019 from BMSB egg mass and yellow sticky card deployments. *Based on results to-date in Utah.

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Family</th>
<th>Collection Method</th>
<th>Actual Size</th>
<th>Can emerge from BMSB?</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Anastatus mirabilis</em></td>
<td>Eupelmidae</td>
<td>BMSB Eggs</td>
<td>✗</td>
<td>Yes*</td>
</tr>
<tr>
<td><em>Anastatus persalli</em></td>
<td>Eupelmidae</td>
<td>BMSB Eggs</td>
<td>✗</td>
<td>Yes*</td>
</tr>
<tr>
<td><em>Anastatus reduvii</em></td>
<td>Eupelmidae</td>
<td>BMSB Eggs / Sticky Cards</td>
<td>✗</td>
<td>Yes*</td>
</tr>
<tr>
<td><em>Telenomus podisi</em></td>
<td>Scelionidae</td>
<td>BMSB Eggs / Sticky Cards</td>
<td>✗</td>
<td>No*</td>
</tr>
<tr>
<td><em>Trissolcus erugatus</em></td>
<td>Scelionidae</td>
<td>BMSB Eggs / Sticky Cards</td>
<td>✗</td>
<td>No*</td>
</tr>
<tr>
<td><em>Trissolcus euschisti</em></td>
<td>Scelionidae</td>
<td>BMSB Eggs / Sticky Cards</td>
<td>✗</td>
<td>Yes*</td>
</tr>
<tr>
<td><em>Trissolcus hullensis</em></td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
<td>✗</td>
<td>Yes*</td>
</tr>
<tr>
<td><em>Trissolcus parma</em></td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
<td>✗</td>
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</tr>
<tr>
<td><em>Trissolcus thyante</em></td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
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<td>Unknown</td>
</tr>
<tr>
<td><em>Trissolcus strabus</em></td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
<td>✗</td>
<td>Unknown</td>
</tr>
<tr>
<td><em>Trissolcus utahensis</em></td>
<td>Scelionidae</td>
<td>BMSB Eggs / Sticky Cards</td>
<td>✗</td>
<td>No*</td>
</tr>
</tbody>
</table>
Figure 5-1. The current distribution and status of BMSB in North America as of April 2019. For updates, see http://www.stopbmsb.org/where-is-bmsb/.
Figure 5-2. A BMSB adult with quick identification characteristics. The white bands on dark antennae is the most helpful feature. Photo by Jeff Wildonger, USDA-ARS-BIIR.
Figure 5-3. Left: An adult BMSB with a freshly laid egg mass; Right top: A parasitoid stings a stink bug egg mass; Right bottom: eggs darken as parasitoids develop.

Figure 5-4. A BMSB egg mass with triangular egg bursters. The nymphal stink bugs inside are close to hatching. Image courtesy of Rutgers New Jersey Agricultural Experiment Station.
Figure 5-5. An *Anastatus* adult on BMSB eggs. Notice that the wasp is larger than an individual egg. Image Courtesy of Ashley Jones, University of Maryland.

Figure 5-6. An adult *Anastatus* female. Adults typically measure 3-5 mm in length and resemble ants in appearance. Image courtesy of John Rosenfeld, bugguide.net.
Figure 5-7. An adult *Trissolcus* female. Adults measure 1-2 mm with a robust body form. Image courtesy of John Rosenfeld, bugguide.net.

Figure 5-8. A *Trissolcus* female on a BMSB egg mass. Notice that the wasp is about the size of an egg. Image courtesy of Elizabeth Beers, Washington State University.
Figure 5-9. The samurai wasp (*Trissolcus japonicus*), a highly effective parasitoid against BMSB. It has been found in 12 U.S. states. Image courtesy of Elijah J. Talamas, USDA ARS.

Figure 5-10. A BMSB egg mass clipped to a corn leaf to attract parasitoid wasps.
Figure 5-11. An *Anastatus* wasp on naturally-laid eggs. Image courtesy of Mark Cody Holthouse, Utah State University.

Figure 5-12. Yellow sticky card hung on a tree to attract parasitoids.
Figure 5-13. Select native parasitoid wasps stinging BMSB in Utah. From the top left: *Trissolcus erugatus*, *Trissolcus utahensis*, *Anastatus reduvii*, *Telenomus podisi*, and *Trissolcus euschisti*. Images by Zach Schumm and Mark Cody Holthouse, Utah State University.
Figure 5-14. A map of the current survey sites and parasitoid recovery locations in Utah through September, 2018.
CHAPTER VI
SUMMARY AND CONCLUSIONS

The current knowledge on the behavior and impact of BMSB in the U.S. is primarily founded on studies conducted in regions with climates and landscapes vastly different than that of Utah. The novel studies herein have addressed the potential economic impact of BMSB to tart cherry, an unstudied crop in regards to BMSB susceptibility and major commodity in Utah, and the movement and behavior of BMSB in the Utah agricultural landscape. I also sought to determine the best monitoring practices for BMSB in this unique region and situation with relatively low BMSB densities as compared to other infested regions. Overall, I predicted that BMSB feeding by adults or nymphs would severely reduce tart cherry quality and yield. Additionally, I predicted that BMSB would not exhibit field edge effects observed in other regions of North America due to the smaller-scale of Utah specialty crop fields, and that BMSB would better respond to pyramid traps that other sampling methods due to its high effectiveness in other regions and the current low populations of BMSB in Utah.

I additionally sought to determine the ability of BMSB to overwinter in the natural landscape in northern Utah, and determine the effectiveness of native parasitoid wasps at killing developing BMSB eggs. These studies were less successful and robust results were not obtained; thus, these results are presented in the Appendix. I predicted that human structures are better suited for BMSB overwintering than the natural landscape due to the extreme winter conditions in northern Utah. I additionally expected
native parasitoid wasps to be effective at killing developing BMSB eggs, but would only show mild to moderate success at reproducing and emerging from BMSB eggs.

The potential for BMSB to induce economic yield loss to the tart cherry crop is dependent on its ability to invade early in the growing season between petal fall and pit hardening, as these fruit bud developmental stages experienced up to 100% abscission of fruits if fed on by nymph or adult BMSB. Interestingly, results did not support quality loss to a degree that impacts tart cherry marketability if nymph or adult BMSB feed after pit hardening of fruits. Due to tart cherry being a processed crop, the fruit is much more tolerant to visible BMSB feeding damage. The low numbers of BMSB in the agricultural landscape in Utah in the early season (described in Chapter III) is promising for growers of tart cherry, which is most vulnerable to damage in the early season.

If BMSB populations in the Utah agricultural landscape continue to be low prior to pit hardening of tart cherry, we anticipate that BMSB may never be a major threat to this specialty fruit crop. However, it is important to note that if infestations in tart cherry orchards increase, long-term feeding may impact the quality of the fruit, which will subsequently impact processing and marketability. We therefore suggest that monitoring for BMSB in tart cherry orchards is the most beneficial practice until populations increase, and if populations are severely high, management using commercial insecticides may become useful.

I suggest in Chapter III that the best sampling method for BMSB in the agricultural landscape to effectively track populations appears to be the pyramid-style trap, as it was the only sampling method tested that showed a significant increase in BMSB detection late in the growing season. Furthermore, sticky panel traps had
extremely low catch throughout the entire growing season. In addition, I argue that for effective inexpensive detection of BMSB (i.e., not long-term monitoring), visual inspection of host plants baited with the dual pheromone lure may be satisfactory.

We also importantly report that we were unable to detect field edge effects on BMSB colonization in the Utah specialty crop landscape, which differs from movement patterns in other regions with BMSB infestations. Due to the small nature of Utah agricultural field sites surrounded by urbanization (typically < 2.5 ha), and lack of wooded areas in proximity to sites, BMSB can invade the entirety of the average Utah field site with normal dispersal behavior. Because no edge effects were observed, we suggest that successful trapping and monitoring of BMSB can be conducted in any location within an orchard if the site is small and only has one BMSB host plant species. In a polyculture site, it would be recommended to monitor in varied crop hosts to assess infestation distribution based on host preference.

BMSB populations in some locations in Utah may be limited due to climate alone. We predicted in our overwintering study (Appendix C) that BMSB would better survive in human structures than in the natural landscape, however most of the bugs used in this study expired regardless of overwintering habitat type (Table C-1). These results could be due to the location of the study in Logan, UT which exists in a northern valley that experiences colder temperatures and harsher winters than other areas with BMSB infestations. Therefore, we expect that overwintering survivorship of BMSB in these warmer areas is higher. Overall however, the lack of humidity (and therefore lower overnight and morning temperatures extending into early summer) throughout the entire state may impact BMSB’s ability to travel into the agricultural landscape early and mid-
season, which is when yield of several crops, including tart cherry (Chapter II), is at highest risk.

I additionally argue that native biological control agents (parasitoid wasps) may be somewhat effective at killing developing BMSB through an efficacy study of *T. utahensis* (Appendix D; Figure D-1). Even though this species was unable to successfully develop in and emerge from BMSB eggs, it was still able to kill nearly 90% of developing BMSB. I was only able to initiate a small colony of this species due to resource limitations, but future research should be focused on testing the effectiveness of prominent native parasitoid wasps against BMSB.

