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Host Plant Use, Phenology, and Biological Control of the Brown Marmorated Stink Bug (Hemiptera: Pentatomidae; *Halymorpha halys*) in Northern Utah

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HOST PLANT USE, PHENOLOGY, AND BIOLOGICAL CONTROL OF THE

BROWN MARMORATED STINK BUG (HEMIPTERA: PENTATOMIDAE;

Halyomorpha halys) IN NORTHERN UTAH

by

Mark Cody Holthouse

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ABSTRACT

Host Plant Use, Phenology, and Biological Control of the Brown Marmorated Stink Bug

(Hemiptera: Pentatomidae; *Halyomorpha halys*) in Northern Utah

by

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Major Professor: Dr. Diane G. Alston
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The invasive and polyphagous brown marmorated stink bug [*Halyomorpha halys* (Stål)] has become an urban nuisance and severe agricultural pest in North America since its initial detection in 1996. In 2012, it was detected in Salt Lake City, Utah and has since become established in urban landscapes along the Wasatch Front. In 2017, *H. halys* feeding damage on specialty fruit and vegetable crops was documented for the first time in Utah. To mitigate potential threats to Utah agriculture by *H. halys*, my research focused on the invasive ecology of *H. halys* in the unique high elevation, arid, and extreme temperature environment of northern Utah.

In chapter II, the many different species of plants associated with the egg, nymph, and adult life stages of *H. halys* in Utah are documented, including several novel host plant associations for North America. *Catalpa speciosa* (Warder), was found to be the most important host for all life stages and will act as an important host for future monitoring and management efforts in the Intermountain West.

In chapter III, I discuss the phenology of *H. halys* in northern Utah, indicating when major life stages are observed, and how established phenology models for this species can track key life stage events. Through controlled field observations, it was determined that *H. halys* is primarily univoltine in northern Utah, with potential for a partial second generation.

Chapter IV highlights the discovery of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) and other native parasitoid wasp species documented guarding or emerging from lab-reared and wild *H. halys* egg masses in northern Utah. Additionally, parasitoid wasps with potential for suppression of *H. halys* were surveyed using yellow and blue sticky cards (Chapter V). In this chapter, I explore the use of blue cards as a viable alternative to the commonly used yellow cards to detect target parasitoids while attracting fewer bycatch species that can reduce efficiency of card processing.

Overall, these research chapters will enable more accurate and efficient management efforts of *H. halys* in Utah should pest populations persist into the future.

(198 pages)

PUBLIC ABSTRACT

Host Plant Use, Phenology, and Biological Control of the Brown Marmorated Stink Bug (Hemiptera: Pentatomidae; *Halyomorpha halys*) in Northern Utah

Mark Cody Holthouse

The invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), has become a significant agricultural and urban nuisance pest in North America, causing millions of dollars of damage to specialty fruit and vegetable crops over the past two decades. This pest uses over 170 host plant species in North America and is difficult to control with most conventional insecticides. Following the establishment of *H. halys* in Utah in 2012, this dissertation explores the plant host species, seasonal development, and biological control agents found in the unique climate conditions of the Intermountain West. Chapter II documents important plant species utilized by each *H. halys* life stage (eggs, nymphs, and adults) in urban landscapes in Utah. *Catalpa speciosa* (Warder) was found to be a sentinel host for *H. halys*, as the vast majority of eggs, nymphs, and adults were found on this tree host. Chapter III discusses *H. halys* phenology, the timing of seasonal development and degree-day requirements in northern Utah. These data show that a spring photoperiod plays a critical role in initiating overwintering adult activity and that *H. halys* is primarily univoltine, producing a single generation, with the possibility of a partial second generation. Chapter IV documented native and exotic parasitoid wasp species found attacking *H. halys* eggs in Utah, and most notably documents the discovery of adventive *Trissolcus japonicus* (Ashmead) populations on wild egg masses in Salt Lake City in 2019. Finally, chapter V discussed the efficacy of blue and yellow sticky cards in monitoring for target parasitoid wasps of *H. halys*. It was found that yellow cards

are more attractive to parasitoids than blue, but that blue cards captured similar target species in fewer numbers, while also capturing far less bycatch (non-target species) than yellow cards. Therefore, blue cards can be used as an alternative to classically used yellow cards to effectively monitor for target parasitoids of *H. halys* and save on processing time due to less bycatch.

Ultimately, this research provides foundational data on the ecology of *H. halys* in northern Utah, allowing for more effective future monitoring, management, and research of this pest in the future.

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Mark Cody Holthouse

CONTENTS

Page

Abstract iii

Public Abstract v

Acknowledgments vii

List Of Tables xiii

List Of Figures xv

Chapter I Introduction: Host Plant Use, Phenology, And Biological Control Of The Brown Marmorated Stink Bug (Hemiptera: Petatomdae; *Halyomorpha halys*) In Northern Utah 1

- Background and Pest Status of *Halyomorpha halys* in Utah 1
- Host Plant Use and Establishment 2
- Phenology 4
- Biological Control 6

Chapter II Urban Host Plant Utilization By The Invasive *Halyomorpha halys* (Stål) (Hemiptera, Pentatomidae) In Northern Utah 22

- Abstract 22
- Introduction 24
- Materials and Methods 26
- Results 27
- Discussion 29
- Conclusion 34
- Acknowledgments 34
- References 35
- Tables and Figures 41

Chapter III Phenology And Voltinism Of The Invasive *Halyomorpha halys* (Stål) In Northern Utah 51

- Abstract 51

1. Introduction 53
2. Materials and Methods 55
3. Results 599
4. Discussion 655
Funding 69
Acknowledgments 69
References 70

Chapter IV Surveys In Northern Utah For Egg Parasitoids Of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) Detect *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) 76

Abstract 76
Introduction 78
Materials and Methods 80
Results 83
Discussion 84
Conclusions 87
Acknowledgements 87
References 88
Tables and Figures 98

Chapter V Comparison of Yellow and Blue Sticky Cards for Detection and Monitoring Parasitoid Wasps of the Invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) 104

Abstract 104
Introduction 106
Materials and Methods 107
Results 111
Discussion 114
Acknowledgements 119
References 120
Tables and Figures 133

Chaper VI Summary and Conclusions 143

Appendices..149

Appendix A Authorship and Citations of Published Chapters 150
Appendix B Letters of Permission...151
Appendix C Brown Marmorated Stink Bug [*Halyomorpha halys* (Stål)] (Utah Pests Fact Sheet Published Version)...156
Appendix D Common Stink Bug of Utah (Utah Pests Fact Sheet Published Version)...164
Appendix E Utah Pests Newsletter..172
APPENDIX F Curriculum Vitae 177

LIST OF TABLES

Page

Table 2-1. Mean number of *H. halys* egg masses (E), nymphs (N), and adults (A) present per sample* of plant species during surveys in northern Utah, 2017 and 2018........41

Table 2-2. Plant species without *H. halys* detections during surveys in northern Utah, 2017 and 2018........44

Table 2-3. Additional *H. halys* host plant species documented in northern Utah, but extramural to the surveys in this study, 2017–2020........47

Table 3-1. Seasonal trap deployment locations in northern Utah by site number and County........56

Table 3-2. Accumulated degree days after the critical spring photoperiod of 13.5 h for key *H. halys* life stages and events by year........60

Table 4-1. Number of deployed and parasitised fresh lab-reared *H. halys* egg masses by native wasps on multiple plant species in northern Utah from June through September, 2017–2019........98

Table 4-2. Number of deployed and parasitised wild *H. halys* egg masses by all wasps, native and exotic, on multiple plant species in northern Utah from June through September, 2017–2019........99

Table 4-3. Mean parasitism of lab-reared and wild egg masses collected in northern Utah, 2017–2019........100

Table 5-1**.** The number of target parasitoid wasps by genus captured on blue and yellow sticky cards in urban, orchard, and vegetable landscapes in 2019 and 2020 combined........134

Table 5-2**.** The number of *Trissolcus* spp. identified on blue and yellow sticky cards in urban, orchard, and vegetable landscapes in 2019 and 2020 combined. 135

Table 5-3. Results from the linear mixed effects model for mean target parasitoids by sticky card color, landscape, deployment period, and subsequent interactions in 2019 and 2020..136

Table 5-4. Results from the linear mixed effects model of mean Diptera and non-target Hymenoptera by sticky card color, landscape type, deployment period, and subsequent interactions in 2019 and 2020. 137

Table 5-5. Mean ($\bar{x}$) and standard error (± SE) of Diptera and non-target Hymenoptera captured in 2019 listed by color and deployment period 138

LIST OF FIGURES

Page

Figure 1-1. Map of *H. halys* (colored states) and *T. japonicus* (colored points) distribution in the U.S. and Canada 16

Figure 1-2. *H. halys* feeding damage on peach. 17

Figure 1-3. *H. halys* feeding damage on apple 18

Figure 1-4. *H. halys* feeding damage on popcorn 19

Figure 1-5. From left to right are the three *H. halys* traps used in this dissertation research: Pherocon® dual funnel tube trap by Trécé Inc., Dead-Inn pyramid trap by AgBio Inc., and Pherocon® Dual panel clear sticky trap by Trécé Inc. 20

Figure 1-6. Photo of praying mantid consuming adult *H. halys* in Salt Lake City, Utah 21

Figure 2-1. Map of 17 host plant survey sites in northern Utah, 2017 and 2018 48

Figure 2-2. Total number of *H. halys* per life stage observed during plant surveys in northern Utah from May through September, 2017 (top row) and 2018 (bottom row) 49

Figure 2-3. The total number of *H. halys* detected at survey sites in 2017 (top left) and 2018 (bottom left) 50

Figure 3-1. Number of *H. halys* adults and nymphs captured in traps *n*=15 (left y-axis), and cumulative degree days (right y-axis) over time in 2017 (A) and 2018 (B) 59

Figure 3-2. Total number of *H. halys* adults and nymphs captured in pyramid traps *n*=8 (left y-axis), and cumulative degree days (right y-axis) over time in 2019 (A) and 2020 (B). 62

Figure 3-3. Number of *H. halys* by developmental life stage in 2018 on catalpa (A) and tart cherry (B) 63

Figure 3-4. Total number of *H. halys* by developmental life stage in 2019 on peach (A), tart charry (B), catalpa (C), catalpa transitioned to peach (D), and tart cherry transitioned to peach (E) 65

Figure 4-1. Blue dots indicate deployment and collection sites of lab-reared and wild egg masses in northern Utah, 2017-2019. *Trissolcus japonicus* was discovered at Sites 1 and 17 101

Figure 4-2. Percent parasitism (± SE) of eggs in wild and lab-reared egg masses with adult wasp emergence in northern Utah, 2017–2019 102

Figure 4-3. Photo of female *Trissolcus japonicus* (FSCA 00090662), found in Salt Lake City, Site 1, on 17 June 2019 103

Figure 5-1. Interactions for card color (yellow and blue) by deployment period (14±1-d intervals late May to September) for mean number of target parasitoid wasps (± SE) in 2019 (A) ($P < 0.001$) and 2020 (B) ($P = 0.06$) 133

Figure 5-2. Interactions for card color (yellow and blue) by landscape type (urban, orchard, and vegetable) for mean number of target parasitoid wasps (± SE) captured from May to September 2019 (A) and 2020 (B). 133

Figure 5-3. **(A)** Interactions for card color and deployment period (14±1-d intervals late May to September) for the mean number of Diptera and non-target Hymenoptera (± SE) bycatch in 2020. **(B)** Card color by landscape type (urban, orchard, and vegetable) interactions for mean number of Diptera and non-target Hymenoptera (± SE) captured from May to September 2020. **(C)** Landscape type by deployment period interaction for the mean number of Diptera and non-target Hymenoptera (± SE) in 2020 133

Figure 5-4. Blue (left) and yellow (right) sticky cards collected from the same site 14 days after deployment 133

CHAPTER I

INTRODUCTION: HOST PLANT USE, PHENOLOGY, AND BIOLOGICAL CONTROL OF THE BROWN MARMORATED STINK BUG (HEMIPTERA: PENTATOMIDAE; *Halyomorpha halys*) IN NORTHERN UTAH

Background and Pest Status of *Halyomorpha halys* in Utah

Halyomorpha halys (Stål), native to eastern Asia, is a recent invasive insect to North America. It was first detected in North America in Allentown, Pennsylvania in 1996. Since then, it has become a severe urban nuisance and agricultural pest in many parts of North America, including four Canadian provinces and 47 states (Figure. 1-1). As a generalist herbivore, *H. halys* takes advantage of a broad range of plants and inhabits diverse eco-regions (Hoebeke and Carter 2003, Holthouse et al. 2021).

This pest was first detected in Utah in 2012 and is now established in six counties (Box Elder, Cache, Davis, Salt Lake, Utah, and Weber) with detection in two other counties (Carbon, and Kane). At present, *H. halys* remains primarily a nuisance pest in urban areas along the Wasatch Front, and Salt Lake and Utah counties host the bulk of Utah's *H. halys* populations. Early establishment has been primarily on ornamental trees (mainly *Catalpa speciosa* (Warder)) and shrubs. However, in 2016, it was detected in several commercial peach orchards, marking its first detection in agricultural crops in Utah, with subsequent damage to peach, apple, popcorn, and squash documented in 2017. Research on the threat of *H. halys* feeding to tart cherry, an economically important tree fruit crop in northern Utah, demonstrated that feeding of F0 adults between petal fall and fruit pit hardening can lead to high levels of fruit abscission; however, later season feeding injury resulted in minimal reductions in fruit quality as fruits are utilized for processing rather than fresh-market products (Schumm et al. 2020). *Halyomorpha halys* populations are established in suburban and urban landscapes along the western foothills of northern Utah's Wasatch Front mountain range which are within close proximity to much of the state's specialty fruit and vegetable crops. Although *H. halys* is a minor agricultural pest in Utah to-date, its continued monitoring and injury assessment are critical given its relatively young invasion status in the state.

Host Plant Use and Establishment

Halyomorpha halys is a successful invasive herbivore pest in the U.S. due to its polyphagous feeding behavior. It uses more than 300 host plants in its native range of eastern Asia, from trees and shrubs to smaller herbaceous plants (Bergmann et al. 2016, Nielsen and Hamilton 2009). In North America, *H. halys* has been documented on over 170 species of plants (Holthouse et al. 2021, Leskey and Nielsen 2018, Rice et al. 2014). Tree fruits, vegetables, row crops, and ornamentals with fruits or seedpods are common hosts (Lee et al. 2013, Yu and Zhang 2007).

In the U.S., *H. halys* has invaded in a progressive manner, first establishing in urban areas, utilizing human structures for overwintering sites, and then progressing into rural and agricultural areas with attractive host plants. In the eastern U.S. specifically, *H. halys* was first detected in urban and residential areas and within three years began expanding into forest, agricultural, and wetland sites (Acebes 2016).