The future of the BMSB invasion in Utah and the Intermountain West is subject to modification with the natural introduction of the samurai wasp (*Trissolcus japonicus* Ashmead) (Appendix E). This parasitoid wasp is known to control BMSB well in its native range, and has been shown to be a promising biological control agent for rearing and redistribution in the U.S. It is possible that with its introduction, coupled with the climate factors that already limit BMSB in Utah, growers may escape severe economic crop losses. Further research to test the potential future impact of *T. japonicus* is suggested, along with experiments to determine its survival and overwintering success in this unique region. Ideally, I hope for redistribution efforts to begin if samurai wasps can successfully overwinter and sustain populations in Utah.

Overall, I suggest that BMSB is still spreading and establishing throughout Utah. Additionally, I suggest that BMSB populations and associated economic damage concerns may fluctuate based on population dynamics due to Utah’s unique climate and the introduction of an effective parasitoid wasp that was first detected in 2019, only seven
years after the introduction of BMSB. I recommend to all growers to report suspect
damage that may be due to BMSB invasions, and to monitor for BMSB using
commercially-available pyramid traps or beat sheets to best combat this pest. There does
not appear to be substantial or widespread economic damage as of 2019, but the potential
is present in the future if populations continue to spread and *T. japonicus* does not survive
or perform well in Utah. Future research should evolve from the findings herein to best
protect Utah’s agricultural commodities, economy, and residents.
APPENDICES
APPENDIX A

AUTHORSHIP AND CITATIONS OF CHAPTERS

Chapter II:
This is pre pre-copyedited, author-produced version of an article accepted for publication with revisions by the Journal of Economic Entomology.

Chapter III:
This is an author-produced version of an article intended for submission to the Proceedings of the Entomological Society of Washington.

Chapter IV:
This is pre pre-copyedited, author-produced version of an article published by the Science Matters Select Journal. The version of record Schumm, Z. R., D. G. Alston, M. C. Holthouse, and L. R. Spears. “Non-sib Male Guarding Behavior Discovered in Trissolcus euschisti (Hymenoptera: Scelionidae). In: Matters Select. 2020. is available online at: https://sciencematters.io/articles/202004000005

Chapter V:
This is a pre-copyedited, author-produced version of an Extension Fact Sheet published by Utah State University Extension. The version of record Schumm, Z. R., M. C. Holthouse, Y. Mizuno, D. G. Alston, and L. R. Spears. 2019. Parasitoid wasps of the invasive brown marmorated stink bug in Utah: 6 pp. Utah State University Extension Fact Sheet, Logan, UT is available online at:
https://digitalcommons.usu.edu/extension_curall/1974/
APPENDIX B

LETTERS OF PERMISSION

05/22/2020

To the Director of Publications,

I am in the process of preparing my master's thesis in the Department of Biology at Utah State University. I am hoping to submit my thesis by June 19, 2020.

The article "Impact of Brown Marmorated Stink Bug (Hemiptera: Pentatomidae) Feeding on Tart Cherry (Rosales: Rosaceae) Quality and Yield in Utah" [ID ECONENT-2020-0149], of which I am first author, reports an essential component of my thesis research. This article has been accepted with major revisions in the Journal of Economic Entomology. I would like permission to print this article as a component of my thesis, which may require minor revisions (however, none are expected and the article should closely match the version resubmitted to the journal for reevaluation). Please note that Utah State University sends every thesis to ProQuest to be made available for reproduction.

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Zachary Schumm
zach.schumm@aggiemail.usu.edu

I hereby give my permission to Zachary Schumm to print the requested article in his thesis:

"Impact of Brown Marmorated Stink Bug (Hemiptera: Pentatomidae) Feeding on Tart Cherry (Rosales: Rosaceae) Quality and Yield in Utah"

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Signed:

Date: 5-22-20

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04/28/2020

To the permissions editor,

I am in the process of preparing my master’s thesis in the Department of Biology at Utah State University. I am hoping to submit my thesis by June 1, 2020.

The article “Non-sib Male Guarding Behavior Observed in *Triissolcus euschisti* (Hymenoptera: Scelionidae)” published in Matters Select (manuscript number 202004000005), of which I am first author, reports an essential component of my thesis research. I would like permission to reprint this article as a component of my thesis, which may require minor revisions (however, none are expected). Please note that Utah State University sends every thesis to ProQuest to be made available for reproduction.

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If you have any questions, feel free to contact me at the email address below. Thank you so much for your assistance!

Zachary Schumm  
zach.schumm@aggiemail.usu.edu

---

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Date: 05/19/2020  
Fee: -
Dear Zach Schumm,

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In case of any queries, please do not hesitate to contact me.

Thank you for your support with ScienceMatters.

Best regards,
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Regional Editorial Director

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March 20, 2020

To whom it may concern:

I, Mark Cody Holthouse, hereby grant my permission for the use of “Seasonal Development and Occurrence of Brown Marmorated Stink Bug in Utah,” of which I am a coauthor, in the thesis of Zachary R. Schumm

Sincerely,

Mark Cody Holthouse
Graduate Research Assistant, Utah State University
cody.holthouse@aggiemail.usu.edu; 530-306-2313
March 20, 2020

To whom it may concern:

I, Mark Cody Holthouse, hereby grant my permission for the use of “Non-sib Male Guarding Behavior in *Trissolcus euschisti* (Hymenoptera: Scelionidae): Novel Outbreeding in a Sib-mating System,” of which I am a coauthor, in the thesis of Zachary R. Schumm

Sincerely,

Mark Cody Holthouse Graduate Research Assistant, Utah State University
cody.holthouse@aggiemail.usu.edu; 530-306-2313
March 20, 2020

To whom it may concern:

I, Mark Cody Holthouse hereby grant my permission for the use of “Parasitoid Wasps of the Invasive Brown Marmorated Stink Bug in Utah,” of which I am a coauthor, in the thesis of Zachary R. Schumm

Sincerely,

Mark Cody Holthouse Graduate Research Assistant, Utah State University

[Email and phone number omitted]
March 20, 2020

To whom it may concern:

I, Mark Cody Holthouse, hereby grant my permission for the use of “Biological Control of the Invasive Brown Marmorated Stink Bug in Utah,” of which I am a coauthor, in the thesis of Zachary R. Schumm

Sincerely,

Mark Cody Holthouse Graduate Research Assistant, Utah State University

cody.holthouse@aggiemail.usu.edu; 530-306-2313
March 20, 2020

To whom it may concern:

I, ______________, hereby grant my permission for the use of “Parasitoid Wasps of the Invasive Brown Marmorated Stink Bug in Utah,” of which I am a coauthor, in the thesis of Zachary R. Schumm.

Sincerely,

Yota Mizuno
E-mail: s1710737@s.tsukuba.ac.jp
Phone number: +8190-9363-8885
To whom it may concern:

I, Elijah Talamas, hereby grant my permission for the use of “Surveys in northern Utah for egg parasitoids of Halyomorpha halys (Stål) (Hemiptera: Pentatomidae) detect Trissolcus japonicus (Ashmead) (Hymenoptera: Scelionidae)” of which I am a coauthor, in the thesis of Zachary R. Schumm, and in the dissertation of Mark Cody Holthouse.

Sincerely,

Elijah Talamas
Biological Scientist IV, Florida Department of Agriculture and Consumer Services
elijah.talamas@fdacs.gov; 352-305-4675
June 3, 2020

To whom it may concern:

I, Mark Cody Holthouse, hereby grant my permission for the use of “Surveys in northern Utah for egg parasitoids of Halycormorpha halys (Stål) (Hemiptera: Pentatomidae) detect Trissoicus japonicus (Ashmead) (Hymenoptera: Scelionidae)” of which I am first author, in the thesis of Zachary R. Schumm. Zach will be including this in the Appendix of his master’s thesis, while I will be including it in my PhD dissertation as a main chapter. Both individuals contributed a satisfactory amount to the work to be included in both documents.

Sincerely,

Mark Cody Holthouse
Graduate Research Assistant, Utah State University
cody.holthouse@aggiemail.usu.edu; 530-306-2313
Dear Mark,

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Best regards,

Vince

—

NB: Please be flexible with meeting requests as I’m juggling childcare due to school closures!

Dr. Vincent S. Smith, Head of Diversity & Informatics Division
Natural History Museum, Cromwell Road, London, SW7 5BD, UK
E-mail: vince@ysmith.info (preferred), Skype: vsmithuk, Tel: +44 (0) 207 942 5127
APPENDIX C

OVERWINTERING SUCCESS OF BROWN MARMORATED STINK BUG

(*Halyomorpha halys* STÅL) IN NORTHERN UTAH

Overview

We sought to determine and quantify the ability of BMSB to overwinter in the Utah natural landscape, as they are known to overwinter inside both human and natural structures, with a preference for buildings and homes. Utah experiences extremely cold winters with heavy snowfall. We therefore postulated that BMSB would not survive well in the natural landscape in northern Utah, and human structures would be the preferred and more acceptable overwintering habitat.