The west coast of the U.S. saw initial detection of *H. halys* in urban areas of California in 2002 (Lara et al. 2016), followed by Oregon and Washington in 2004 (Sparks 2014; Milnes et al. 2016). Since then, BMSB has become an agricutlral pest for a variety of crops in these states (Beers et al. 2019, Mohekar et al. 2016, Rijal and Gyawaly 2018, Sparks 2014, Wiman et al. 2015).

A similar urban-agriculture progression has been observed for *H. halys* in Utah, though populations in agricultural landscapes to-date are still relatively low. Niche expansion of *H. halys* in the mid-Atlantic region from introduction in the mid-1990s to significant economic damage beginning in 2008 suggests about a decade delay in establishment and spread (Hoebeke and Carter 2003, Leskey and Hamilton 2014). In 2010, an outbreak of *H. halys* caused a $37 million loss of apple production in mid-Atlantic states (Herrick 2011). It has now been 9 years since the initial invasion of *H. halys* into Utah, so the next few years will likely indicate its long term role and agricultural pest status in the state.

To-date, *H. halys* can be found on over 60 host plants in Utah, most of which are ornamental trees and shrubs, mainly in urban areas. These species are currently listed at the Utah Pests website (Holthouse et al. 2017). As previously mentioned, *H. halys* has been found on plants of agricultural significance in Utah, causing feeding damage to apple, peach, popcorn, and squash (Figures. 1-2–4).

Phenology

Halyomorpha halys is adapted to exploiting diverse habitats and is considered a plant pest during most of its life cycle (Nielsen and Hamilton 2009). It has five nymphal instars leading to a mature adult stage (Bergmann et al. 2016). First instar nymphs rely solely on their egg casings for nourishment. All other life stages use stylet-like mouthparts to harvest sap from fruiting bodies, seeds, and vegetative structures of host plants from spring to fall (Bergmann et al. 2016, Rice et al. 2014). In the fall, adults congregate in response to a male-produced aggregation pheromone; fall diapause is initiated by several key environmental factors, including photoperiod and temperature. Adults prefer to aggregate in cracks and crevices of buildings, on and within human-built structures, and under the bark of damaged and dead trees to avoid cold temperatures. During the winter, they remain in reproductive diapause until spring or until their fat body reserves are depleted (Lee et al. 2013). Adult aggregation facilitates mating opportunities and overwintering survival (Weber et al. 2014; Harris et al. 2015). Little is currently known about *H. halys* seasonal phenology in Utah's arid, high elevation environment, such as the number of generations per season and when winter diapause is initiated and terminated.

Developmental rate, voltinism, and overwintering behaviors of *H. halys* are correlated with latitude and geographical parameters (Zhu et al. 2012). The phenology models refined by Nielsen et al. (2008), show that *H. halys* requires 537.6 degree-days (DD) to develop from egg to imaginal ecdysis, and another 147.7 DD for adult females to reach sexual maturity (this information is taken from New Jersey and Pennsylvania with an optimal reproductive temperature of 25°C and lower and upper developmental temperature thresholds of 14.2°C and 35.8°C). Recent research has shown *H. halys* physiology, particularly diapause initiation and cessation, is largely dependent on photoperiod (Nielsen et al. 2016, Nielsen et al. 2017, Watanabe 1979).

Halyomorpha halys voltinism in its native home range of Asia is variable, but is generally limited to one (univoltine) or two (bivoltine) generations in Japan, Korea, and China; however, there can be as many as 4-6 generations in southern China (reviewed by Lee et al. 2013, Hoffmann 1931). In North America, *H. halys* is generally bivoltine in southern latitudes and univoltine in more northern latitudes (Ingles and Daane 2018, Nielsen and Hamilton 2009, Nielsen et al. 2016). Given the DD requirement for complete adult development, we assume that *H. halys* is most likely univoltine in northern Utah, but this has not yet been confirmed. Observation of nymphs attracted to traps in fall may indicate the potential for a second generation (F2). The cold winters, high elevation, and low humidity are likely factors in limiting *H. halys* growth rate. Data on the phenology, or timing and progression of development in relation to seasonal cycles, has not yet been formally determined for *H. halys* in Utah.

Traps using the attractant *H. halys* pheromone combination of (3S,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol, (3R,6S,7R,10S)-10, 11-epoxy-1-bisabolen-3-ol, and synergist Methyl (E,E,Z)-2,4,6-decatrienoate (MDT), commonly known as the Trécé Dual Lure (Trécé Inc., Adair, OK), have provided effective seasonal monitoring of *H. halys* phenology (Acebes-Doria et al. 2018, Ingles and Daane 2018, Leskey and Nielsen 2018). Traps can effectively support monitoring programs for growers and pest managers without relying on active, visual observations of host plants which are less efficient and time-consuming. Several trap types are available for *H. halys*, some of the more commonly used types have included the Dead-Inn pyramid trap (AgBio Inc., Westminster, CO), the Pherocon® Trécé sticky dual panel adhesive trap (Trécé Inc., Adair, OK), and the Pherocon® Trécé dual funnel tube trap (Trécé Inc., Adair, OK) (Figure. 1-5) (Acebes-Doria et al. 2018, Alston et al. 2019, Ingles and Daane 2018, Rice et al. 2018, Schumm et al. 2021).

Biological Control

Halyomorpha halys is a challenging insect to manage with insecticides due to its stylet mouthparts that pierce and suck (avoiding contact with insecticides) and tolerance to several chemical classes. Synthetic pyrethroids and neonicotinoids have been the most effective insecticide classes used against this pest; however, these insecticides can disrupt integrated pest management programs by killing natural enemies and causing secondary pest outbreaks (Gill et al. 2011, Leskey et al. 2012, Tooker 2012). Additionally, there are few options for chemical treatments in some habitats, such as inside buildings, and in home gardens and urban landscapes. To promote less reliance on insecticides, interest has grown in identifying natural enemies effective in killing *H. halys* in its native and invaded ranges (Dieckhoff et al. 2017, Leskey and Nielsen et al. 2018, Morrison et al. 2016, Talamas et al. 2015ab).

Generalist predators have been observed attacking *H. halys* life stages, including praying mantis (Figure. 1-6), assassin bug, robber fly, ground beetle, earwig, and several species of spiders (Morrison et al. 2016, Rice et al. 2014). Though more specific, or targeted biological controls will likely be most effective in limiting *H. halys* population expansion (Cornelius et al. 2016, Lee et al. 2013), generalist predators in the Intermountain West likely provide significant population suppression. Microorganisms, such as microsporidia, can also provide control of *H. halys*. According to Hajek et al. (2017), a new species of mircrosporidia (*Nosema maddoxi* Becnel, Solter, Hajek, Huang, Sanscrainte, & Estep) is associated with recent collapse of *H. halys* lab colonies, and has been detected in *H. halys* and green stink bug (*Chinavia hilaris* (Say)) wild populations in several regions of North America.

In its native home range of eastern Asia, *H. halys* egg masses are attacked by several species of parasitoid wasps (Dieckhoff et al. 2017, Lee et al. 2013, Rice et al. 2014, Yang et al. 2009). For example, in Chinese pear orchards, *Trissolcus flavipes* (Thomon) (now described as *T. japonicus* Ashmead (Hymenoptera: Scelionidae),) and *Telenomus mitsukurii* (Ashmead) caused *H. halys* egg parasitism rates of 63.3% and 84.7%, respectively (Yu and Zhang 2007).

Initially, U.S. entomologists thought that *H. halys* arrived without natural enemies, contributing to its status as an extreme agricultural and urban pest. Recently however, adventive populations of the samurai wasp, *T. japonicus*, have been detected attacking *H. halys* eggs in over ten states in the U.S. (Figure. 1-1) (Milnes et al. 2016, Talamas et al. 2015a, Jarrett et al. 2017). Research on *T. japonicus* has generated excitement in its prospects to provide effective biological control of *H. halys* (Dieckhoff et al. 2017, Talamas et al. 2015a). Interestingly, *T. japonicus* may also provide indirect control of *H. halys* by enabling hyper-parasitism by native *Trissolcus* species not able to exploit *H. halys* on their own, as was found for *Trissolcus cultratus* (Mayr) in

Switzerland (Konopka et al. 2016). For these reasons, *T. japonicus* offers an exciting prospect in the North American struggle against *H. halys*. Unfortunately, there can be negative consequences to native stink bug species from the newly established populations of *T. japonicus* (Hepler et al. 2020); however, field surveys in Washington State have shown that *T. japonicus* most often prefers *H. halys* eggs over native stink bug species (Milnes and Beers 2019).

Biological control efforts remain a core component of the nearly global fight against *H. halys*, and may be of major significance in the management of *H. halys* in Utah. To-date, *T. japonicus* is established in Davis, Salt Lake, and Utah counties and shows consistently high rates of *H. halys* egg mass parasitism.

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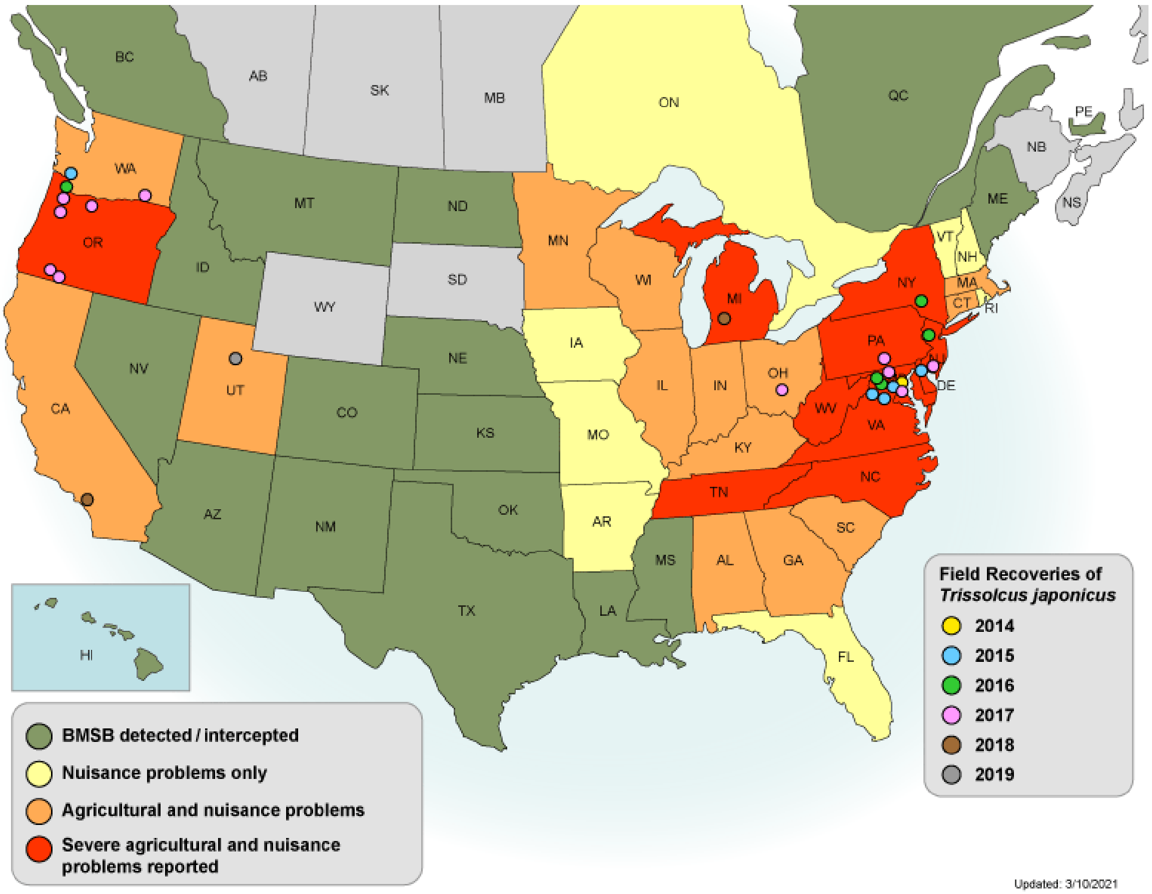

Figure 1-1. Map of *H. halys* (colored states) and *T. japonicus* (colored points) distribution in the U.S. and Canada (Updated 3/10/2021, https://www.stopbmsb.org/biological-control/samurai-wasp-trissolcus-japonicus/).

Figure 1-2. *H. halys* feeding damage on peach. Photo by Lori Spears, Utah State University.

Figure 1-3. *H. halys* feeding damage on apple. Photo by Marion Murray. Utah State University.

Figure 1-4. *H. halys* feeding damage on popcorn. Photos by Cami Cannon. Utah State University.

Figure 1-5. From left to right are the three *H. halys* traps used in this dissertation research: Pherocon® dual funnel tube trap by Trécé Inc., Dead-Inn pyramid trap by AgBio Inc., and Pherocon® Dual panel clear sticky trap by Trécé Inc. All traps are baited with Pherocon® BMSB dual dure by Trécé Inc. The lures are composed of two rubber components, and can be seen in the left and right photos. (Dual funnel trap photo by Greg Krawczyk, Pennsylvania State University, and the other two remaining photos by Mark Holthouse).

Figure 1-6. Photo of praying mantid consuming adult *H. halys* in Salt Lake City, Utah. Photo by Erin Petrizzo.

CHAPTER II

URBAN HOST PLANT UTILIZATION BY THE INVASIVE *Halyomorpha halys* (Stål) (HEMIPTERA, PETATOMIDAE) IN NORTHERN UTAH[1,2]

Abstract

The invasive and highly polyphagous brown marmorated stink bug, *Halyomorpha halys* (Stål), is a severe agricultural and urban nuisance pest in North America. Since its initial invasion into Utah in 2012, *H. halys* has become well established in urban and suburban locations along the western foothills of the Wasatch Front in northern Utah. Bordering the Great Basin Desert, this area is unique from other North American locations with *H. halys* due to its high elevation (> 1200 m), aridity (30-year mean RH = 53.1%; dew point = -1.9°C), and extreme temperatures (the 30-year mean minimum and maximum in January and July in Salt Lake City range from -3.1 to 3.6°C and 20.3 to 32.4°C). To document which plant species harbor *H. halys*, surveys were conducted in 17 urban/suburban sites in four counties during 2017 and 2018. *Halyomorpha halys* was more abundant in Salt Lake and Utah counties than in the more northern counties of Davis and Weber, and was found on 53 plant species, nine of which hosted two or more developmental stages in both years. The majority of hosts were in the families Fabaceae, Rosaceae, and Sapindaceae. Northern catalpa, *Catalpa speciosa* (Warder), was the most consistent host, supporting a majority of *H. halys* detections in all life stages; thus we identify it as a sentinel host. Twenty-nine species were novel hosts for *H. halys* in North America; of these, *Acer ginnala* Maxim, *Populus tremuloides* Michx., *Prunus armeniaca* X *domestica* 'Flavor King', and *Prunus virginiana* 'Schubert' were detected with two or more life stages of *H. halys* in both years. Peak populations of *H. halys* occurred from mid-June to mid-September. We describe *H. halys* plant utilization by life stage and seasonal period to aid future detection and management of this invasive insect in the greater Intermountain West region.