Methods

In Logan, Utah (a high-elevation city located in the northern part of the state), we placed diapause-ready adult BMSB males and females in six different overwintering habitats across two overwintering seasons (2017 – 2018 and 2018 – 2019) from just prior to the first frost (mid-October) to just after the (anticipated) last frost (mid-March). We included both natural structures and human structures for controls: ponderosa pine (*Pinus ponderosa*) bark, quaking aspen bark (*Populus tremuloides*), milkvetch (*Astragalus sp.*) seed pods, leaf litter, insulated attic, and uninsulated shed (Figure C-1). Cages were constructed to accommodate BMSB and prevent them from escaping in their specific habitats, including no-see-um mesh wrapped around tree bark and sealed with duct tape,
insulation foam and binder clips, sleeve cages with one open end surrounding milkvetch seed pods and sealed with a zip tie, and cube cages constructed of PVC pipe surrounded with no-see-um mesh for attic, shed, and leaf litter cages (attic and leaf litter cages: ~ 30 cm L X 30 cm W X 30 cm D; shed cages: ~ 20 cm L X 20 cm W X 10 cm D). 144 bugs were used during the 2017 – 2018 overwintering period, and each habitat was given four replicate enclosures of 6 BMSB (3 male and 3 female). During the 2018 – 2019 period, only 16 bugs were used, with four replicate cages of one male and one female being placed in the uninsulated shed and insulated attic environments.

**Results and Discussion**

Only 2 bugs survived across both years: one on pine bark, and one in leaf litter, thus providing no support for the hypothesis that BMSB would survive better in human structures (Table C-1). Because all but 2 bugs expired during the overwintering period across both years, we were unable to complete statistical analyses on data. We can overall conclude, however, that BMSB may not be able to overwinter well in specific regions of Utah that experience the harsh winter temperatures and weather extremes. If this experiment were repeated with more BMSB and in a slightly warmer location than Logan, Utah (e.g. in a central Utah location near Salt Lake City) where BMSB are already well established, we expect that survivorship of BMSB would increase substantially.
Table C-1. Number of BMSB exposed to different overwintering environments and proportion of BMSB that survived.

<table>
<thead>
<tr>
<th>Year</th>
<th>Habitat</th>
<th># Reps</th>
<th>Bugs / Rep</th>
<th>Total # Bugs</th>
<th>Total # Survived</th>
<th>Proportion Survived</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017 – 2018</td>
<td>Attic</td>
<td>4</td>
<td>6</td>
<td>24</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td>Shed</td>
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<td>6</td>
<td>24</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Pine Trunk</td>
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<td>6</td>
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<td>1</td>
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<tr>
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<td>Aspen Trunk</td>
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<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Milkvetch Pods</td>
<td>4</td>
<td>6</td>
<td>24</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Leaf Litter</td>
<td>4</td>
<td>6</td>
<td>24</td>
<td>1</td>
<td>0.04</td>
</tr>
<tr>
<td>2018 – 2019</td>
<td>Attic</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Shed</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure C-1. Photos of overwintering habitats and BMSB enclosures. Clockwise from top left: insulated attic, uninsulated shed, ponderosa pine trunk, quaking aspen trunk, milkvetch seed bods, and leaf litter.
APPENDIX D

EFFECTIVENESS OF *Trissolcus utahensis*, A NATIVE NATURAL ENEMY OF BROWN MARMORATED STINK BUG (*Halyomorpha halys* STÅL) IN UTAH

Overview

Native parasitoid wasps that parasitize stink bug eggs exist throughout North America. Utah has been unstudied in regards to presence and effectiveness of native parasitoid wasps at killing developing BMSB eggs. We conducted surveys to collect and identify parasitoid wasps attacking BMSB in Utah, and formed lab colonies of wasp species when able to test their effectiveness at killing BMSB.

Methods

BMSB sentinel egg mass deployment

Once daily, lab-reared cages of BMSB were checked for eggs, and masses were removed. Egg masses < 24 hr. old were utilized for sentinel egg mass deployment. Egg masses were usually laid on paper towel supplied in cages. We used scissors to carefully cut out a perimeter of paper towel around the egg mass, leaving ~4 mm of paper towel around each side of the egg mass. The egg masses and paper towel substrate were adhered to a 3 cm x 3 cm piece of white cardstock paper using permanent double-sided tape, with the tops of BMSB eggs facing out. We then used transparent, single-sided tape to tape down corners of exposed paper towel, securing the egg mass and paper towel substrate to the cardstock paper. Any remaining exposed double-sided tape was covered with fine-grain reptile sand.
The entire card with adhered BMSB egg masses were then clipped to the underside of leaves of various host plants in northern Utah, both in agricultural and ornamental landscapes (see chapter V for site and host plant details). Sentinel egg mass cards were left on the host plant for 24 – 72 hours. Upon collection, we placed cards in 47 mm clear, sealable petri dishes. Parasitoid wasps were often found parasitizing BMSB eggs at the time of collection. These wasps were collected, and lab colonies were initiated to run effectiveness tests on BMSB.

To begin colonies of native parasitoid wasps to be used for testing, we reared wasps brought in from the field on native stink bug eggs that were reared in the same manner as BMSB eggs for sentinel egg mass deployment. We were ultimately able to start a small lab colony of *Trissolus utahensis* to use for effectiveness trials against BMSB.

**Effectiveness Test**

To test effectiveness of *T. utahensis*, fresh (< 24 hr. old) BMSB egg masses were adhered to 1.5 cm x 5 cm piece of cardstock paper in the same manner as sentinel egg masses. The card, along with a single newly-emerged, mated *T. utahensis* female were then transferred to an 8-dram plastic snap-cap vial with a streak of honey on the underside of the lid to supply a food source for the wasp.

The female wasp was given 48 hours to parasitize the egg mass in an environmental chamber maintained at 23°C, 60% RH, and 16:8 light/dark photoperiod. After 48 hours, the female was transferred to an identical tube with a new BMSB egg mass, so that each wasp had two egg masses to parasitize for 48 hours each. Once the
wasp had the opportunity to parasitize two egg masses, it was added back to a stored colony of wasps for colony upkeep purposes.

We allowed parasitized egg masses to develop for four weeks, after which we counted the number of emerged stink bugs and wasps, and dissected each unemerged egg in each mass to determine the fate of each egg. We then calculated parasitism rate (number of parasitoids that were able to emerge), and BMSB survival rate (the number of BMSB that emerged vs. the total number of eggs on the egg mass). We were able to repeat this study with 20 *T. utahensis* females.

**Results and Discussion**

*T. utahensis* parasitoids were ultimately able to kill, on average, 89 percent of developing BMSB. Only 11 percent of BMSB survived and were able to emerge from the egg masses (Figure D-1). No wasps were able to complete development inside and emerge from BMSB eggs, indicating that BMSB eggs may not be a suitable host for *T. utahensis*. However, it appears that even if a parasitoid species cannot complete development and sustain populations in BMSB eggs, they may still be effective at killing developing BMSB. These results indicate that native parasitoid wasps may offer mild to moderate BMSB kill in the natural landscape, but their impact may be minimal as they cannot sustain populations using BMSB as a host.
Figure D-1. The effectiveness of *T. utahensis* at parasitizing BMSB eggs. Proportions are the mean percent BMSB kill and mean percent BMSB survivorship after stinging both egg masses.
APPENDIX E

SAMURAI WASP (Trissolcus japonicus ASHMEAD) DISCOVERED IN UTAH BY UTAH STATE UNIVERSITY

Description

Two BMSB egg masses were found on northern catalpa (Catalpa speciosa) leaves in Salt Lake City, Utah on June 17, 2019 (N40° 46’ 15.069” W111° 51’ 18.619”). These trees were in a managed urban landscape amidst residential homes. Both egg masses were found on separate trees planted approximately 9 meters apart from one another, and both egg masses were found approximately 2 meters above the ground. No guarding parasitoid wasps were seen at collection. Descriptions of individual egg masses are provided below. Three female wasps from egg mass # 2 were identified by Utah State University and sent to Elijah Talamas for confirmation. All wasps from egg mass # 1 were identified by Utah State University. A lab colony has been initiated from wasps emerged from egg mass # 2.

**Egg Mass 1**

# Eggs: 28

Appearance at collection: All eggs black

Fate: 28 *T. japonicus* emerged

**Egg Mass 2**

# Eggs: 27
Appearance at collection: 1 BMSB emerged; 5 eggs brown; 21 eggs black

Fate: 21 *T. japonicus* emerged

**Personnel**

Diane Alston, PhD

Lori Spears, PhD

Cody Holthouse (PhD Candidate)

Zach Schumm (MS Candidate)

Kate Richardson (lab technician)

James Withers (lab technician)

Erin Berdahl (extension intern / lab technician)

Stephanie Hall (lab technician)
APPENDIX F

SURVEYS IN NORTHERN UTAH FOR EGG PARASITOIDS OF *Halyomorpha halys* (STÅL) (HEMIPTERA: PENTATOMIDAE) DETECT *Trissolcus japonicus* (ASHMEAD) (HYMENOPTERA: SCELIONIDAE)\(^1,2\)

*Coauthored by Mark Cody Holthouse (first author) and Elijah Talamas

Abstract

The highly polyphagous and invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), has become a significant insect pest in North America since its detection in 1996. It was first documented in northern Utah in 2012 and reports of urban nuisance problems and plant damage have since increased. Biological control is the preferred solution to managing *H. halys* in North America and other invaded regions due to its alignment with integrated pest management and sustainable practices. Native and nonnative biological control agents have been assessed for efficacy, namely parasitoid wasps. *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) is an effective egg parasitoid of *H. halys* in its native range of southeast Asia and has recently been documented parasitizing *H. halys* eggs in North America and Europe. Field surveys for native and exotic egg parasitoids using wild (in situ) and lab-reared *H. halys* egg masses were conducted in suburban and agricultural sites in northern Utah from June to September 2017–2019. Seven native wasp species in the families Eupelmidae and Scelionidae were discovered guarding *H. halys* eggs, adult wasps from five of these species completed emergence. Native species had low mean rates of adult emergence.
from wild (0.5–3.8%) and lab-reared (0–0.4%) eggs. In 2019, an adventive population of
*T. japonicus* was discovered for the first time in Utah, emerging from wild *H. halys* eggs
at a mean rate of 16%. Our results support other studies that observed significant
biological control of *H. halys* from *T. japonicus*, and improved parasitoid wasp detection
with wild as compared to lab-reared *H. halys* egg masses.