Keywords

Brown marmorated stink bug, *Catalpa speciosa*, host plant, Intermountain West, sentinel host, survey

[1] We thank the journal NeoBiota, by Pensoft, for allowing the reprinting of this publication in this dissertation

[2] Coauthored by Lori R. Spears and Diane G. Alston

Introduction

Native to Asia, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) has become an urban nuisance and severe agricultural pest in many parts of the world (Gariepy et al. 2014, Haye et al. 2015, Hoebeke and Carter 2003, Leskey et al. 2012, Macavei et al. 2015, Maistrello et al. 2016). In North America, *H. halys* has been detected in 46 U.S. states and four Canadian provinces and observed on over 170 plant species, including a wide variety of ornamental trees, woody shrubs, vegetables, row crops, and specialty fruit crops (StopBMSB.org, Haye et al. 2015). Research shows that optimal development is achieved when *H. halys* has access to multiple host species, especially those with both foliage and reproductive structures present (Acebes-Doria et al. 2016). Documentation of preferred *H. halys* hosts and plant communities is critical to studying its dispersal into novel geographic regions, such as Utah. Plant surveys for *H. halys* and other polyphagous invasive species have documented ornamental hosts and unmanaged wooded areas near suburban regions as critical in initial population establishment (Bakken et al. 2015, Branco et al. 2019). Urban and suburban areas also offer overwintering sites for *H. halys* in human-made structures, especially in areas with low winter temperatures, heavy snow accumulation, and few natural overwintering sites (e.g., dead tree stands) (Lee et al. 2014).

In northern Utah, surveys in 2017 and 2018 were initiated to document plant species harboring *H. halys* egg mass, nymph, and adult life stages, and their seasonal occurrence. Surveys were conducted along the urbanized western foothills of the Wasatch Front, which is considered part of the greater Rocky Mountain Range and stretches 258 km south from the Idaho border to central Utah. Approximately 80% of Utah's human population lives within 25 km of the Wasatch Range, creating a band of urban and suburban sprawl between the western mountain foothills and the eastern edge of the Great Basin desert where much of Utah's vegetable and fruit crop production occurs (data.census.gov, nass.usda.gov). Established urban populations of *H. halys* in northern Utah present risk to specialty and field crops. For example, early season feeding by *H. halys* on tart cherry (*Prunus cerasus* 'Montmorency') fruit can invoke substantial abscission and yield loss (Schumm et al. 2020), while injury to a wide variety of vegetable and small fruit crops in urban farms reduced product quality and yields (Z. Schumm, personal communication).

The high elevation (>1200 m), aridity (30-year mean RH = 53.1%; dew point = -1.9°C), and extreme seasonal temperature fluctuations of northern Utah (the 30-year mean minimum and maximum in January and July in Salt Lake City range from -3.1 to 3.6°C and 20.3 to 32.4°C) (ncdc.noaa.gov, climate.usu.edu, worldclimate.com) present a novel environmental setting for *H. halys*. Many other regions of the world with established *H. halys* populations, especially those in North America, include more humid and lower elevation habitats (Bariselli et al. 2016, Faúndez and Rider 2017, Gariepy et al. 2014, Rice et al. 2014). Plant surveys in northern Utah will provide insights into *H. halys* invasion of other inter-mountainous regions, including identification of novel plant hosts. Documentation of primary, or sentinel, host plant species (those that support two or more life stages of *H. halys*) can aid in supporting further research and development of targeted management practices for *H. halys* (Mansfield et al. 2019).

Materials and Methods

A total of 17 urban and suburban host plant survey sites were selected in 2017 and 2018 based on previous positive *H. halys* collections in Davis, Salt Lake, Utah, and Weber counties (Fig. 2-1). Two sites were replaced in 2018 due to a lack of stink bug detections in 2017 for a total of 15 sites per year. Sites were sampled biweekly from May 16 to August 24, 2017, and from May 8 to August 22, 2018. In both years, a subset of six sites was surveyed until the last week of September to provide later seasonal data for sites with higher *H. halys* populations. In 2017, these six sites were numbers 3, 5, 7, 8, 9, and 10; in 2018, they were 3, 4, 7, 9, 10, and 13 (Fig. 2-1).

At each site, a line sampling transect, 200 m long by 40 m wide, was established. Twenty of the total available plants within each transect were randomly selected regardless of species and surveyed by one or two observers using visual inspection (e.g., underside of leaves, limbs, and tree trunks) and beating sheets (BioQuip Products Inc., Rancho Dominguez, CA) for 3 min (Bakken et al. 2015). Pole pruners and a stepladder (3 m standing height) were used to examine 3–5 m height of tree canopies. For small-sized plants where all foliage could be fully inspected in less than 3 min, observers moved to the next plant upon completion. When *H. halys* was detected, plants were inspected for an additional 7 min to estimate densities of each life stage observed (egg, nymph, and adult) for a total observation time of 10 min. Mean *H. halys* counts per plant species and year were calculated to provide a relevant comparison of host plant preference; however, as plant species were not equally represented in transects, the mean number of *H. halys* per visual sample is provided (Table 2-1). Means were not compared statistically.

Each plant surveyed within a site was assigned a unique serial number and resampled on biweekly visits, providing insights into seasonal phenology of *H. halys* on the representative plant species. Each surveyed plant was tracked with the mapping application Collector by Esri, and data were transferred into ArcGIS Online and ArcGIS Pro for management and visualization (Esri, Redlands, CA). Plant identifications were confirmed by the Utah State University Intermountain Herbarium (UTC), where voucher specimens of each species are archived.

Results

A total of 53 plant species from 17 families were observed with one or more *H. halys* life stages present between May and September of 2017 and 2018 (Table 2-1). Of these, 29 are novel hosts according to the national StopBMSB.org plant species repository. Seven plant species were documented with two *H. halys* life stages present across both years: *Acer ginnala* Maxim., *Acer platanoides* L., *Cercis canadensis* L., *Malus domestica* Borkh., *Populus tremuloides* Michx., *Prunus armeniaca* X *domestica* 'Flavor King', and *Robinia pseudoacacia* L. Two species, *Catalpa speciosa* (Warder) and *Prunus virginiana* 'Schubert', had all three *H. halys* life stages present in both years. The majority of *H. halys* observed were found on *C. speciosa*, comprising 91% of all *H. halys* detected in this study. Plant species without observations of *H. halys* are listed in Table 2-2. Additional plant species with *H. halys* detections in northern Utah observed external to these surveys are listed in Table 2-3.

Halyomorpha halys egg masses were detected in low numbers (< 40 masses) in both survey years (Table 2-1), with detections beginning the first week of June and continuing into early September (Fig. 2-2). Most egg masses were found on *C. speciosa*, followed by *P. virginiana* 'Schubert', and only single sightings on *C. canadensis*, *Fagus sylvatica* 'Purpurea Tricolor', and *Acer grandidentatum* Nutt. (Table 2-1). Egg masses were difficult to detect due to their cryptic coloration and small size, which likely contributed to underrepresentation of this life stage in surveys. Nymphs were the most prevalent life stage detected, and were observed between June and late September (Fig. 2-2). Nymphs were found on 44 of the total 53 plant species, with the highest numbers found on *C. speciosa* (Table 2-1). Fewer adults were detected compared to nymphs, but adults were observed throughout the entire duration of survey periods in both years, with peak detections in September of 2017 (five times higher than in September 2018), and August and September of 2018 (Fig. 2-2). Adults were found on 36 plant species, most commonly on *C. speciosa*, with sporadic high density sightings on several species within the families Rosaceae and Sapindaceae, specifically those within the genera *Acer* and *Malus* (Table 2-1). Total numbers of nymphs and adults detected were nearly 1.5 times greater in 2017 than 2018 (3,611 in 2017, and 2,515 in 2018) (Figs 2-2, 2-3).

In general, sites surveyed in Salt Lake and Utah counties had higher densities of *H. halys* in both years than sites in Weber and Davis counties to the north (Fig. 2-3). The site containing the highest densities of *H. halys* was in the Avenues neighborhood (Site 9) of Salt Lake City. This area contains street blocks lined with large, mature ornamental trees and is within 3 km of the University of Utah campus where *H. halys* was originally detected in Utah in 2012. Site 3 in northern Provo, Utah County, had the second highest density of *H. halys* sightings. Both locations were next to large apartment buildings with several *C. speciosa* trees in close proximity.

Discussion

Surveys in northern Utah for *H. halys* have documented several prominent host plant species belonging to the families Bignoniaceae, Fabaceae, Rosaceae, and Sapindaceae. These families, along with their most commonly encountered genera (*Catalapa*, *Cercis*, *Malus*, *Prunus*, and *Acer*), have been documented as beneficial hosts for *H. halys* in other regions of North America (Bakken et al. 2015, Bergmann et al. 2016, Hoebeke and Carter 2003), and Asia (Lee et al. 2013). Twenty-nine of the plant species observed in this northern Utah study were novel *H. halys* host detections for North America (StopBMSB.org). Some novel hosts, such as the native *P. tremuloides*, supported both nymph and adult *H. halys* on the bark and foliage. No direct observation of feeding or plant damage was recorded; however, *P. tremuloides* may be an important host for *H. halys* establishment in Utah as it is a commonly planted ornamental tree and known to sustain biodiversity, native habitat, and other ecosystem services in the intermountain region (Rogers et al. 2020). Our surveys were only conducted in urban areas; therefore, further study is needed to confirm the potential for wild *P. tremuloides* to support *H. halys*, including other intermountain areas where this tree is an important native plant.

Acer ginnala was a novel host with consistent nymph and adult detections in both survey years, especially from May to June. This early season preference could be due to nutrient availability and plant health, as many *A. ginnala* experience foliar chlorosis in mid to late summer due to a lack of iron from alkaline soils in Utah (Mengel 1994), possibly making this host less desirable in the mid and later season. The only host species besides *C. speciosa* to exhibit all three life stages of *H. halys* was *P. virginiana* 'Schubert', which is also a novel host species. This association is likely due to its large plantings in northern Utah residential areas, attractive fruiting structures for feeding, and dense protective canopy. This species is also exploited by several native stink bug species, specifically *Chinavia hilaris* (Say). However, the Utah native *P. virginiana*, did not host *H. halys* during these surveys, suggesting the ornamental *P. virginiana* 'Schubert' is a more suitable host, possibly because it offers a larger canopy and is more common near *H. halys* overwintering sites, such as human-made structures. More extensive sampling of the native *P. virginiana* is suggested to support a more comprehensive comparison.

The most common and consistent host plant for *H. halys* in northern Utah is the northern catalpa, *C. speciosa*; the highest number of egg masses, nymphs, and adults were found on this host in both survey years. Our observations support other surveys in North America and Eurasia where *H. halys* was common on *C. speciosa* (Bakken et al. 2015, Musolin et al. 2018). Resources of this plant that seem to attract *H. halys* are its large leaves, flowers, and reproductive pod structures. The undersides of the large leaves are especially advantageous for *H. halys* oviposition. As a primary and sentinel host, *C. speciosa* is a target for prevention, detection, and management practices against the spread and further establishment of *H. halys* into agricultural lands in Utah. Contrary to other reports in North America that document *Ailanthus altissima* (Mill.) Swingle as a prominent host plant (Bakken et al. 2015, Bergmann et al. 2016, Rice et al. 2014), our surveys of this species (sampled 40 times in 2018 only, Table 2-2) did not detect *H.*

halys. We project that the host status of *A. altissima* could change in Utah given its apparent preference by *H. halys* in other regions of North America.

The occurrence and abundance of certain plant species impacted the survey results, as stated for *P. virginiana* 'Schubert' above. This is largely due to *H. halys* quickly dispersing by flight (Wiman et al. 2015) and using plants for a variety of functions (Bergmann et al. 2016), including resting between flights. Therefore, it is reasonable to assume that more abundant plant species in an urban landscape are more likely to harbor dispersing adults. *Acer plantanoides* was a major component of urban vegetation cover in all of the surveyed counties in northern Utah, likely contributing to some of its observed *H. halys* abundance. A similar association can likely be applied to common ornamental plant species in families Fabaceae, Rosaceae, and Sapindaceae. We did observe some exceptions; a notable one being the genus *Rosa*, with few *H. halys* detections.

Although *H. halys* has been detected on plants, in pheromone traps, and by the public in multiple locations in Utah, established populations are primarily concentrated along the Wasatch Front (west side of the Rocky Mountain range). To-date, highest densities of *H. halys* reside within Salt Lake and Utah counties. The concentration of *H. halys* in the larger metropolitan areas of Salt Lake and Utah counties is most likely due to its original detection and establishment in Salt Lake City with expansion into nearby urban centers. These urban areas offer overwintering shelter in human structures (Lee et al. 2014), wooded areas with mature ornamental hosts (Bakken et al. 2015), and human mediated vectors of transport (e.g., Interstate 15, Union Pacific Railroad) (Wallner et al. 2014). Urban centers with high populations of *H. halys* are in close proximity to northern

Utah's agricultural production areas, especially specialty fruit and vegetable crops which are at risk of feeding damage by *H. halys* (Schumm 2020, Schumm et al. 2020). Identification of ornamental plants that harbor *H. halys* in the urban-agricultural interface is critical to inform preventative management decisions, and better manage future crop invasions.

Using *C. speciosa* and other prominent host plants identified in this study as sentinel hosts, property owners and land managers in Utah, as well as other surrounding states in the greater Intermountain West, can more accurately track the invasion and establishment by *H. halys* (Mansfield et al. 2019). Beyond host plant species data, these surveys provide temporal context for *H. halys* development across its multiple life stages in northern Utah. Nymphs were observed in significantly higher numbers than egg masses and adults from mid-June through early September. This suggests that Utah growers and land managers should initiate monitoring using beat sheets or traps in May or early June, with treatment needs assessed from June through September with consideration of crop and harvest timelines.

Interestingly, overall populations of *H. halys* nymphs and adults decreased from 2017 to 2018. The reason for this population decline is unknown. No major differences in relative humidity, temperature, and cumulative degree-days occurred between the two survey years utilizing the predictive phenology model of Nielsen et al. (2008, 2016). For example, in Salt Lake City where the majority of sites were located, the mean minimum/maximum temperatures and minimum relative humidity in May of 2017 and 2018 was 7.7/21.9℃ and 24.4% and 9.3/23.6℃ and 24.2%, respectively. In September 2017 and 2018, the mean minimum/maximum temperatures and minimum relative humidity was 10.2/24°C and 29.7% and 11.2/28.6°C and 13.6%, respectively (climate.usu.edu). Temperatures and relative humidity were more similar between years in June through August survey periods, and fell between environmental conditions observed in May and September. Regardless, *H. halys* populations are still relatively low in Utah compared to other regions of North America where climate conditions are more favorable for *H. halys* (Rice et al. 2014, Nielsen et al. 2016). Extreme high temperature and low humidity are known to negatively affect *H. halys* survival and reproduction (Fisher et al. 2020, Haye et al. 2014, Nielsen et al. 2008).

Another limiting factor could be egg mortality by parasitoid wasps. *Trissolcus japonicus* Ashmead, a parasitoid of *H. halys* native to its home range, was first detected in Utah in Salt Lake City in June, 2019, and expanded its abundance and range in 2020 (Holthouse et al. 2020; K. Richardson, personal communication). However, egg mass parasitism rates by native wasps in northern Utah surveys were similar between 2017 and 2018, and *T. japonicus* was found only after these host plant surveys were conducted. Another organism that may have caused this population decrease is *Nosema maddoxi* Becnel, Solter, Hajek, Huang, Sanscrainte, and Estep (Hajek et al. 2017). This microsporidian is known to cause mortality in *H. halys* adults and nymphs and was detected in wild caught *H. halys* specimens in Salt Lake City and Provo, Utah in 2017 (Preston et al. 2020; C. Preston, personal communication). However, in 2018, dissections of 141 adult *H. halys* collected from several locations in Salt Lake City and Provo, Utah, revealed no *N. maddoxi* spores, implying the microsporidian was absent or collection/dissection methods were ineffective in detecting its presence (M. Holthouse, unpublished data). Despite our inability to explicitly define a cause for declines in *H.*

halys populations along the Wasatch Front since 2017, this trend has continued into 2020 (M. Holthouse, unpublished data).

Conclusion

Plant surveys for the invasive brown marmorated stink bug, *H. halys,* within the urban landscape of northern Utah, have revealed 53 host plant species from 17 families capable of harboring one or more developmental life stages of the insect. Of these plant species, *C. speciosa*, northern catalpa, harbored the predominance of *H. halys* eggs, nymphs, and adults across survey sites and years. Peak numbers of *H. halys* nymphs, the most abundant life stage, occurred between June and early September in both years with highest densities in Salt Lake and Utah counties. A notable novel host is *P. tremuloides*, an important native tree in the Intermountain West and other interior western regions. We documented that *H. halys* can be found season-long on a wide variety of managed ornamental plants, and identified 29 novel host species in northern Utah.

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Tables and Figures

Table 2-1. Mean number of *H. halys* egg masses (E), nymphs (N), and adults (A) present per sample* of plant species during surveys in northern Utah, 2017 and 2018. Plant species in bold were documented with two or more *H. halys* life stages in 2017 and 2018. The number of times each plant species was surveyed (no. of unique specimens × no. of visits) is found in the column labelled (*n*). The NS term indicates no surveys were conducted on the indicated plant and year.

		Year							
		2017				2018			
Family name	Scientific name	(*n*)	E	N	A	(*n*)	E	N	A
Apocynaceae	*Vinca major*†	40	-	0.05	-	37	-	-	-
Araliaceae	*Hedera helix*†	35	-	-	0.08	32	-	0.16	-
Berberidaceae	*Mahonia repens*†	18	-	-	0.06	29	-	-	-
Bignoniaceae	*Campsis radicans*†	10	-	-	0.10	8	-	0.13	0.13
	Catalpa speciosa	284	0.05	8.81	2.70	288	0.11	7.22	0.78
Caprifoliaceae	*Lonicera maackii*†	10	-	0.20	-	10	-	0.10	-
Cornaceae	*Cornus alba* 'Elegantissima'†	10	-	0.10	0.10	10	-	-	-
Cupressaceae	*Thuja plicata*†	11	-	-	-	11	-	0.18	0.09
Fabaceae	*Caragana arborescens*	9	-	0.11	0.11	8	-	-	0.38
	Cercis canadensis	26	0.04	0.81	-	27	-	0.07	0.15
	Gleditsia triacanthos	10	-	0.10	-	10	-	0.10	-
	Gleditsia triacanthos var. *inermis*	24	-	-	-	30	-	-	0.03
	Robinia pseudoacacia	36	-	0.03	0.08	47	-	0.02	0.02
	Robinia pseudoacacia 'Purple Robe'	10	-	-	0.10	11	-	-	-
Fagaceae	*Fagus sylvatica* 'Purpurea Tricolor'†	30	0.03	0.03	0.20	30	-	-	-
	Quercus macrocarpa 'Urban Pinnacle'†	17	-	-	-	11	-	-	0.05
Malvaceae	*Tilia cordata*†	8	-	0.13	-	8	-	-	-

Oleaceae	*Forsythia* X *intermedia* 'Lynwood Gold'†	NS	NS	NS	NS	8	-	0.06	-
	Fraxinus pennsylvanica	39	-	0.03	0.05	32	-	-	0.03
	Ligustrum vulgare†	29	-	0.10	-	22	-	-	-
	Syringa vulgaris†	62	-	0.10	0.10	62	-	-	0.05
Rosaceae	*Amelanchier* X *grandiflora* †	18	-	-	-	16	-	0.06	-
	Crataegus mollis †	11	-	-	0.09	11	-	-	-
	Crataegus monogyna	8	-	0.13	0.13	8	-	-	-
	Malus domestica	55	-	0.35	0.47	53	-	0.25	0.89
	Malus floribunda†	8	-	0.13	0.75	8	-	-	0.13
	Malus 'Prairifire'†	8	-	-	0.63	8	-	-	0.13
	Malus sylvestris†	18	-	0.06	-	16	-	-	-
	***Prunus armeniaca* X *domestica* 'Flavor King'**†	28	-	0.21	0.14	22	-	0.05	0.18
	Prunus avium	35	-	0.03	0.03	29	-	0.10	-
	Prunus cerasifera	9	-	-	-	8	-	0.13	-
	Prunus cerasifera 'Nigra'	73	-	0.04	0.08	76	-	-	0.03
	Prunus domestica	11	-	-	0.55	21	-	0.71	0.05
	Prunus persica	51	-	-	-	35	-	0.11	0.17
	***Prunus virginiana* 'Schubert'**†	61	0.02	0.30	0.30	54	0.06	0.31	0.28
	Pyrus calleryana	24	-	-	-	30	-	0.03	-
	Rosa acicularis†	89	-	0.03	0.03	109	-	-	-
	Spiraea japonica 'Goldflame'†	10	-	0.30	-	10	-	0.20	-
Salicaceae	*Populus angustifolia*†	NS	NS	NS	NS	8	-	0.25	-
	Populus tremuloides†	49	-	0.12	0.53	39	-	0.11	0.23
	Salix purpurea†	10	-	0.20	-	10	-	-	-
Sapindaceae	*Acer freemanii*	10	-	0.10	-	10	-	-	-
	Acer ginnala†	9	-	2.78	1.78	8	-	0.25	0.13
	Acer grandidentatum†	14	0.06	-	-	16	-	-	-

	Acer negundo	78	-	-	0.03	112	-	0.02	0.06
	Acer nigrum†	8	-	0.25	0.13	NS	NS	NS	NS
	Acer palmatum 'Fireglow'	18	-	-	0.06	18	-	0.06	-
	Acer platanoides	127	-	0.26	0.06	118	-	0.03	0.04
	Acer platanoides 'Crimson King'	17	-	0.04	0.35	26	-	-	-
	Acer rubrum	8	-	-	-	8	-	0.13	-
Scrophulariaceae	*Buddleia davidii*	25	-	0.04	0.12	24	-	-	-
Ulmaceae	*Ulmus pumila*†	70	-	-	0.06	80	-	-	0.05
Vitaceae	*Vitis Vinifera*	28	-	-	-	28	-	0.04	-

*All plants were sampled for a minimum of 3 min; plants with one or more *H. halys* life stages were sampled for an additional 7 min, a total of 10 min.

†Novel host plant species for *H. halys* documented in Utah (as compared to current North American literature)

Table 2-2. Plant species without *H. halys* detections during surveys in northern Utah, 2017 and 2018. Surveys (*n*) indicates the number of times a species was sampled.

Family name	Scientific name	Surveys (*n*)
Adoxaceae	*Sambucus cerulea*	8
	Viburnum opulus	16
Amaryllidaceae	*Allium aflatunense*	35
Anacardiaceae	*Cotinus coggygria*	20
	Rhus typhina	7
	Rhus typhina 'Laciniata'	56
Apocynaceae	*Asclepias syriaca*	7
Asteraceae	*Artemisia tridentata*	15
Berberidaceae	*Berberis thunbergii* var. *atopurpurea* 'Rose Glow'	15
	Berberis vulgaris	21
Betulaceae	*Betula nigra*	7
	Betula papyrifera	17
Cannabaceae	*Celtis occidentalis*	15
Caprifoliaceae	*Lonicera* X *heckrottii* 'Goldflame'	17
	Symphoricarpos albus	21
Celastraceae	*Euonymus alatus*	30
	Euonymus fortunei	48
Cornaceae	*Cornus alba* 'Siberica'	24
	Cornus kousa	15
	Cornus sericea	19
Cucurbitaceae	*Cucumis sativus*	9
Cupressaceae	*Juniperus chinensis*	15
	Metasequoia glyptostroboides	16
Elaeagnaceae	*Elaeagnus angustifolia*	23
Fabaceae	*Cladrastis kentukea*	8
	Cladrastis lutea	15
	Maackia amurensis	8
Fagaceae	*Quercus gambelii*	74
	Quercus rubra	8
Ginkgoaceae	*Ginkgo biloba*	21
Grossulariaceae	*Ribes alpinum*	21
Hydrangeaceae	*Philadelphia* X *virginalis*	8
Juglandaceae	*Juglans regia*	53
Lamiaceae	*Nepeta cataria*	16
Lauraceae	*Lindera benzoin*	15

Magnoliaceae	*Liriodendron tulipifera*	21
	Magnolia denudata	15
Malvaceae	*Alcea rugosa*	56
	Hibiscus syriacus	7
	Tilia platyphyllos	16
	Tilia tomentosa	8
Oleaceae	*Forsythia* X 'Northern Sun'	8
	Syringa 'Bailbelle'	8
	Syringa reticulata 'Ivory Silk'	8
	Syringa vulgaris 'Ludwig Spaeth'	8
	Syringa X *hyacintriflora*	15
Plantaginaceae	*Penstemon strictus*	16
Rosaceae	*Crataegus crus-galli* var. *inermis*	16
	Crataegus laevigata 'Paul's Scarlet'	14
	Crataegus X *lavellei*	16
	Fragaria vesca	15
	Malus ioensis	33
	Physocarpus opulifolius 'Dart's Gold'	23
	Physocarpus opulifolius 'Diablo'	8
	Prunus americana	8
	Prunus dulcis	14
	Prunus mahaleb	16
	Prunus X *cistena*	19
	Pyrus pyrifolia	7
	Rosa spp.	168
	Prunus virginiana	59
	Sorbus alnifolia	8
Rutaceae	*Tetradium daniellii*	8
Salicaceae	*Populus deltoides*	7
	Salix lasiolepis	8
Sapindaceae	*Acer campestre*	18
	Acer griseum	21
	Acer saccharinum	7
	Aesculus hippocastanum	16
	Aesculus X *carnea* 'Briotii'	8
	Koelreuteria paniculata	8
Saxifragaceae	*Astilbe* X *arendsii* 'White Gloria'	17
Simaroubaceae	*Ailanthus altissma*	40
Solanaceae	*Capsicum annuum* 'Big Bertha'	9
	Lycium barbarum	19
	Solanum melongena	25
Ulmaceae	*Ulmus americana* 'Lewis & Clark'	8
	Ulmus parvifolia 'Emer II'	8

	Ulmus propinqua 'Emerald Sunshine'	8
Vitaceae	*Parthenocissus quinquefolia*	66

Table 2-3. Additional *H. halys* host plant species documented in northern Utah, but extramural to the surveys in this study, 2017–2020.

Family name	Scientific name
Asteraceae	*Helianthus annuus*
Boraginaceae	*Borago officinalis*
Cucurbitaceae	*Cucurbita pepo*
Fabaceae	*Phaseolus vulgaris*
Lamiaceae	*Ocimum basilicum*
Moraceae	*Morus alba*
Poaceae	*Zea mays*
	Zea mays 'Everta'
Rosaceae	*Prunus armeniaca*
	Prunus cerasus
	Prunus persica
	Pyrus communis 'Williams'
	Rubus idaeus
Salicaceae	*Populus fremontii*
Solanaceae	*Solanum lycopersicum*