**Keywords**

parasitoid wasp, stink bug, egg mass, biological control, integrated pest management

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1 Coauthored by Mark C. Holthouse (first author) and Elijah Talamas

2 We thank the Biodiversity Data Journal team for allowing the printing of this
manuscript in this thesis.
Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is a severe agricultural and urban nuisance pest that originates from southeast Asia (Hoebeke and Carter 2003) and has invaded numerous countries worldwide (Cesari et al. 2015, Gariepy et al. 2014, Haye et al. 2015b, Macavei et al. 2015, Milonas and Partsinevelos 2014, Vétek et al. 2014). As of 2019, it has been detected in 44 U.S. states and four Canadian provinces, with 11 states reporting severe agricultural damage (StopBMSB.org). *Halyomorpha halys* was first detected in Utah in 2012 and has been considered a pest to fruit and vegetable crops since 2017. With the threat of increasing economic agricultural damage, development of proactive management tactics is imperative. In the U.S. Mid-Atlantic region, where *H. halys* has been a severe pest, effective control has relied on broad spectrum insecticides, leading to resistance in several chemical classes and increased application frequency to crops (Lee et al. 2014, Leskey et al. 2012a, 2012b, 2014). Physical or cultural control (e.g., trap cropping and mass trapping) can offer some mitigation of plant damage but may not be economically viable (Mathews et al. 2017). The most effective management tactics have paired cultural and chemical tactics (e.g., orchard perimeter insecticide applications and treatment of trap trees) (Blaauw et al. 2014).

Biological control by egg parasitoids has proven effective in suppressing *H. halys* populations in its native range (Yang et al. 2009, Zhang et al. 2017). *Halyomorpha halys* sentinel egg mass surveys in North America have identified parasitism by native parasitoids in the families Scelionidae and Eupelmidae (Cornelius et al. 2016a, 2016b,
Talamas et al. 2015a, 2015b, Balusu et al. 2019). However, parasitism rates are low, likely due to inability of native species to overcome healthy *H. halys* egg defenses (Abram et al. 2014, 2017, Dieckhoff et al. 2017, Herlihy et al. 2016). Measuring native parasitoid effectiveness against *H. halys* eggs solely by wasp emergence may underestimate their impact, as partial development of a native wasp inside *H. halys* eggs can cause egg mortality (Abram et al. 2017, Cornelius et al. 2016b, Z. Schumm unpublished data). Therefore, evaluating native wasp parasitism rates, especially in novel landscapes where new behavior or species may be observed, deserves critical analysis.

*Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) is an egg parasitoid native to the home range of *H. halys* (Yang et al. 2009). Adventive populations of *T. japonicus* have been discovered emerging from *H. halys* egg masses in North America (Milnes et al. 2016, Talamas et al. 2015a) and Europe (Stahl et al. 2019, Sabbatini Peverieri et al. 2018). Research has assessed the effectiveness of these adventive populations against *H. halys* and a recent study in Washington state revealed parasitoid emergence rates reaching 77% (Milnes and Beers 2019). Conversely, initial parasitism of *H. halys* eggs by *T. japonicus* in Europe has been as low as 2% (Stahl et al. 2019). Interestingly, parasitism of *H. halys* eggs by *T. japonicus* in laboratory testing has revealed the potential for facultative hyperparasitism by a Palearctic egg parasitoid, *T. cultratus* (Mayr), presumably by diminishing natural egg defenses (Konopka et al. 2017).

*Trissolcus japonicus* has high specificity for *H. halys* but will also attack eggs of other pentatomids (Milnes and Beers 2019). Laboratory paired-host tests demonstrated significantly higher *T. japonicus* parasitism rates of *H. halys* over other stink bug species. However, no-choice tests documented *T. japonicus* readily parasitizing *Banasa dimidiata*
(Say) and Holcostethus abbreviatus Uhler (Hedstrom et al. 2017). Recent field tests in
the Pacific Northwest found significantly lower T. japonicus parasitism rates of native
stink bug egg masses (0.4–8%) compared to H. halys (77%) (Milnes and Beers 2019).
These findings suggest that although non-target effects occur, natural settings may
support more targeted control of H. halys by T. japonicus.

The primary objective of this study was to utilize H. halys egg mass surveys to
identify potential parasitoid species for suppression of this invasive insect pest in
northern Utah. Northern Utah provides novel geographic and environmental conditions
for detection of H. halys parasitoids as compared to other studies, most notably high
elevation (>1200m), arid sites with hot summer and cold winter climate (Herlihy et al.
Secondly, we compared parasitism rates of wild (in situ) versus lab-reared egg masses to
contribute to the understanding of effective survey approaches and projection of natural
parasitism rates in the field (Jones et al. 2014).

Materials and Methods

Survey Sites

Surveys for native and exotic parasitoid wasps of H. halys eggs in northern Utah
were conducted in the warmer summer months, June through September, in 2017, 2018,
and 2019. The surveys included a total of 17 field sites. Sites 1, 4, 5, 8, and 10–17 were
located in suburban landscapes containing mixed woody ornamental trees and shrubs.
Sites 2, 3, 6, 7, and 9 were in conventionally managed agricultural row crops and
orchards (Figure 1). Survey sites were chosen based on areas of established *H. halys* populations and preferred host plant availability (Tables 1 and 2).

**Stink Bug Colony**

*Halyomorpha halys* egg masses were reared in the Department of Biology at Utah State University, Logan, Utah. The colony was initiated and continuously supplemented from wild *H. halys* collections in northern Utah beginning in 2016, and further supplemented in 2019 by egg masses from a colony at the New Jersey Department of Agriculture. The lab colony was maintained at 25–28°C, 40–60% RH, with a 16:8 hr photoperiod. Fresh lab-reared egg masses were deployed within 24–48 hr post-oviposition. Egg masses were oviposited onto paper towels and attached to wax-covered cardstock (4x4 cm) using double-sided sticky tape with sand to cover excess adhesive.

**Survey Methods**

Cardstock cutouts were attached to the underside of plant leaves (Table 1) 2–3 m above the ground using metal safety pins, and collected approximately 48 hr after deployment. The number of lab-reared egg masses deployed each season was dependent on lab colony fecundity: 114, 93, and 28 in 2017, 2018, and 2019, respectively. Wild *H. halys* egg masses were identified through 30-min bouts of physical inspection of preferred host plants (Table 2). Each branch was inspected up to a height of 3 m using a step ladder. The number of wild egg masses identified in the survey was 5, 8, and 106 in 2017, 2018, and 2019, respectively. Wild egg masses were collected at the time of detection.
Upon collection, all egg masses were inspected for the presence of guarding parasitoid wasps. If present, wasps were collected with an aspirator (Carolina Scientific Supply Co. Burlington, NC) and placed into a 47 mm plastic petri dish (Fisher Scientific Co. L.L.C. Pittsburgh, PA) with the associated egg mass to allow for further oviposition during transport to the lab in a cooler at ambient temperature, 15.5–24°C.

In the lab, egg masses were stored under the same conditions as the *H. halys* colony described above. Guarding female wasps were removed upon arrival to the lab, preserved in ethanol, and later pinned for identification. Incubating egg masses were observed for the presence of hatched, parasitized (emerged parasitoid wasp), missing, or predated eggs (e.g., chewing or sucking damage) approximately one week after collection, following procedures established by Ogburn et al. (2016). Egg masses were observed again six weeks after collection to identify late-emerging wasps or those with partially developed wasps within eggs (Stahl et al. 2019). Wasp species were identified using the keys to Nearctic *Trissolcus* (Talamas et al. 2015b), Nearctic *Telenomus* (Johnson 1984), and Nearctic *Anastatus* (Burks 1967).

**Statistical Methods**

Parasitism (percent eggs producing adult wasps) was compared among years and egg mass types with a generalized linear model and a quasi-binomial distribution to account for over-dispersion, (R version 3.6.1; R Core Team, 2019), using packages *car* (Fox and Weisberg 2019) and *emmeans* (Lenth 2019). The alpha level was set to 0.05.
Results

Over the three year survey period, a total of 39 individuals from five native parasitoid wasp species were found emerging from six wild and five lab-reared *H. halys* egg masses. The species *Anastatus mirabilis* (Walsh & Riley), *A. pearsalli* Ashmead, *A. reduvii* Ashmead, *Trissolcus eushisti* (Ashmead), and *T. hullensis* (Harrington) were documented from both guarding females and successful emergence from *H. halys* egg masses (Figure 2). *Trissolcus utahensis* (Ashmead) and *Telenomus podisi* Ashmead were observed guarding *H. halys* eggs, but were not documented to successfully emerge as adults. *Catalpa speciosa* (Warder), *Malus domestica* Borkh, and *Prunus persica* (L.) Batsch were the only plant species on which lab-reared egg masses were parasitized, and this parasitism by native wasp species exclusively (Table 1). In June 2019, the Asian parasitoid *T. japonicus* was first discovered in Utah emerging from two wild *H. halys* egg masses at site one in Salt Lake City (Figures 1–3). *Trissolcus japonicus* was detected consistently from June through September, 2019, with 452 wasps emerging from 21 wild egg masses (Figure 2). Parasitized wild egg masses were collected on two tree species, *C. speciosa* and *Acer grandidentatum* Nutt, with attack by *T. japonicus* occurring only on *C. speciosa* and accounting for 16% of all parasitism in 2019 (Table 2).