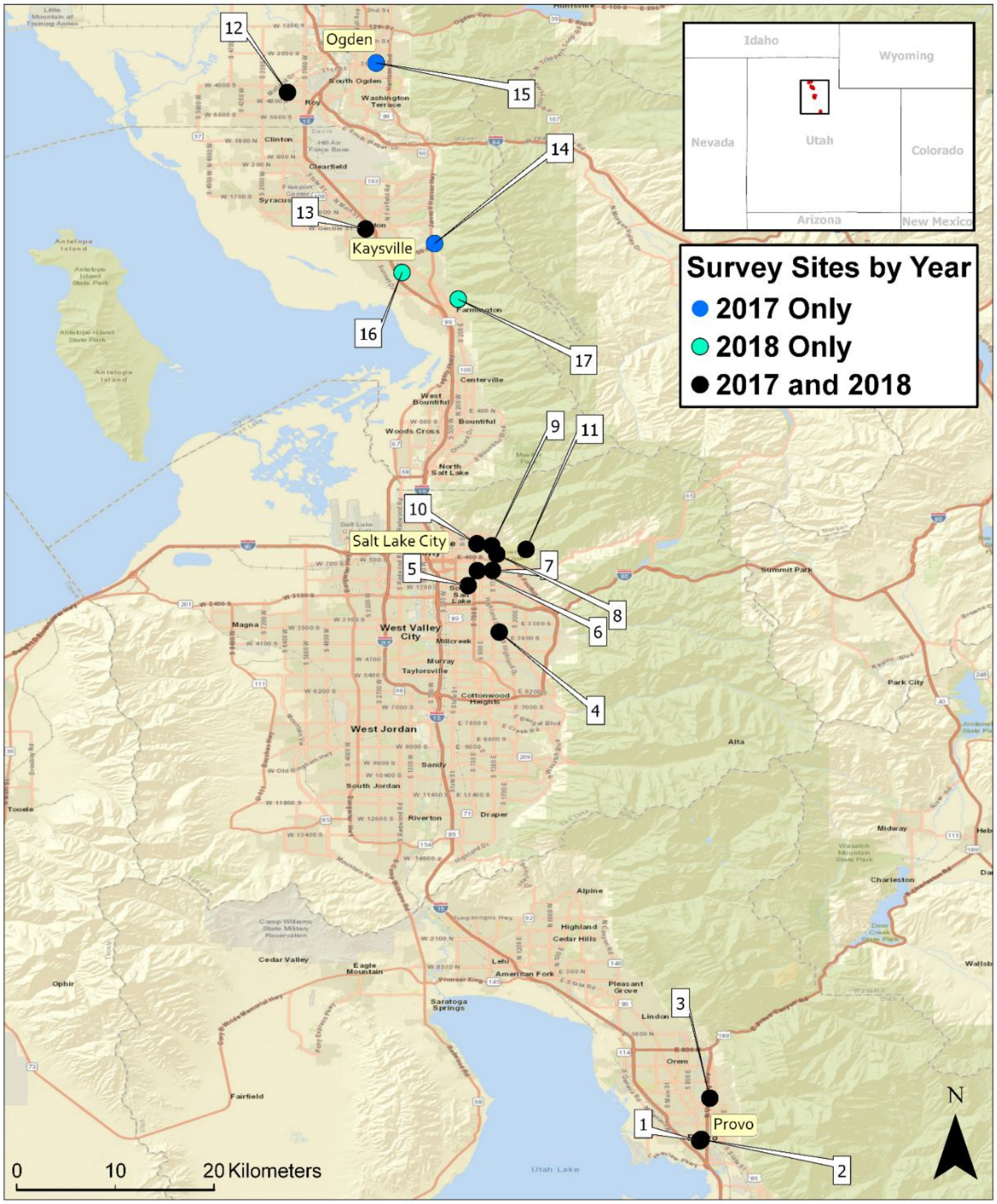

Figure 2-1. Map of 17 host plant survey sites in northern Utah, 2017 and 2018. Black dots represent sites that were visited in both years, blue dots represent sites visited only in 2017, and turquoise dots represent sites visited only in 2018. Geographical coordinates are as follows: Site 1: 40°13'44.7"N, 111°39'56.2"W; Site 2: 40°13'49.9"N, 111°39'50.6"W; Site 3: 40°16'05.2"N, 111°39'22.6"W; Site 4: 40°41'33.6"N, 111°50'53.8"W; Site 5: 40°44'06.4"N, 111°52'35.9"W; Site 6: 40°44'55.0"N, 111°52'05.8"W; Site 7: 40°44'56.1"N, 111°51'15.8"W; Site 8: 40°45'49.1"N, 111°51'02.1"W; Site 9: 40°46'16.5"N, 111°51'18.6"W; Site 10: 40°46'23.4"N, 111°52'07.1"W; Site 11: 40°46'04.8"N, 111°49'25.8"W; Site 12: 41°11'03.7"N, 112°02'29.2"W; Site 13: 41°03'35.9"N, 111°58'12.3"W; Site 14: 41°02'48.1"N,

111°54'26.2"W; Site 15: 41°12'40.3"N, 111°57'37.8"W; Site 16: 41°01'13.0"N, 111°56'13.1"W; and Site 17: 40°59'45.5"N, 111°53'08.5"W.

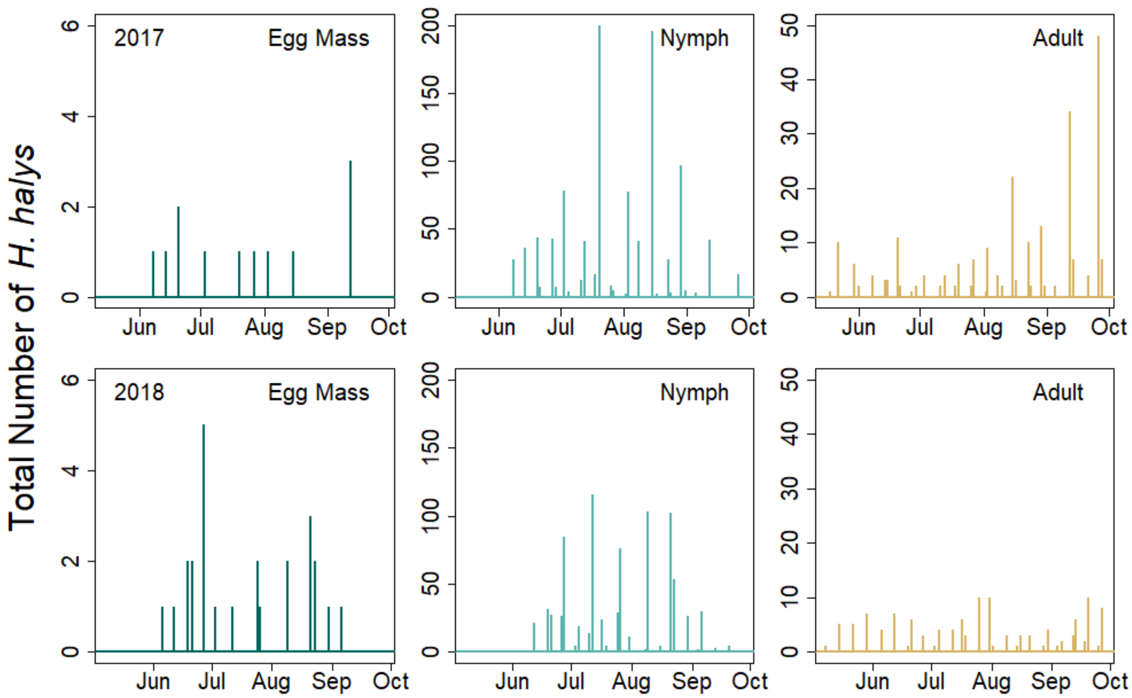

Figure 2-2. Total number of *H. halys* per life stage observed during plant surveys in northern Utah from May through September, 2017 (top row) and 2018 (bottom row). Tick marks on the x-axis represent the beginning of a month. Note the unique y-axis scales for each life stage.

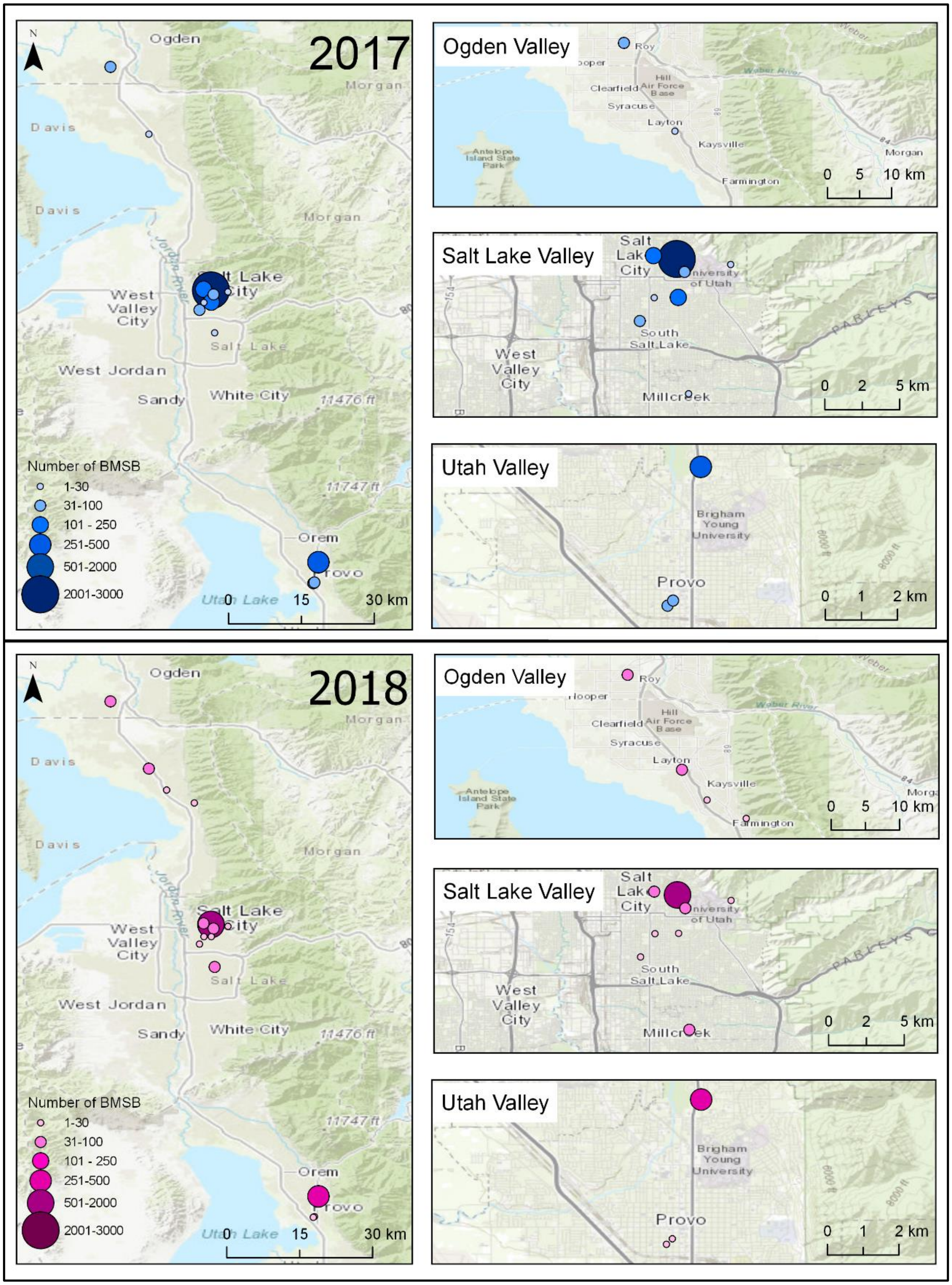

Figure 2-3. The total number of *H. halys* detected at survey sites in 2017 (top left) and 2018 (bottom left). The maps on the right show magnified views of Ogden Valley (Weber and Davis counties), Salt Lake Valley (Salt Lake County), and Utah Valley (Utah County).

CHAPTER III

PHENOLOGY AND VOLTINISM OF THE INVASIVE *Halyomorpha halys* (Stål) IN NORTHERN UTAH[1,2]

Abstract

Halyomorpha halys has become an agricultural pest and urban nuisance in many parts of the world. Its nearly global distribution reveals its extreme adaptability to variable climatic conditions. This study aims to elucidate the seasonal phenology and voltinism of *H. halys* in the novel conditions of northern Utah. Pheromone baited traps were used to detect nymph and adult *H. halys* from spring through fall in urban/suburban sites with known *H. halys* populations. Observed trap catch data were compared against established degree day (DD) models to confirm model utility in predicting seasonal development of *H. halys* in an arid, high elevation location with cold winters and hot summers. Trap capture showed initial adult detection occurred just after a photoperiod biofix of 13.5 h (7.28–23.4 DD) and peak nymph and adult populations occurred July through August (400-600 DD). Additionally, controlled experiments for adult reproduction and subsequent progeny development on catalpa, tart cherry, peach, and catalpa-peach and tart cherry-peach rotations revealed that *H. halys* is primarily univoltine in Utah, and produces higher numbers of nymphs when peach is available for nymphal development. These results will aid future pest managers in synchronizing management efforts with key life stages of *H. halys* across the growing season in northern Utah and other intermountain locations.

Keywords
Hemiptera; invasive; Pentatomidae; phenology; voltinism; degree days

[1] We have prepared this chapter for future submission to the journal Insects, by MDPI, and have thereby utilized their formatting and style guides

[2] Coauthored by Diane G. Alston and Lori R. Spears

1. Introduction

Temperature and photoperiod play an integral role in driving insect development [1, 2] and can dictate the success of invasive insect species in novel geographical ranges [3]. Understanding the developmental rate and population dynamics of insects in relation to localized environmental conditions can aid pest managers in effectively timing control efforts [4, 5, 6].

Halyomorpha halys (Stål) (Hemiptera: Pentatomidae) has become a harmful invasive insect pest in many regions of North America [7–9] and Europe [10–13]. It is highly adaptive to a wide variety of environmental conditions, making regional data on its phenology critical for development of effective pest management programs in recently invaded locations [14–16]. Current methods for tracking the seasonal phenology of *H. halys* rely primarily on dual-pheromone baited traps and field observation of development on host plants [17].

In the United States, *H. halys* has displayed variability in its voltinism with more northern latitudes generally harboring primarily F1 overwintering adults and southern latitudes supporting more F2 overwintering adults [16–18]. This variablility is linked to regionally specific photoperiods and temperatures, as *H. halys* requires a photoperiod of ≥13.5 h and a temperature range of 14.2–35.8°C to develop and reproduce [16, 19]. Time periods outside of these parameters initiate or sustain winter diapause in *H. halys*. Regions with two or more generations per season may experience increased *H. halys* populations as this pest is known to feed season-long on a diverse variety of crops [20-21].

H. halys phenology is also influenced by host plant phenology and availability [22–23]. Research by Acebes-Doria et al. [24] found that mixed host plant diets support superior nymphal development and adult fitness compared to single host plant diets. In addition, they found that peach supported superior nymphal development compared to other prominent hosts like apple, catalpa, and tree of heaven alone.

H. halys was first discovered in Utah in 2012, with agricultural damage first being observed on apple and peach in 2017. Research has shown that tart cherry, an economically significant fruit crop in Utah, is also at risk of *H. halys* feeding damage, especially between the petal fall and fruit pit hardening developmental stages [25]. In light of these agricultural threats, this study is focused on the unique seasonal phenology and voltinism of *H. halys* given the extreme temperature variability, aridity, and high elevation conditions of northern Utah [26].

Current knowledge suggests that BMSB is univoltine in northern Utah; however, late season occurrence of nymphs during recent host plant surveys suggests that a partial second generation may occur [26]. Additionally, phenology model predictions made by Nielsen et al. [16] for other western states like California, Oregon, and Washington have revealed that *H. halys* can be bivoltine in these locations.The major objectives of this study were: (1) document the seasonal phenology of *H. halys* in northern Utah using pheromone baited traps; (2) validate an established degree day (DD) model for *H. halys* and the utility of photoperiod as a spring biofix following winter diapause [16, 19]; and (3) determine the voltinism of *H. halys* on several prominent single and mixed host plants in Utah. The results of this study will contribute to our understanding of the pest status of

H. halys in northern Utah and provide pest managers with regionally specific timing for prevention and effective managment of *H. halys* populations.

2. Materials and Methods

2.1. Trap Deployment

2.1.1. Seasonal Trapping

Dead-Inn black corrugated plastic pyramid traps (AgBio Inc., Westminster, CO, USA) 1.2 m tall with a yellow entry cone on top were deployed at 17 survey sites and checked weekly for *H. halys* adults and nymphs from 16 May through 26 October in 2017 and 8 May through 25 October in 2018 (Table 3-1). Pyramid traps were baited with *H. halys* dual pheromone lures (Trécé Inc., Adair, OK, USA) which were replaced every 12 weeks. Site selection in 2017 included site numbers 1-15 and was based on detections of *H. halys* in previous years or the presence of important host plants such as *Catalpa speciosa* (Warder) [26]. In 2017, sites 12 and 15 captured <10 *H. halys* the entire survey period and were replaced with two novel sites, 16 and 17, in 2018 (Table 3-1). Overall, 15 traps were deployed in each year. All sites were located in suburban landscapes containing mixed ornamental trees and woody shrubs.

Table 3-1. Seasonal trap deployment locations in northern Utah by site number and county 2017–2020.

County	Site	Latitude	Longitude
Davis	12	41°02'47.0"N	111°54'26.0"W
	14	41°03'37.0"N	111°58'13.8"W
	16	41°01'13.3"N	111°56'10.5"W
	17	40°59'43.8"N	111°53'06.8"W
Salt Lake	4	40°41'35.0"N	111°50'54.0"W
	5	40°44'08.0"N	111°52'36.0"W
	6	40°44'54.0"N	111°52'05.0"W
	7	40°44'55.4"N	111°51'17.7"W
	8	40°45'49.5"N	111°51'02.9"W
	9	40°46'15.1"N	111°51'19.0"W
	10	40°46'23.2"N	111°52'07.2"W
	11	40°46'04.0"N	111°49'26.0"W
	18	40°46'49.1"N	111°53'46.6"W
	19	40°46'02.9"N	111°51'11.4"W
	20	40°46'12.0"N	111°51'58.7"W
	21	40°46'49.9"N	111°53'46.4"W
Utah	1	40°13'42.7"N	111°39'56.0"W
	2	40°13'47.5"N	111°39'50.9"W
	3	40°16'07.0"N	111°39'21.0"W
Weber	13	41°11'07.9"N	112°02'26.8"W
	15	41°12'40.2"N	111°57'37.8"W

2.1.2. Earlier-Seasonal Trapping

In 2019 and 2020, trap deployment was initiated earlier in the spring than previous years to include the overwintered *H. halys* pre-emergence period (<13.5 h photoperiod). These deployments included weekly trap checks at 8 sites in Salt Lake County from 25 March to 21 October in 2019 and from 8 April to 21 October in 2020. For early-season trapping studies, previous sites 7–10 and new sites 18–21 (< 8 km from sites 7–10), all with suitable *H. halys* host habitat, were used (Table 3-1).

2.2 Degree Day Model

Degree days (DD) were calculated based on a sine curve and horizontal cutoff method outlined by Baskerville and Emin [27], along with the lower and upper developmental temperature thresholds of 14.2°C and 35.8°C [26]. A critical photoperiod biofix of 13.5 h was used to assume initiation and termination of winter diapause cues in adult *H. halys* and marked the beginning of DD accumulation in this study [16]. Daily temperature data were acquired from the Utah Climate Center using a weather station centrally located along the Wasatch Front in Murray, Utah at an elevation of 1307.6 m (GPS coordinates: 40°37'52.7"N, 111°55'07.5"W). Degree day accumulations and figures were constructed using packages *pollen* [28], tidyr [29], weathermetrics [30], and ggplot2 [31] within R software (R version 4.0.2) [32]. These DD accumulations were plottled alongside all four years of trapping data in this study.

2.3. Voltinism

Experiments were conducted at the Utah State University Horticultural Research Farm in Kaysville, Utah. Wild *H. halys* adults (F0) emerging from overwintering were collected in Salt Lake County starting 20 April in 2018 and 2019. Wild-collected adults were held in a rearing chamber at an average temperature of 24.6 °C, average relative humidity of 45.5%, and in a light regime of 16L:8D until they were deployed onto host plants.

In 2018, *H. halys* were deployed on two single, continuous plant hosts: tart cherry, *Prunus cerasus* L.(starting 4 June) and catalpa (starting 18 June). On tart cherry, 40 *H. halys* adults were evenly distributed among 4 cylindrical sleeve cages (30 x 80 cm) (7 females and 3 males per cage), made of white no-see-um mesh (Mosquito Curtains, Alpharetta, GA, USA). Sleeve cages were placed over tree branches and closed at both ends with a zip tie to confine *H. halys* on leaves and fruiting structures. On catalpa, 30 adults were evenly distributed among 3 cages (8 females and 2 males per cage). One fewer cage was deployed on catalpa due to reduced availability of overwintered *H. halys* adults. Each cage was inspected weekly to determine the number of adults, egg masses, and nymphs present. Once detected, egg masses were removed from adult cages and placed individually within hanging stainless steel mesh tea diffusers (5 x 5 cm, Frontier Co-op, Norway, IA, USA) within a new cage so that all first or second instar nymphs could be counted before release into a new cage. Weekly observations and counts as above were completed through 8 October for both plant host cohorts in 2018.

On 21 May 2019, *H. halys* adults were deployed on three single, continuous plant hosts and two mixed host treatments: peach, *Prunus persica* L, tart cherry, catalpa, tart cherry-peach, and catalpa-peach. 6 adult *H. halys* (based on the 60 available wild caught adults) were deployed in each of two sleeve cages (5:1 and 4:2 female:male sex ratio for the first and second bag, respectively) on peach, tart cherry, and catalpa. *H. halys* in the mixed host treatments were placed on tart cherry or catalpa (5:1 and 4:2 female:male respectively for each of the two sleeve cages on each plant host) through the development of 2nd instar nymphs, and then transferred to peach at the 3rd instar. The host rotation treatments were designed to study the effects of *H. halys* development given more than one host plant, and included peach as a documented optimal host for later nymphal development [24]. Cages were inspected weekly as in 2018; life stage counts were completed 9 October 2019. No statistical comparisons between plant host treatments were conducted in either year, as some F1 adult sleeve cages were consolidated (cages within the same host treatment with single sex cohorts) to allow for adult copulation and population persitance on that host. This allowed for continued phenological observation, but resulted in a loss of uniform sleeve cage replication across host treatments.

3. Results

3.1. Trapping and Seasonal Phenology

The 15 traps deployed in 2017 captured 542 adults and 768 nymphs; however, in 2018, fewer *H. halys*, 259 adults and 325 nymphs, were captured during the season (Figure 3-1AB).

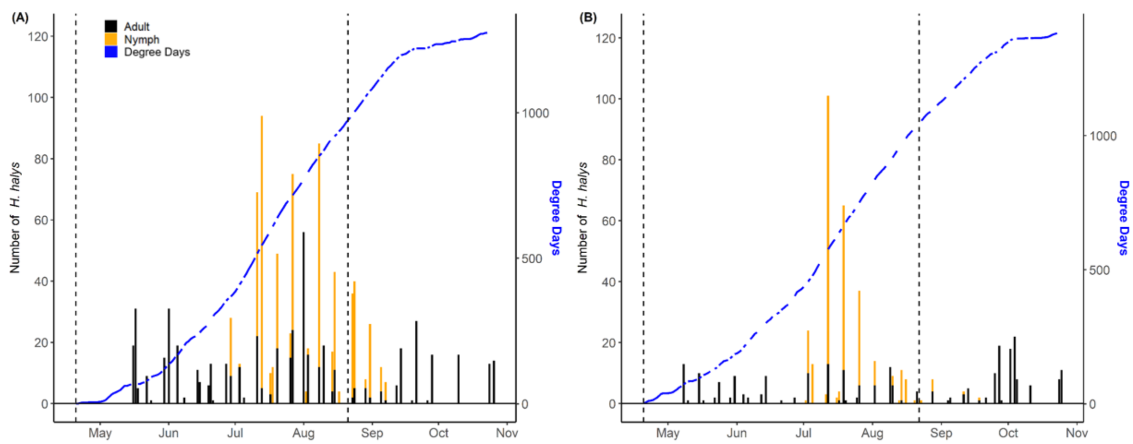

Figure 3-1. Number of *H. halys* adults and nymphs captured in traps *n*=15 (left y-axis), and cumulative degree days (right y-axis) over time in 2017 (A) and 2018 (B). Model utilized lower and upper temperature thresholds of 14.2°C and 35.8°C, respectivfely. Vertical dotted lines mark the date of the critical photoperiod of 13.5 h in spring and fall when degree-day models were initiated (spring). Traps were checked 16 May through 26 October in 2017 and 8 May through 25 October in 2018 (Davis, Salt Lake, Utah, and Weber coutnies).

The critical 13.5 h spring photoperiod occurred 20 April in 2017 and 2018, before trapping started on 16 May 2017 and 8 May 2018. Adults were detected on the first day of trap deployment in both years, indicating adult activity had begun sometime before 68 and 71.4 DD in 2017 and 2018, respectively (Table 3-2, Figure 3-1AB).

Table 3-2. Accumulated degree days after the critical spring photoperiod of 13.5 h for key *H. halys* life stages and events by year. Degree day values are based on when respective life stages were captured in pyramid traps.

Life Stage/Event	**2017**	**2018**	**2019**	**2020**
F0 Adult	68*	71.4*	7.3	23.4
F0 Nymph	368.8	401.5	330.9	299
Peak Nymph/Adult Capture	409.3–918.9	455.3–977.9	477.2–1025.8	561.9–1099.9
Final Trap Capture	1276.5	1384.4	1172.1	1336

*Traps in 2017–2018 were deployed after the critical spring photoperiod when *H. halys* were already active in the wild, therefore initial F0 adult trap capture in those years is not reflective of initial wild adult activity post winter diapause.

Nymphs first appeared in traps on 29 June (368.8 DD) in 2017 and on 27 June (401.5 DD) in 2018 (Table 3-2, Figure 3-1AB).

Peak adult and nymph activity occurred from approximately 3 July to 15 August, ranging from 409.3–918.9 DD and 455.3–977.9 DD in 2017 and 2018, respectively (Table 3-2, Figure 3-1AB). This peak in activity is likely due to the fact that F1 adult *H. halys* reach imaginal ecdysis at 537.6 DD, indicating overlapping activity of F0 and F1 adults [26]. The second critical photoperiod in the fall occurred on 22 August and was marked by 984.4 DD in 2017 and 1045.6 DD in 2018 (Table 3-2, Figure 3-1AB). Overall populations of *H. halys* were low at this time with an uptick in adult captures occurring approximately 21 September through 5 October (1198.7–1248.6 DD) in 2017 and 14 September through 10 October (1286.4–1361.3 DD) in 2018. A total of 1276.5 and

1384.4 DD were accumulated between the spring critical photoperiod and the last trap check date in October in 2017 and 2018, respectively (Table 3-2, Figure 3-1AB).

In 2019, 101 adults and 161 nymphs were captured in the 8 deployed traps over the entire season. The first detection of adults occurred on 22 April, just two days after the critical photoperiod date and at 7.3 accumulated DD (Table 3-2, Figure 3-2A). In 2020, 40 adults and 91 nymphs were captured, with the first adult detections occurring on 27 April, 8 days after the critical photoperiod date of 19 April and at 23.4 DD (Table 3-2, Figure 3-2B). In both years, F0 adult populations initially peaked between 15–21 May, with a range of 78–86 DD in 2019 and 95–128 DD in 2020. Nymphs were first detected in pyramid traps on 3 July in 2019 at 330.9 DD and on 16 June in 2020 at 299 DD (Figure 3-2AB). In both years, the total number of nymphs was highest from 17 July through 6 September. This date range corresponded to 477.2–1025.8 DD in 2019 and 561.9–1099.9 DD in 2020 (Table 3-2, Figure 3-2AB). That same date range also accounted for a noticeable increase in the number of adults in 2019, and is indicative of F1 adult maturation at 537.6 DD, as noted for 2017 and 2018. In both years, the 13.5 h fall photoperiod occurred on 22 August, at 874.6 DD in 2019 and 956.8 DD in 2020 (Figure 3-2AB). A total of 1172.1 DD were accumulated between the spring critical photoperiod and the last trap check date in October 2019 and 1336 DD in 2020 (Table 3-2, Figure 3-2AB).

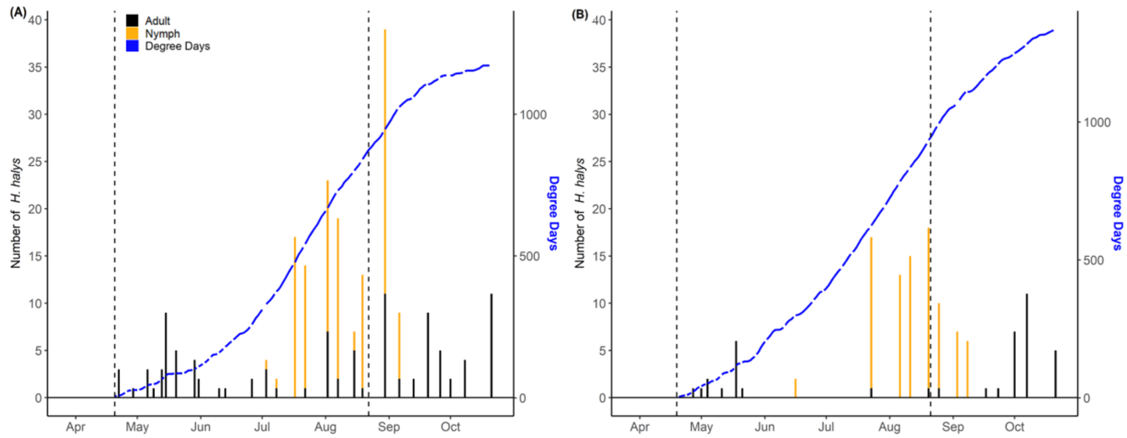

Figure 3-2. Total number of *H. halys* adults and nymphs captured in pyramid traps *n*=8 (left y-axis), and cumulative degree days (right y-axis) over time in 2019 (A) and 2020 (B). Model utilized lower and upper temperature thresholds of 14.2°C and 35.8°C, respectively. Vertical dotted lines mark the date of the critical photoperiod of 13.5 h in spring and fall when degree-day models were initiated (spring). Traps were checked 25 March to 21 October in 2019 and from 8 April to 21 October in 2020 (Salt Lake County).

3.2. Voltinism

In 2018, the cohort of *H. halys* confined to tart cherry displayed minimal bivoltinism, as one F2 nymph developed to the second instar by 9 October (Figure 3-3A). Those on catalpa branches were strictly univoltine, producing F1 adults as the final developmental stage by 8 October (Figure 3-3B). F0 oviposition was highest on tart cherry on 18 June (24 egg masses), and 2 and 9 July on catalpa (13 and 15 egg masses, respectively) before declining to 5–6 masses per week until 3 September. It is important to note that the later initiation of F0 oviposition on catalpa compared to tart cherry is most likely due to later deployment by 14 days.

Following the first spike in egg masses, first instar nymphs became increasingly abundant from late June through early July on both plant species, followed by a sudden drop to zero individuals on 23 July. A second wave (>60 *H. halys*) of F1 first instars occurred in early August for tart cherry and late August for catalpa. F1 second and third instar nymph populations were relatively high for much of July and August on both plant species, but catalpa displayed a secondary spike (>150 *H. halys*) in numbers in early September (Figure 3-3B). F1 fourth and fifth instar nymphs were initially observed 9 July on tart cherry and 30 July on catalpa, with peak numbers occurring in early to mid-August, respectively.