When native wasp species successfully emerged from *H. halys* eggs, the mean number of parasitized eggs per affected egg mass was low. In 2019, the mean egg parasitism rate per mass for *T. japonicus* was 78.5%. Also in 2019, a group of 19 wild egg masses experienced a mean parasitism rate of 67.3%. However, the parasitoids had already emerged and their identity is unknown (Figure 2).
Mean parasitoid emergence from lab-reared egg masses was 0.39 and 0.06% in 2017 and 2018, with no wasps emerging in 2019. Mean parasitoid emergence rates from wild collected egg masses in 2017, 2018, and 2019 were 2.85, 3.81, and 28.1%, respectively (Figure 4). The generalized linear model did not reveal a significant two-way interaction between year and egg type (P>0.05; F2,348=1.6349). Significantly more wasps emerged from wild than lab-reared egg masses (P<0.05; F1,348= 9.4984). There were no significant differences in mean wasp emergence among years (P>0.05; F2,348= 0.2267) (Figure 4).

**Discussion**

Surveys of wild and lab-reared *H. halys* eggs in northern Utah demonstrated relatively high diversity of native parasitoid wasps (five species), but these exhibited parasitism rates of less than 4% in a given year. These findings are congruent with other North American surveys of *H. halys* egg parasitoids (Dieckhoff et al. 2017, Abram et al. 2019). Low native parasitism rates could be caused by deterrence from natural chemical defenses on and within *H. halys* eggs, or a lack of effective venom at the time of female oviposition needed for successful wasp development in the exotic host egg (Haye et al. 2015a, Tognon et al. 2016). Other research suggests that using parasitism (i.e., the complete emergence of adult wasps) as a metric of native parasitoid effectiveness underestimates native wasp effects on *H. halys* eggs, as unmerged or partially developed wasps often kill the stink bug host (Cornelius et al. 2016b, Z. Schumm unpublished data). Although our egg dissections revealed many unhatched *H. halys* eggs with undifferentiated contents, the ultimate cause of egg death could not be ascertained and no
partially developed wasps were found in our \textit{H. halys} egg mass inspections following field collection.

Our results support those of Jones et al. (2014) who found that wild (\textit{in situ}) egg masses more accurately detect the presence and ability of parasitoid wasps to emerge from \textit{H. halys} eggs when compared to field-deployed lab-reared egg masses. These results may be due to a variety of factors, including age of the egg mass upon deployment, egg mass exposure to field conditions, or deployment height of egg masses in host trees. Hedstrom et al. (2017) noted the importance of semiochemical cues associated with the success of \textit{T. japonicus} in finding and stinging \textit{H. halys} egg masses. Therefore, lower parasitism rates of lab-reared egg masses could be due to chemical contamination during transport or effects from lab rearing conditions. However, this question cannot be adequately addressed within the bounds of this study.

Our results indicate that the exotic \textit{T. japonicus} has the potential to provide biological control of \textit{H. halys} in northern Utah. Although current parasitism rates provided by \textit{T. japonicus} in northern Utah are modest relative to those in its native range (Yang et al. 2009, Zhang et al. 2017). Parasitism rates were not statistically different among years, but our data clearly show higher parasitism in 2019, when \textit{T. japonicus} was discovered. The dissonance of biological and statistical conclusions in our results is likely due to the varying, and in some cases, quite low, sample size of egg masses within a year. \textit{Trissolcus japonicus} may have killed more \textit{H. halys} eggs than we were able to document based on identification of the causal wasp. Indeed, many egg masses were attacked by “unknown” parasitoids in 2019, with higher mean parasitism rates in affected egg masses
than observed for native wasp species, suggesting that at least some of the “unkowns” were *T. japonicus*.

The northern Utah region differs in its climate and topography from most locations in which *T. japonicus* has been documented or predicted to become established in North America (Avila and Charles 2018). Given the arid, high elevation conditions of northern Utah that include cold winters and hot summers, the detection of an adventive *T. japonicus* population implies novel range expansion into the greater Intermountain West region. These results support the possibility of an eventual intersection of eastern and western *T. japonicus* populations in North America (Jarrett et al. 2019; Milnes et al. 2016, Talamas et al. 2015a). Further research should focus on the capacity of *T. japonicus* to persist in the Intermountain West, specifically data on overwintering behavior where heavy snow fall accumulation and consistent sub-zero temperatures occur (Lowenstein et al. 2019, Nystrom Santacruz et al. 2017). Laboratory rearing and wild releases, in conjunction with conservation efforts, are critical next steps in supporting the future establishment of *T. japonicus* populations in Utah.

**Conclusions**

Our findings show that an adventive population of *T. japonicus* in northern Utah is causing greater mortality of *H. halys* eggs compared to native wasp species, and wild (*in situ*) egg masses provide a more accurate measure of parasitoid activity compared to those deployed from lab colonies. This study reports the first establishment of *T. japonicus* in the Intermountain West, a novel geographic location for this parasitoid in North America.
Acknowledgements

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[https://doi.org/10.1653/024.097.0211](https://doi.org/10.1653/024.097.0211)


https://doi.org/10.11646/zootaxa.3780.1.8


Table F-1. Parasitism of fresh lab-reared *H. halys* egg masses by plant species in northern Utah from June through September 2017–2019. Percent parasitism is the proportion of parasitized eggs based on total egg numbers.

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Total Egg Masses (Eggs)</th>
<th>Parasitized Egg Masses (Eggs)</th>
<th>% Egg Parasitism*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acer negundo</td>
<td>13 (311)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Ailanthus altissima</td>
<td>7 (187)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Catalpa speciosa</td>
<td>62 (1503)</td>
<td>1 (5)</td>
<td>0.33</td>
</tr>
<tr>
<td>Cercis canadensis</td>
<td>19 (474)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Elaeagnus angustifolia</td>
<td>5 (137)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Helianthus annuus</td>
<td>1 (25)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Malus domestica</td>
<td>48 (1099)</td>
<td>1 (1)</td>
<td>0.09</td>
</tr>
<tr>
<td>Malus sp.</td>
<td>6 (122)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Prunus armeniaca</td>
<td>11 (277)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Prunus cerasus</td>
<td>12 (298)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Prunus domestica</td>
<td>3 (83)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Prunus persica</td>
<td>17 (453)</td>
<td>3 (7)</td>
<td>1.54</td>
</tr>
<tr>
<td>Robinia pseudoacacia</td>
<td>3 (73)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Sambucus sp.</td>
<td>6 (168)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
<tr>
<td>Zea mays</td>
<td>22 (559)</td>
<td>0 (0)</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*Parasitism by native wasp species only; *Trissolcus japonicus* was not detected in lab-reared eggs.

Table F-2. Parasitism of wild *H. halys* egg masses by plant species deployment site and year in northern Utah from June through September 2017–2019. Percent parasitism is the number of parasitized eggs divided by the total number of eggs.

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Total Egg Masses (Eggs)</th>
<th>Parasitized Egg Masses (Eggs)</th>
<th>Total % Egg Parasitism</th>
<th>% Egg Parasitism by <em>T. japonicus</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acer grandidentatum</td>
<td>2018 1 (22)</td>
<td>1 (1)</td>
<td>4.55</td>
<td>0.00</td>
</tr>
<tr>
<td>Catalpa speciosa</td>
<td>2017 4 (108)</td>
<td>1 (4)</td>
<td>3.70</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>2018 6 (164)</td>
<td>1 (7)</td>
<td>4.30</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>2019 105 (2791)</td>
<td>41 (796)</td>
<td>28.5</td>
<td>16.2</td>
</tr>
<tr>
<td>Prunus cerasus</td>
<td>2018 1 (28)</td>
<td>0 (0)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>2019 1 (28)</td>
<td>0 (0)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Zea mays</td>
<td>2017 1 (28)</td>
<td>0 (0)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure F-1. Blue dots indicate deployment and collection sites of lab-reared and wild egg masses in northern Utah, 2017-2019. *Trissolcus japonicus* was discovered at site 1. Geographical coordinates are as follows: site 1: 40°46'14.8"N, 111°51'18.6"W; site 2: 41°3'36.899"N, 112°0'46.944"W; site 3: 41°45'48.39"N, 111°48'46.148"W; site 4: 41°44'11.685"N, 111°49'14.446"W; site 5: 41°43'41.968"N, 111°49'4.005"W; site 6: 41°11'9.164"N, 112°2'25.368"W; site 7: 41°1'18.787"N, 111°55'59.663"W; site 8
40°16'07.6"N, 111°39'20.7"W; site 9: 41°01'12.2"N, 111°55'49.4"W; site 10: 40°59'44.2"N, 111°53'09.8"W; site 11: 40°45'08.2"N, 111°52'25.2"W; site 12: 41°44'32.9"N, 111°48'32.8"W; site 13: 41°03'37.0"N, 111°58'13.8"W; site 14: 40°46'03.3"N, 111°49'27.5"W; site 15: 41°01'13.1"N, 111°56'12.9"W; site 16: 40°46'23.0"N, 111°52'07.3"W; site 17: 40°46'49.3"N, 111°53'46.5"W.

Figure F-2. Percent parasitism (+SE) of eggs within wild and lab-reared egg masses exhibiting adult wasp emergence in northern Utah, 2017–2019. Sample size (n) represents the number of egg masses parasitized by the indicated wasp species in each year. Bars without standard error lines represent single egg masses. The “Unknown” species category represents egg masses in which parasitoid wasp emergence was confirmed, but no wasp specimens remained to confirm species identification.
Figure F-3. Photo of female *Trissolcus japonicus* (FSCA 00090662), found in Salt Lake City, site 1, on June 17, 2019. Key identifying characters include the episternal foveae occurring in a continuous line from the postacetabular sulcus to the mesopleural pit.
Figure F-4. Percent parasitism (±SE) of lab-reared and wild eggs collected in northern Utah, 2017–2019. Different letters above bars indicate significance between egg types. Sample size (n) represents the number of egg masses collected. No parasitoid wasp emergence occurred in lab-reared egg masses in 2019.
APPENDIX G

PARASITOID WASPS OF THE INVASIVE BROWN MARMORATED STINK BUG

IN UTAH (UTAH PEDEST FACT SHEET PUBLISHED VERSION)

Parasitoid Wasps of the Invasive Brown Marmorated Stink Bug in Utah

Zachary R. Schumm, Mark Cody-Holthouse, Yota Mineo, Diane G. Altom, Lori R. Spears

The brown marmorated stink bug (BMSB), *Halyomorpha halys* Stål, is an invasive agricultural and nuisance pest native to eastern Asia. It was first confirmed in the U.S. in Allentown, PA in 1996 and has since spread to 44 U.S. states, many of which have now experienced economic crop damage from this pest (Fig. 1). In Utah, BMSB is now established in five counties: Box Elder, Weber, Davis, Salt Lake, and Uinta, and has been detected in Cache and Kane counties. While crop damage to peaches, apples, squash, and popcorn has been identified, it is currently causing mostly nuisance problems due to overwintering bugs on and inside human structures.

Adult BMSB are marked brown and black, camouflaging well with woody vegetation. To separate this species from native look-alikes, notice the characteristic white band on their antennae. Native species do not have this feature. BMSB also has smooth shoulders and a black/white pattern on the edge of the abdomen (Fig. 2).

BMSB is a successful invader for many reasons: it is polyphagous (feeds on many plant types), highly mobile, has few natural enemies, and adults have a tough exoskeleton that is covered in a waxy, water-repellent cuticle that helps protect them from pesticide applications. Biological control, through the use of egg parasitoids, is the most suitable option for long-term management of BMSB.

Fig. 1. A BMSB with quick identification characteristics: The white bands on dark antennae is the most helpful feature.

Fig. 2. A BMSB with quick identification characteristics: The white bands on dark antennae is the most helpful feature.

General Parasitoid Information

There are at least two families of stink bug parasitoids in Utah: Eupelmidae and Scolioidea. These are small, typically black wasps that may be mistaken for small gnats or ants. They will fly in search of stink bug egg masses. Once they find the eggs, they will sting them, depositing one of their own eggs into the stink bug egg. The wasp egg will hatch, and the larva will feed and develop within the stink bug egg, effectively killing the host. The adult wasp will emerge a couple of weeks later.
The Eupelmids attacking BMSB are all generalist parasitoids, meaning that they stig the eggs of a wide variety of insects. Native parasitoids in this group are moderately successful at stinging and developing inside BMSB eggs, but are unlikely to control BMSB populations due to their generalist nature.

The second family, Scelionidae, includes some stink bug specialists, meaning they only sting stink bug eggs. Specialists are more promising as a control agent for BMSB. Although many of the native Scelionid species will sting BMSB eggs, some will not develop into an adult and emerge. Those that can complete development within BMSB eggs have the potential to be more effective control agents.

Stink bug eggs are usually bright in color (Fig. 3) and take 5 to 7 days to develop and hatch. Eggs will develop a triangular egg "buster" shortly before stink bugs emerge from the egg (Fig. 4). However, if parasitized by a wasp, the eggs will turn dark brown or black after about a week. As the wasps develop, the eggs will continue to darken until the adult wasps emerge about 14 days later (Fig. 3).

There is usually a skewed sex ratio in emerging wasps. In a typical stink bug egg mass that consists of 1-20 eggs, one to three wasps will be male, and the rest will be female. Male wasps will emerge first and wait for the females to emerge. Once mated, the females fly off in search of new egg masses to sting.

**Parasitoid Wasp Families in Utah**

**Eupelmidae - Generalist Egg Parasitoids**

Eupelmids are small (1-5 mm), slender wasps that are generalist egg parasitoids. One genus, *Anastatus*, will parasitize BMSB, as well as other stink bugs and insects. They can resemble ants at first glance. Females often have a white band or white triangles on the wings. There are three species of *Anastatus* known to attack BMSB in Utah (Table 1). When seen on a stink bug egg mass, a general rule is that these wasps are much larger than an individual egg (Fig. 5).

Females are typically larger than males, and under direct light can exhibit brown, green, or blue iridescence. Males are typically all black, smaller (< 4 mm), and lack wing patterns making males indistinguishable to species without a microscope.

**Scelionidae - Specialist Egg Parasitoids**

Scelionids are very small (1-2 mm), but often robust wasps that are specialists on different insect groups (Fig. 7). One genus within this family, *Tridiocus*, only stings stink bug eggs. The wasps attacking BMSB can only be identified to species by using microscopes.
Table 5.1: Parasitoid wasp species found in Utah as of April 2019 from egg mass and yellow sticky card deployments. *Based on results to-date from surveys in Utah.

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Family</th>
<th>Collection Method</th>
<th>Actual Size</th>
<th>Can Emerge from BMSE?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anastatus rafaelis</td>
<td>Eupelmidae</td>
<td>BMSE Eggs</td>
<td>—</td>
<td>Yes*</td>
</tr>
<tr>
<td>Anastatus paracalci</td>
<td>Eupelmidae</td>
<td>BMSE Eggs</td>
<td>—</td>
<td>Yes*</td>
</tr>
<tr>
<td>Anastatus nakajimai</td>
<td>Eupelmidae</td>
<td>BMSE Eggs</td>
<td>—</td>
<td>Yes*</td>
</tr>
<tr>
<td>Telamorini palusii</td>
<td>Scelionidae</td>
<td>BMSE Eggs / Sticky Cards</td>
<td>—</td>
<td>No*</td>
</tr>
<tr>
<td>Trissolcus auratus</td>
<td>Scelionidae</td>
<td>BMSE Eggs / Sticky Cards</td>
<td>—</td>
<td>No*</td>
</tr>
<tr>
<td>Trissolcus australis</td>
<td>Scelionidae</td>
<td>BMSE Eggs / Sticky Cards</td>
<td>—</td>
<td>Yes*</td>
</tr>
<tr>
<td>Trissolcus bellulus</td>
<td>Scelionidae</td>
<td>BMSE Eggs / Sticky Cards</td>
<td>—</td>
<td>Yes*</td>
</tr>
<tr>
<td>Trissolcus penmaae</td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
<td>—</td>
<td>Unknown</td>
</tr>
<tr>
<td>Trissolcus phylane</td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
<td>—</td>
<td>Unknown</td>
</tr>
<tr>
<td>Trissolcus stakens</td>
<td>Scelionidae</td>
<td>Sticky Cards</td>
<td>—</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

as they are entirely black, small, and lack wing patterns or other characteristics to separate them with the naked eye. However, they can be generally identified in the field to family or genus using the tool that they are as small as or smaller than a stink bug egg (Fig. 8). There are at least two genera of stink bug parasites in the family Scelionidae in Utah (Trissolcus and Telamorini), with at least eight different species between these two genera (Table 1).

Surveys are ongoing for other species of parasitoid wasps in Utah, particularly Trissolcus japonicus (samurai wasp) (Fig. 9). This wasp is native to eastern Asia, the native range of BMSE. In its native range, BMSE causes minimal economic damage, presumably due to effective biological control by the samurai wasp.

Samurai wasp was collected in China and is undergoing host range testing in U.S. quarantine facilities to assess non-target effects for release in the U.S. However, samurai wasp has arrived on its own to the U.S. It has been found in 12 states as of January 2019 (Maryland, Pennsylvania, New Jersey, New York, Delaware, Oregon, Ohio, Virginia, West Virginia, Michigan, California, and Washington).

If samurai wasp is found in Utah, it can be reared and redistributed throughout the state to contribute to biological control of BMSE. Until samurai wasp is located in Utah, its release is prohibited.

Samurai wasp is more likely to be found in areas where BMSE are abundant (urban areas of Salt Lake and Utah valleys). However, it could be found in any location with established BMSE populations, making widespread surveys highly valuable.

Fig. 5.8. The samurai wasp (Trissolcus japonicus), a highly effective parasitoid against BMSE, first been found in 12 U.S. states.

Methods used to survey for stink bug parasitoids include physical placement of stink bug egg masses on host plants in the field, finding naturally-laid stink bug egg masses laid directly on host plants, and deployment of yellow sticky cards.

**Physical Egg Mass Placement:**

Lab-reared stink bug eggs are attached to small squares of cardboard paper. These cards are then clipped to the underside of leaves on common hosts of stink bugs in Utah (fruit trees, vegetables, and ornamental trees such as southern catalpa (Catalpa speciosa)) (Fig. 10). Cards are left for 3 to 4 days to attract parasitoids. When collecting cards, parasitoids guarding the eggs are also collected to further assess their efficacy in stinging and developing in eggs.