F1 adults were first observed on tart cherry on 23 July, 501.6 DD after initial F0 adult deployment. A month later, the first F1 adults appeared on catalpa, 8 August, 698.9 DD after initial F0 adult deployment (Figure 3-3AB). On 13 August, F1 adults on tart cherry produced the first F1 egg mass, subsequent F1 egg masses gave rise to the first successful hatch of a single F2 first instar nymph on 3 September and it survived until the second instar on 24 September (Figure 3-3A). No F1 egg masses were produced on catalpa.

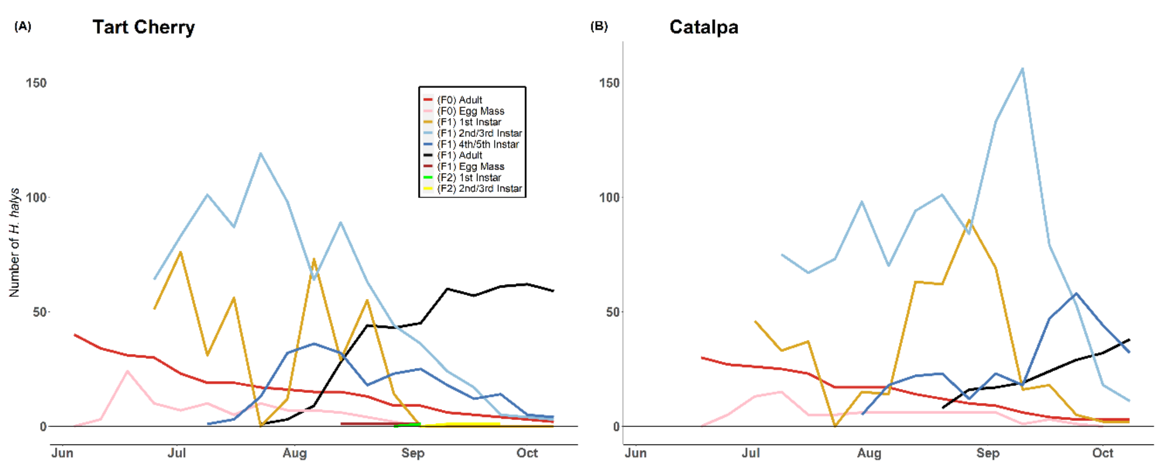

Figure 3-3. Number of *H. halys* by developmental life stage in 2018 on tart cherry (A) and catalpa (B). Initial F0 adult deployments in June included 40 on tart cherry (7:3 female:male) and 30 on catalpa (8:2 female:male).

Observations in 2019 documented univoltine populations of *H. halys* across all host treatments (Figure 3-4A–E). Overall, oviposition by F0 adults was low across most host plants (≤ 5 egg masses per week), though oviposition on tart cherry did increase slightly relative to other plant species in July (Figure 4BE). The highest number of first instar nymphs occurred from mid-June to early July on all plant species (Figure 3-4A–E). Numbers of second and third instar nymphs were variable across the different host plant treatments; most were initially observed 11–18 June across all groups, with relatively high numbers of third instar nymphs in cages where peach was available for all or part of nymphal development. Very few of these progressed into the fourth and fifth instar stage. This made for small populations of F1 adults in September for most host treatments, though a secondary spike in fourth and fifth instar nymphs on catalpa resulted in the highest F1 adult populations (Figure 3-4A). This trend was most apparent in the tart cherry-peach treatment where high numbers of second and third instar nymphs in July and August gave rise to very few fourth or fifth instar nymphs (< 15% survival). Ultimately, no F1 adults were observed on the tart cherry-peach treatment and just one F1 adult in catalpa-peach (Figure 3-4E).

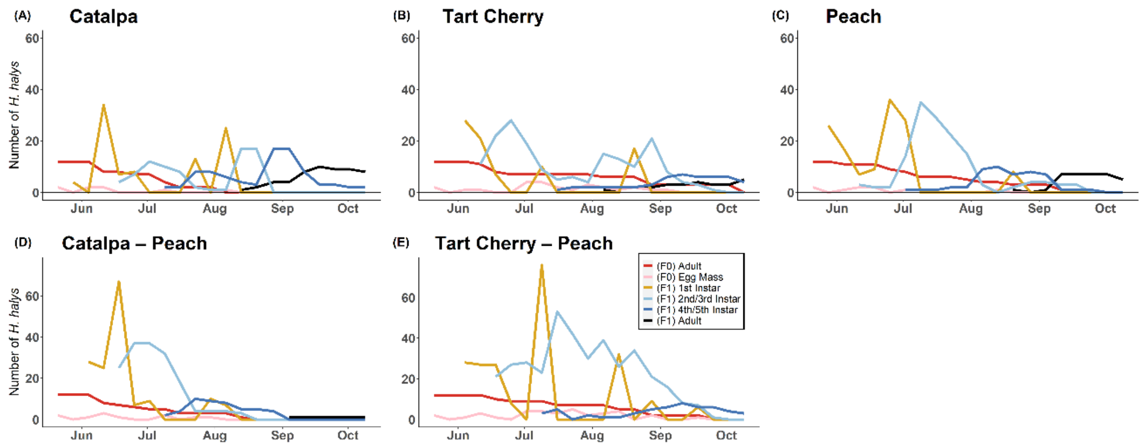

Figure 3-4**.** Total number of *H. halys* by developmental life stage in 2019 on peach (A), tart charry (B), catalpa (C), catalpa transitioned to peach (D), and tart cherry transitioned to peach (E). Initial F0 adult deployments in June included 12 (9:3 female:male) on catalpa, tart cherry, peach, catalpa-peach, and tart cherry-peach.

4. Discussion

Our multi-year trapping trials confirm the utility of pheromone-baited traps in tracking the seasonal phenology of *H. halys* in northern Utah, as has been demonstrated in other invaded regions of North America [33–35]. Nielsen et al. [26] determined that egg to adult maturation normally requires 537.6 DD, based on lower and upper temperature thresholds (14.2°C and 35.8°C, respectively), which explains the sudden increase in the number of assumed F1 adults captured in traps at 400-600 DD in 2017-2019 in Utah. Though it is likely that an undefined portion of these mid-season adults are F0 adults, our voltinism observations confirmed that F1 adults are active during this period. Voltinism experiments showed that initial egg laying activity on catalpa, peach, and tart cherry occurred the day of deployment in 2019, at 86.3 DD, which is less than the established 147.7 DD noted by Nielsen et al. [26], but similar to field observations in the mid-Atlantic region of the U.S. [36]. It is possible that the timing of F0 adult oviposition that year was artificially expedited or delayed due to holding conditions in the lab after collection and before field deployment. Interestingly, late season spikes in adult trap captures (approximately 1200–1300 DD) noted during all four years of trap deployment, indicate a later occurrence of fall aggregating adults in Utah than has occurred in Allentown, Pennsylvania in previous years (850–1000 DD) [36].

The use of the critical photoperiod of 13.5 h set forth by Nielsen et al. [16], was validated by observations of initial F0 adult activity in 2019 and 2020 within 2-8 days of photoperiod biofix dates of 20 and 19 April, 2019 and 2020, respectively. The 13.5 h critical photoperiod on 20 August 2017, 2018, and 2020 also marked an overall decrease in nymph trap captures and a gradual increase in adult captures. This rise in adult numbers is indicative of late season adult aggregations and diapause preparation behavior cued by shorter day lengths [8, 37]. Based on the trap data and DD model used in this study, future pest managers in northern Utah can more effectively monitor for nymph and adult life stages of *H. halys* and develop strategies to mitigate pest populations before they arise, a critical component of integrated pest management [38].

Results from voltinism studies indicate that *H. halys* is primarily univoltine in northern Utah, with the potential for a partial second generation composed of early instar nymphs. However, this partial second generation will likely not contribute to increased overwintering populations of *H. halys* in Utah. Though it is important to note that future studies should continue to assess the potential for bivoltine populations in Utah as changing climate conditions may provide the opportunity for increases in seasonal DD accumulations [6, 39]. The greatest production of nymphs in 2019 was observed when peach was a secondary host, and the cohort with access to tart cherry and peach had higher sustained populations of nymphs than the catalpa-peach treatment. Tart cherry blooms in April–May and catalpa in late May–June, which means F1 nymphs had earlier access to developing and nutrient rich fruit structures on tart cherry compared to catalpa. This difference in bloom periods could account for the higher numbers of nymphs in tart cherry-peach compared to catalpa-peach treatments. Peach has been documented as a highly suitable host, especially when fruit and foliage are both present, as was the case for this study (21 May through 4 September) [24].

In our observations, peach had slightly higher numbers of second and third instar nymphs in July but relatively similar numbers of F1 adults produced in September when compared to *H. halys* populations confined to catalpa or tart cherry. Catalpa, peach, and tart cherry all supported a full F1 generation, but contrary to expectations, the dual-host treatments resulted in very few to no F1 adults despite the high nymphal populations. This was not in line with our initial hypothesis that larger F1 adult populations would be produced when nymphs had access to multiple hosts. The cause for low numbers of F1 adults on mixed host treatments is not clear from our results, but it could be due to stress caused by human-mediated transfer of third instar nymphs from the first to second host. In general, voltinism observations were likely affected by the short-term spring storage of adults under lab rearing conditions before deployment into sleeve cages and the inability of *H. halys* adults and nymphs to disperse to preferred hosts for feeding and oviposition resources as under wild conditions [8, 40].

Another limiting factor in the experimental design of the voltinism study was the small sample size. Wild *H. halys* were sparse in April and May of both years, making the initial number of adults (70 in 2018 and 60 in 2019) much fewer than was desired. This was also the cause for the later initial deployment times in 2018, which likely delayed initial egg laying, especially for catalpa. Low numbers of wild collected adults also made for unbalanced sex ratios, which translated to uneven potential for egg production between years and plant species; consequently, F1 adult numbers were relatively low as well, which forced sleeve cage consolidation and left comparison between plant treatments as observational only.

Our results support that *H. halys* is primarily univoltine in northern Utah, and the overwintering population is composed of reproductive diapausing F1 adults. Future management tactics would be most effective in preventing these adult populations in subsequent years by targeting the 2^{nd}–5^{th} nymphal instars which first occurred at approximately 300–350 DD and reached their peak populations between 400-1000 DD. Nymphs cannot fly and generally occur in higher densities on host plants than the highly dispersive and flight-capable adults, making them easier targets for control [41]. Timing insecticide sprays to target susceptible life stages is key for effective control of destructive pest populations.

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CHAPTER IV

SURVEYS IN NORTHERN UTAH FOR EGG PARASITOIDS OF *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) DETECT *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) [1,2]

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 non-native biological control agents, namely parasitoid wasps, have been assessed for efficacy. *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 parasitising *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 and adult wasps from five of these species completed emergence. Native species had low mean rates of adult emergence from wild (0.5–3.7%) and lab-reared (0–0.4%) egg masses. In 2019, an adventive population of *T. japonicus* was discovered for the first time in Utah, emerging

from 21 of the 106 wild *H. halys* egg masses found that year, and none from lab-reared eggs. All *T. japonicus* emerged from egg masses collected on *Catalpa speciosa* (Warder). Our results support other studies that have observed 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

[1] We thank Biodiversity Data Journal, by Pensoft, for allowing the reprinting of this publication in this dissertation

[2] Coauthored by Zachary R. Schumm, Elijah Talamas, Lori R. Spears, Diane G. Alston

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 2020, it has been detected in 46 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 of 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 increased application frequency and disruption of integrated pest management, including secondary pest outbreak (Lee et al. 2014, Leskey et al. 2014, Leskey et al. 2012a, Leskey et al. 2012b). 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, Encyrtidae and Eupelmidae (Abram et al.

2017, Cornelius et al. 2016a, Cornelius et al. 2016b, Balusu et al. 2019, Talamas et al. 2015a, Talamas et al. 2015b). However, parasitism rates are low, likely due to inability of native species to overcome healthy *H. halys* egg defences (Abram et al. 2017, Abram et al. 2014, 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. 2019a, Abram et al. 2014, Cornelius et al. 2016a, Schumm 2020). Therefore, evaluating native wasp parasitism rates, especially in novel landscapes where new behaviour 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 *T. japonicus* have been discovered emerging from *H. halys* egg masses in North America (Milnes et al. 2016, Talamas et al. 2015b) 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).

Though adult wasp emergence has been documented on eggs of some native Pentatomidae species, *Trissolcus japonicus* has shown superior adult emergence rates on *H. halys* eggs (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 parasitising *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 utilise *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, most notably high elevation (>1200 m) and arid sites with a hot summer and cold winter climate (Utah Climate Center 2020), as compared to other regions where *H. halys* occurs (Herlihy et al. 2016, Jarrett et al. 2019, Milnes et al. 2016, Stahl et al. 2019). Secondly, we compared parasitism rates of wild (*in situ*) versus lab-reared egg masses to better understand effective survey approaches and projection of natural parasitism rates in the field (Abram et al. 2017).

Materials and Methods

Survey Sites.

Surveys for native and exotic parasitoid wasps of *H. halys* eggs in northern Utah were conducted from June through September in each of 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 4-1 and 4-2).

Stink Bug Colony.

Halyomoprha 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 in Trenton, New Jersey. The lab colony was maintained at 25–28°C, 40–60% RH, with a 16:8 hr photoperiod.

Survey Methods.

Fresh lab-reared egg masses were deployed at field sites within 24–48 hr post-oviposition. All lab-reared egg masses were oviposited on to paper towels, assessed for the number of eggs they contained and attached to wax-covered cardstock (4 cm x 4 cm), using double-sided sticky tape with sand to cover excess adhesive before field deployment. Lab-reared egg masses mounted on cardstock were attached to the underside of plant leaves (Table 4-1) 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 the 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 4-2). 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. Collected egg masses were inspected for the number of hatched (*H. halys* emergence), parasitised (parasitoid wasp emergence), missing (number of lab-reared eggs not present after field collection), unhatched or predated eggs (e.g. chewing or sucking damage) present 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 (defined as the proportion of egg masses in which one or more eggs produced adult wasps) was compared amongst years and egg types (wild and lab-reared) using a generalised linear model with a quasi-binomial distribution to account for over-dispersion due to small sample sizes in some years and zero-inflation. We report means and intervals that have been inverse-linked from the logit scale of the statistical model to the original proportion scale. Computations used the *glm* function in the *stats* package and various functions in the *car* (Fox and Weisberg 2019) and *emmeans* (Lenth 2019) packages in R software (R version 3.6.1; R Core Team, 2019).

Voucher Specimens

Three voucher specimens of *Trissolcus japonicus* from this study have been deposited in the Florida State Collection of Arthropods, Gainesville, Florida (FSCA 00090589, FSCA 00090661, FSCA 00090662). A Darwin Core Archive of the data associated with these specimens is provided in *Suppl. material 1*.