**SURVEYING FOR PARASITOIDS**

[Fig. 5.9: Parasitoid wasp on an egg mass. Notice that the wasp is about the size of an egg.]

[Fig. 5.10: A BMSE egg mass clipped to a card to attract parasitoid wasps.]
Finding Naturally-laid Egg Masses:

Stink bug egg masses can be found on the underside of leaves, on the fruiting structures, and occasionally on the stems of host plants (Fig. 11). Just as with deployed egg masses, parasitoids guarding the egg masses are collected to assess efficacy in killing and developing in stink bug eggs.

If You See a Parasitoid Wasp:

If you see a wasp on an egg mass, be mindful that it is beneficial for your garden/crops, as the wasps are potentially killing the stink bugs that would normally emerge and begin eating your plants. You can choose to either leave the stink bug eggs and parasitoids on the plant (preferred) or choose to remove the stink bug eggs from the plant and freeze or destroy them before they hatch.

It is possible that if the parasitoid wasps are left on the egg masses, then you may end up with more wasps, and consequently fewer stink bugs negatively impacting your plants. Parasitoids that are known to attack BMSB eggs in Utah can be seen in Figure 13.

REPORT PARASITOID WASPS

Reports of stink bug egg masses with parasitoid wasps on them are invaluable to protect all Utah communities and property owners, and could help find new wasp species that may assist with biological control of BMSB. USU Extension has created a Report an Invasive Pest in Utah website to report a finding, upload a photo, and find contact information for submitting a specimen for identification. Collect the egg mass and wasp in a bag or sealable container for specimen submission.
Fig. 5-14. A map of the current survey sites and parasitoid recovery locations in Utah through September, 2018.
ADDITIONAL RESOURCES


*Stephensbug*  
A comprehensive website on BMSB identification, management, and new research.


PHOTO CREDITS

1 Map courtesy of Stephensbug  
2 Image courtesy of JeffHoffinger, USDA-ARS  
3 Image courtesy of Zach Schumm, Utah State University  
4 Image courtesy of Rutgers New Jersey Agricultural Experiment Station  
5 Image courtesy of Ashley Jones, University of Maryland  
6 Image courtesy of John Rosenthal, bugjunkie.net  
7 Image courtesy of John Rosenthal, bugjunkie.net  
8 Image courtesy of Elizabeth Bean, Washington State University  
9 Image courtesy of Eliza J. Talman, USDA ARS  
10 Image courtesy of Zach Schumm, Utah State University  
11 Image courtesy of Zach Hoffhouse, Utah State University  
12 Image courtesy of Zach Schumm, Utah State University  
13 Image courtesy of Cody Hoffhouse and Zach Schumm, Utah State University  
14 Map courtesy of Zach Schumm, Utah State University

FUNDING

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Seasonal Development and Occurrence of Brown Marmorated Stink Bug in Utah

Successful control or management of any insect pest is dependent on an accurate understanding of when the pest is most vulnerable. Phenology, or the seasonal timing of development, helps us to understand how to prevent and respond to potential pest damage, including the invasive brown marmorated stink bug (BMSB, Halyomorpha halys). BMSB has become an overwhelming pest in many U.S. states, feeding on hundreds of different host plants and adapting to a wide array of climatic conditions.

In Utah, BMSB has slowly built its population size since its discovery in 2012, with highest concentrations in and around urban and suburban neighborhoods. BMSB is commonly found on many ornamental shrubs and trees, especially catalpa. The first reports of BMSB damaging crop plants in Utah occurred in 2017 on apple, peach, corn, and squash. In 2018, field research showed that BMSB was also able to feed on tart cherry and cause significant damage to the early season fruit stage, though this damage has not yet been reported outside of experimental conditions.

USU researchers have been focused on understanding BMSB development throughout the year given the cold, hot, and high elevation conditions in Utah. Generally, BMSB adults can be found May through September on a variety of different host plants. The adults are known to emerge from their overwintering shelter in April, but testing is ongoing to narrow down the start and peak emergence dates.

Females reach sexual maturity within two weeks of emerging, which means egg production starts...
Seasonal Development and Occurrence of the Invasive BMSB, continued

in early to mid-May and can continue through September. They lay eggs in masses of roughly 28, and a single female can produce an average of 224 eggs in her lifetime. Nymphs are first present in June and then reach peak numbers in mid-July. Adult BMSB numbers peak in early July, with a second peak occurring in late September. Population spikes can have real significance for susceptible agricultural crops that ripen in July.

It had been thought that BMSB was limited to a single adult generation in Utah each season, but more recently, we suspect that there is actually a second adult generation that occurs just before the end of September. A second generation could mean more feeding and subsequent damage than was first anticipated for the intermountain West. Thus far, only a partial second generation has been observed in field testing in Utah.

As with any invasive pest, continual monitoring of BMSB will be of utmost importance as management strategies are developed. To learn more about BMSB, consult the Utah State University fact sheets Brown Marmorated Stink Bug and Brown Marmorated Stink Bug Management for Fruits and Vegetables in Utah.

Mark Cody Holthouse and Zachary Schumma (USU Biology Graduate Students), Lori Spars (Invasive Species Specialist), and Diana Allon (Entomologist)

For more information:

See usafacts.usu.edu/crops/bmsb-host-plants for a current listing of known host plants in Utah

Entomology News and Information

Biological Control of Brown Marmorated Stink Bug

Brown marmorated stink bug (BMSB, Halyomorpha halys) is an invasive economic and nuisance pest native to eastern Asia that invaded the United States in the late 1990’s. In Utah, BMSB is established in five counties (Box Elder, Davis, Salt Lake, Utah, and Weber), and has been detected in Cache and Kane counties. It feeds on a variety of Utah’s agricultural commodities and ornamental plants, making it a potential economic concern as populations spread and establish.

BMSB is challenging to manage with insecticides due to its harshness and mobility. Researchers are surveying for and testing the effectiveness of natural and exotic enemies of BMSB to reduce populations.

In USU studies, cards containing BMSB egg masses were clipped to foliage of stink bug host plants. On this egg mass, a small parasitoid wasp is stinging the eggs.

At USU, researchers are surveying for natural enemies of BMSB with artificially-placed stink bug egg masses.

continued on next page

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and yellow sticky cards. A suite of natural enemies have been identified; some of these are under efficacy testing against BMSB eggs in the lab. From these findings, generalist egg predators (e.g. earwigs, lacewings, and katydids) are relatively low in abundance and are not effective, especially in the agricultural landscape. Parasitoid wasps of stink bug eggs are more abundant and diverse. They lay eggs inside a stink bug egg, and the immature wasp feeds on the host egg before emerging as an adult wasp about two weeks later.

We have identified five wasp species that have been able to sting, develop, and emerge inside BMSB eggs in Utah. Three are in the family Eupelmidae and are generalist parasitoids that sting many types of insect eggs: Anastatus mirabilis, A. paralis, and A. radialis. Two are in the family Scelionidae and specialize only on stink bug eggs: Trissolcus auratus, and T. fulvus. Unfortunately, none of these species have shown high efficacy, with only 3-18% of wasps completing development and emergence as adults.

We have additionally tested the efficacy of a parasitoid wasp species native to Utah, Trissolcus uraethes, and found it was able to sting and kill nearly 89% of developing stink bug eggs in the lab. However, the immature wasps were unable to develop properly inside BMSB eggs. Like T. uraethes, most or all native parasitoid wasps will sting and kill the developing stink bugs within the eggs at a moderate to high success rate, but will not complete development into adult wasps, making them inefficient control agents for BMSB.

The samurai wasp (Trissolcus japonicus), a wasp native to the homelands of BMSB in eastern Asia, is a highly effective parasitoid at both killing and developing within BMSB eggs, and is a promising biological control agent for BMSB in the U.S. This wasp was originally kept in U.S. quarantine facilities to undergo testing to confirm its effectiveness and ensure that it does not harm native, beneficial stink bug species. However, wild populations began to appear in 2014, and populations have now been found in twelve states (Maryland, Pennsylvania, New Jersey, New York, Delaware, Oregon, Ohio, Virginia, West Virginia, Michigan, California, and Washington). Surveys for biological control agents in Utah are focused on finding this particular parasitoid species. Once it is detected in Utah, redistribution efforts will likely be approved to assist with controlling BMSB populations. Surveys for this wasp will be continuing in Cache, Box Elder, Weber, Davis, Salt Lake, and Utah counties.

*Based on current surveys in Utah

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Zachary Schumm and Mark Cody Holthouse (USU Biology Graduate Students), Lori Spears (Invasive Species Specialist), and Diane Alston (Entomologist)
APPENDIX I
CURRICULUM VITAE

Zachary R. Schumm
(443)-617-7327; zach.schumm@aggiemail.usu.edu

EDUCATION

MSc  Utah State University
June 2020
Department of Biology
MS Biology / Ecology (plus extension outreach)
Advisors: Diane Alston, PhD and Lori Spears, PhD

BSc  University of Delaware
May 2016
Department of Entomology and Wildlife Ecology
BS Entomology; BS Wildlife Ecology & Conservation

PUBLICATIONS (* = extension, † = abstracts, ‡ = article)


*Holthouse, M. C., Spears, L. R., Schumm, Z. R., and Alston, D. G. 2019. The samurai wasp brings new hope in the fight against brown marmorated stink bug in Utah (1 pp.). Utah State University Extension Fact Sheet, Logan, UT.


SEMINARS AND EXTNSION PRESENTATIONS (* = presenter)


POSTER PRESENTATIONS (* = presenter, † = award honored)


### COURSE TEACHING EXPERIENCE (*=regularly scheduled, †=guest lecture)

**2020*** General Biology II Lab  
Utah State University  
3 sections / 69 students  
Hypothesis-based ecological experimentation

**2019*** General Biology I Lab  
Utah State University  
3 sections / 60 students  
4.6 / 5 average instructor evaluation score  
Discovery-based molecular projects (DNA / PCR)

**2019†** Elements of Entomology  
Utah State University  
2 guest lectures / 48 students  
Guest lecture on Arachnida biology and identification

### SCHOOL PROGRAMS TEACHING EXPERIENCE

**2011 – Present** Owner, Sole Proprietorship  
SchumBug; Zach’s Nature Gallery  
- Developed and implemented environmental education programs focused on insects and their relatives
- Designed and set up educational displays to teach all ages and backgrounds on the importance of insects and their relatives
- Kept a professional-grade collection of live and preserved insects and arachnids (6,000+ preserved; 40+ live)
- Communicated to diverse groups as large as 200 (pre-k to adult)
- Created lasting relationships with prestigious institutions such as Delaware Museum of Natural History and Port Discovery Children’s Museum
- Youngest speaker ever invited to speak at Towson University Saturday Morning Science Program
- Programs paused during master’s program

2012 – 2015 **Educator and Programmer**  
*Wildlife Adventures, LLC*  
- Taught and developed wildlife educational programs  
- Managed volunteers and other employees  
- Cared for animals utilized for educational programs  
- Safely transported animals of all types (mammal, bird, reptile, invertebrate, rodents, amphibians)  
- Set up educational displays for museums and camps  
- Safely assisted the general public and school groups on proper handling and treatment of animals and wildlife  
- Assisted with nature themed summer camps for children

### FUNDING

2019 **Capital and Support Fund**  
$1848.15  
*Grant-style application to acquire funding for Utah State University Entomology Club*

### AWARDS AND HONORS (* = nominee, † = awarded)

2019* **Master’s researcher of the year (nominee)**  
*Department of Biology, Utah State University*
2019† First Place Academic Poster
   Entomological Society of America
   St. Louis, MO

2019† Dr. Leslie Paxton Barker Travel Award
   Department of Biology, Utah State University

2019† Graduate Enhancement Award
   Utah State University
   Community involvement and leadership

2019† Graduate Enhancement Award
   Utah State University
   Community involvement and leadership

2018† Third Place Academic Poster
   Entomological Society of America
   Reno, NV

2016† Department Chair’s Award
   University of Delaware, Entomology & Wildlife Ecology
   Departmental involvement during undergrad program

2014 - 2016† Dean’s List
   University of Delaware
   4 semesters

2012 - 2016† George M. Worrilow Agricultural Scholarship
   University of Delaware

2012† Harford County Environmental Scholarship
   Harford County, MD

2012† Charlie Riley Community Service Scholarship
   Harford County, MD

2012† President’s Volunteer Service Award
   United States Office of the President

2006† Mimi Baklor Memorial Volunteer of the Year Award
   Kennedy Krieger Institute
OUTREACH AND COMMUNITY INVOLVEMENT

2019  Utah State University Biology Grad Student Association
      30+ events; 4,500+ attendees
      Developed outreach activities related to biological sciences
      Increased outreach event attendance by over 100%

2017 – 2018  Utah State University Entomology Club
      40+ events; 7,000+ attendees
      Developed entomology teaching activities and classes
      Increased outreach attendance by over 200%
      Increased fundraising by over 400%

2012 – 2016  Entomology Club at University of Delaware
      Developed outreach activities
      15,000+ Outreach event attendance
      Increased fundraising by over 50%

2012 – 2016  University of Delaware The Wildlife Society Student Chapter
      Assisted with outreach events
      Gave seminar talks

LEADERSHIP ROLES

2019  Biology Grad Student Association Outreach Chair
      Utah State University
      Elected by peers

2018 – 2019  President – Entomology Club
      Utah State University
      Elected by peers

2017 – 2018  Science Outreach Coordinator – Entomology Club
      Utah State University
      Elected by peers

2015 – 2016  Ag Ambassador Coordinator
      University of Delaware College of Ag. and Natural Resources
      Elected by administrators and peers

2013 – 2016  Ag Ambassador
      University of Delaware College of Ag. and Natural Resources
Selected by administrators

2014 – 2016  President; Zookeeper – Entomology Club
University of Delaware
Elected by peers

2013 – 2014  Treasurer – Entomology Club
University of Delaware
Elected by Peers

PROFESSIONAL AFFILIATIONS

2018 – Present  Member
Entomological Society of America

CERTIFICATIONS

2016  Biosafety level 2 quarantine
USDA ARS
Newark, DE

EMPLOYMENT

2014 – 2017  Research Assistant
USDA ARS Beneficial Insects Lab (BIIRU), Newark, DE
- Researched the invasive brown marmorated stink bug
- Reared stink bug colonies
- Set up experiments on invasive insect biological control
- Propagated all needed plants in a greenhouse setting
- Reared parasitoid wasps for biological control program
- Conducted field surveys and collections for stink bugs
- Surveyed for natural enemies of invasive insects
- Data management and statistical analyses
- Trained employees

2014 – 2016  Collection Assistant
University of Delaware Department of Entomology & Wildlife
- Databased insect specimens into an online database
- Utilized google earth to georeferenced specimens
- Repaired and stored insect specimens appropriately
- Organized Smithsonian Institution planthoppers
- Confirmed and updated species nomenclatures
- Trained new technicians

2012 – 2015  Educator and Programmer
Wildlife Adventures, LLC
- Taught and developed wildlife educational programs
- Managed volunteers and other employees
- Cared for animals utilized for educational programs
- Safely transported animals of all types (mammal, bird, reptile, invertebrate, rodents, amphibians)
- Set up educational displays for museums and camps
- Safely assisted the general public and school groups on proper handling and treatment of animals and wildlife
- Assisted with nature themed summer camps for children

BUSINESS OWNERSHIP

2011 – Present  Owner, Sole Proprietorship
SchumBug; Zach’s Nature Gallery
- Developed and implemented environmental education programs focused on insects and their relatives
- Designed and set up educational displays to teach all ages and backgrounds on the importance of insects and their relatives
- Kept a professional-grade collection of live and preserved insects and arachnids
- Communicated to groups as large as 200
- Created lasting relationships with prestigious institutions such as Delaware Museum of Natural History and Port Discovery Children’s Museum
- Youngest speaker ever invited to speak at Towson University Saturday Morning Science Program

MAJOR SKILLS AND COMPETENCIES
- Science communication to diverse audiences
- Course / extension class development and implementation (Wildlife, entomology, life, and general biological sciences)

- Arthropod family identification (200+ by sight)

- Insect sampling, collecting, storing, and preservation

- Adobe Suite (Indesign, Illustrator, and some Photoshop)

- Greenhouse management (pest and disease management)

- Budget management

- Database and website management

- Management and hiring of employees

- ArcGIS and ArcMap (See examples of created maps [here](#))

- GPS, compass, and map use

- Plant identification (150+ to genus or higher)

- Bird identification (100+ by sight or sound to family or higher)

- Mammal identification (100+ to family or higher by sight or skeleton)

- Vegetation data collection

- Coding experience (R preferred)

- Computer software (All MS programs)

- Mist netting and Tomahawk trap usage

- Photography (landscape, wildlife, and microscope)

- Ability to work long hours in extreme conditions (heat, cold, rain, etc.)

- Ability to drive 15+ hours without fatigue

- Woodworking and carpentry (power tools)

- Ability to not lose chap stick (current streak at 17 in a row!)
Courses Taken (credit hours)

Entomology (19 credit hours)
- Insect taxonomy (plus lab)
- Insect ecology and conservation
- Insect field taxonomy (lab course)
- Insect anatomy and physiology (plus lab)
- Intro to entomology
- Entomology laboratory
- Apiology and apiculture (plus lab)

Wildlife Ecology (36 credit hours)
- Wildlife conservation and ecology
- Conservation biology
- Wildlife management
- Advanced conservation biology
- Wildlife habitat management (plus lab)
- Mammalogy (plus lab)
- Wildlife policy and administration
- Ornithology (plus lab)
- Wildlife research techniques (plus lab)
- Biogeography
- Tropical biodiversity conservation (Abroad: Costa Rica)
- Debates in conservation biology (Abroad: Costa Rica)

Statistics (16 credit hours)
- Basic statistical practice
- Design of Experiments
- Design and Analysis of Ecological Research
- Intro to data analysis
- Economics of Agriculture and natural resources

Communication and Writing (9 credit hours)
- Oral communication
- Technical writing
- Intro to voice and speech

Mapping and Geospatial Analysis (6 credit hours)
- Intro to GIS
- Advanced GIS and spatial analysis (see work here)

Plants and Soils (10 credit hours)
- Botany (plus lab)
- Intro to soil science
- Indigenous woody plants (plus lab)

**Miscellaneous (12 credit hours)**
- Biogeography
- Principles of animal and plant genetics
- Evolution
- Photographic approaches

* Transcripts of all academic courses are available