Results

Over the three year survey period, a total of 39 parasitoids from five native wasp species emerged from six wild and five lab-reared *H. halys* egg masses. *Anastatus mirabilis* (Walsh & Riley), *A. pearsalli* Ashmead, *A. reduvii* Ashmead, *Trissolcus euschisti* (Ashmead) and *T. hullensis* (Harrington) were documented from both guarding females and successful emergence from *H. halys* egg masses (Figure 4-2). *Trissolcus utahensis* (Ashmead) and *Telenomus podisi* Ashmead were observed guarding *H. halys* eggs, but did not 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 parasitised and this parasitism was by native wasp species exclusively (Table 4-1). In June 2019, the Asian parasitoid *T. japonicus* was first discovered in Utah emerging from two wild *H. halys* egg masses at Site 1 in Salt Lake City (Figures 4-1–4-3), and was detected consistently from June through September. Further, a single egg mass with emergent *T. japonicus* was found at Site 17 in August 2019. *Trissolcus japonicus* was only detected at these two suburban landscape sites. A total of 452 *T. japonicus* emerged from 21 of the 106 wild egg masses found in 2019 (Figure 4-2). Parasitised 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* (Table 4-2).

When native wasp species successfully emerged from *H. halys* eggs, the mean number of parasitised eggs per affected egg mass was low, 4–25%. When considering only those egg masses giving rise to adult *T. japonicus* in 2019, the mean egg parasitism rate per mass was 78.5%. Additionally, in 2019, a group of 19 wild egg masses experienced a similarly high mean parasitism rate of 67.3%, though these egg masses did not have adult wasps present at the time of collection, only signs of chewing and emergence (Figure 4-2).

Mean parasitism of lab-reared egg masses was 0.42% and 0.05% in 2017 and 2018, respectively, with no wasps emerging in 2019. Mean parasitism rates of wild-collected egg masses in 2017, 2018 and 2019 were 2.9%, 3.7% and 28.2%, respectively (Table 4-3). The generalised linear model did not reveal a significant two-way interaction between year and egg type ($P = 0.196$, $F_{2,348} = 1.63$). Significantly more wasps emerged from wild than lab-reared egg masses ($P = 0.002$, $F_{1,348} = 9.50$). There were no significant differences in mean wasp emergence amongst years ($P = 0.797$, $F_{2,348} = 0.23$).

Discussion

Surveys of wild and lab-reared *H. halys* eggs in northern Utah demonstrated relatively high diversity of native parasitoid wasps, but these native species all exhibited low rates of parasitism. These findings are congruent with other North American surveys of *H. halys* egg parasitoids (Dieckhoff et al. 2017, Abram et al. 2019b). Low native parasitism rates could be caused by deterrence from natural chemical defences 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 the use of parasitism emergence as a metric of parasitoid effectiveness underestimates native wasp effects on *H. halys* eggs since partially developed wasps that do not complete emergence often kill the stink bug host (Abram et al. 2019a, Cornelius et al. 2016b, Schumm 2020). Although our egg dissections revealed many unhatched *H. halys* eggs with undifferentiated contents (Milnes and Beers 2019), the ultimate cause of egg death could not be ascertained.

Our results support those of Jones et al. (2014) and Abram et al. (2017) who found that wild (*in situ*) egg masses more accurately detect the presence and ability of parasitoid wasps to emerge from *H. halys* eggs than do field-deployed lab-reared egg masses. This difference may be due to a variety of factors, including the age of the egg mass upon deployment, length of egg mass exposure to field conditions and deployment height of egg masses in host trees. Hedstrom et al. (2017) noted the importance of semiochemical cues associated with the success of *T. japonicus* in finding and stinging *H. halys* egg masses. Research by Boyle et al. (2019) has also shown that kairomones, left by *H. halys* on host plant leaves, are detectable by *T. japonicus* and the wasp resides on these leaves longer than those lacking such kairomones. Therefore, lower parasitism rates of lab-reared egg masses could be due to reduced kairomones cues.

Although current parasitism by the exotic *T. japonicus* in northern Utah is modest, relative to those in its native range (Yang et al. 2009, Zhang et al. 2017), our results indicate that *T. japonicus* has the potential to provide biological control of *H. halys* in the Intermountain West. Parasitism rates were not shown to be different amongst years, but our data clearly show higher parasitism in 2019, when *T. japonicus* was discovered, as compared to previous years. The dissonance of biological and statistical conclusions in our results is likely due to the variable and low sample size of egg masses. *Trissolcus japonicus* may have killed more *H. halys* eggs than we were able to document, based on identification of the causal wasp. Indeed, many egg masses were attacked by parasitoids that had already emerged from eggs before collection in 2019, with higher mean parasitism rates in affected egg masses than those observed for native wasp species, suggesting that at least some of the unidentified parasitoids were *T. japonicus*. It is also of interest to point out that *T. japonicus* was detected in two suburban landscape sites in Salt Lake County in 2019 and not in agricultural sites. The affinity of *H. halys* for catalpa and several other species of ornamental trees may be an important factor is supporting establishment of adventive *T. japonicus* in the Intermountain West and other novel regions.

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, detection of an adventive *T. japonicus* population implies potential for range expansion into other locations within 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, Talamas et al. 2015b, Milnes et al. 2016). Further research should focus on the capacity of *T. japonicus* to persist in the Intermountain West, specifically focusing on overwintering behaviour where heavy snowfall accumulation and consistent sub-zero temperatures occur (Lowenstein et al. 2019, Nystrom Santacruz et al. 2017). In fact, follow-up surveys in 2020 have documented continued detection of *T. japonicus* in Salt Lake and expansion into Utah counties (K. Richardson, personal communication). Laboratory rearing and 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 higher levels of reproductive parasitism 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 detection of *T. japonicus* in the Intermountain West, a novel geographic location for this parasitoid in North America.

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Tables and Figures

Table 4-1. Number of deployed and parasitised fresh lab-reared *H. halys* egg masses by native wasps on multiple plant species in northern Utah from June through September, 2017–2019. Parasitism denotes adult wasp emergence.

Plant Species	Total Egg Masses (Eggs)	Parasitised Egg Masses (Eggs)
Acer negundo	13 (311)	0 (0)
Ailanthus altissima	7 (187)	0 (0)
Catalpa speciosa	62 (1503)	1 (5)
Cercis canadensis	19 (474)	0 (0)
Elaeagnus angustifolia	5 (137)	0 (0)
Helianthus annuus	1 (25)	0 (0)
Malus domestica	48 (1099)	1 (1)
Malus sp.	6 (122)	0 (0)
Prunus armeniaca	11 (277)	0 (0)
Prunus cerasus	12 (298)	0 (0)
Prunus domestica	3 (83)	0 (0)
Prunus persica	17 (453)	3 (7)
Robinia pseudoacacia	3 (73)	0 (0)
Sambucus sp.	6 (168)	0 (0)
Zea mays	22 (559)	0 (0)

Table 4-2. Number of deployed and parasitised wild *H. halys* egg masses by all wasps, native and exotic, on multiple plant species in northern Utah from June through September, 2017–2019. Parasitism denotes adult wasp emergence.

Plant Species	Year	Total Egg Masses (Eggs)	All Parasitized Egg Masses (Eggs)	Egg Masses Parasitized by *T. japonicus* (Eggs)*
Acer grandidentatum	2018	1 (22)	1 (1)	0 (0)
Catalpa speciosa	2017	4 (108)	1 (4)	0 (0)
	2018	6 (164)	1 (7)	0 (0)
	2019	105 (2791)	43 (796)	21 (452)
Prunus cerasus	2018	1 (28)	0 (0)	0 (0)
	2019	1 (28)	0 (0)	0 (0)
Zea mays	2017	1 (28)	0 (0)	0 (0)

*****Wasp identity confirmed upon adult emergence from *H. halys* eggs.

Table 4-3. Mean parasitism of lab-reared and wild egg masses collected in northern Utah, 2017–2019. LCL and UCL refer to the lower and upper limit of a 68% confidence interval, respectively and approximately depict the mean +/- 1 SE.

Egg Type	Year	Mean Parasitism (%)	LCL	UCL
Lab-reared	2017	0.42	0.19	0.94
Wild	2017	2.94	0.74	11.00
Lab-reared	2018	0.05	0.00	0.73
Wild	2018	3.74	1.41	9.53
Lab-reared	2019	0.00	0.00	100.00
Wild	2019	28.20	25.90	30.64

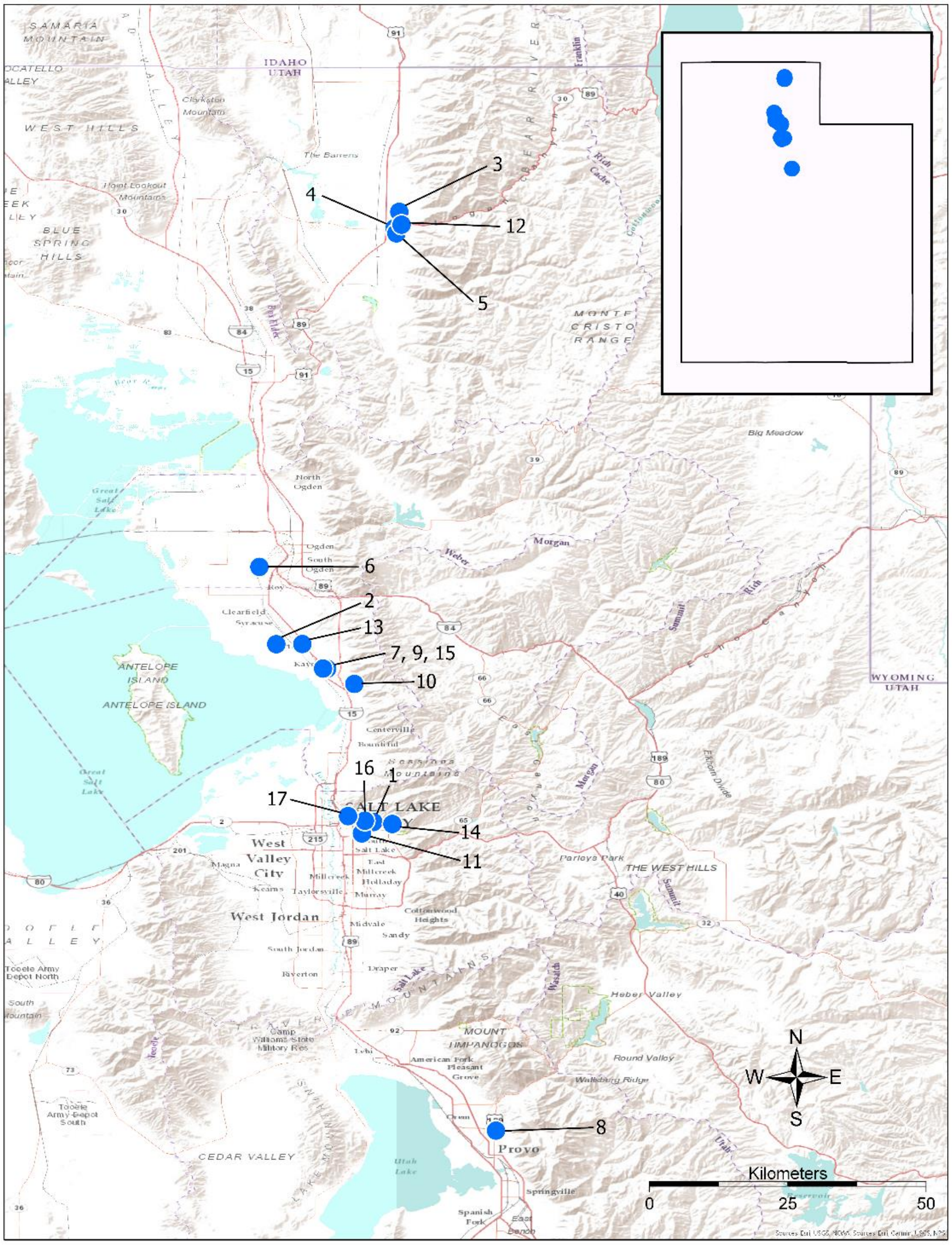

Figure 4-1. Blue dots indicate deployment and collection sites of lab-reared and wild egg masses in northern Utah, 2017-2019. *Trissolcus japonicus* was discovered at Sites 1 and 17. Geographical coordinates are as follows: Site 1: 40°46'14.8"N, 111°51'18.6"W; Site 2: 41°3'36.899"N, 112°0'46.944"W; Site 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; and Site 17: 40°46'49.3"N, 111°53'46.5"W.

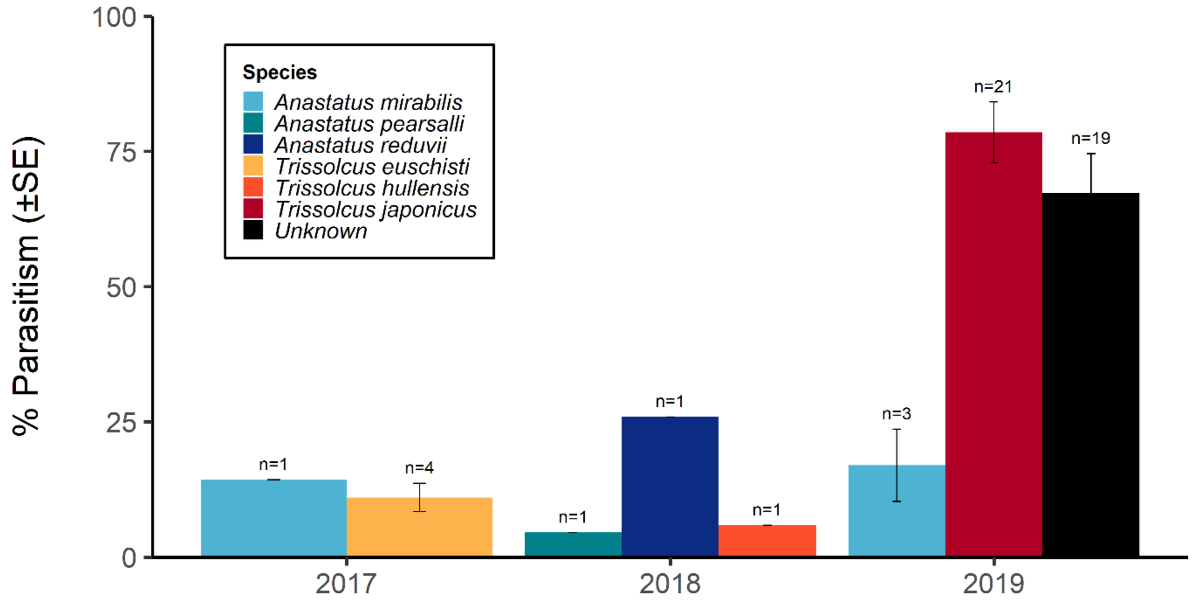

Figure 4-2. Percent parasitism (± SE) of eggs in wild and lab-reared egg masses with adult wasp emergence in northern Utah, 2017–2019. Sample size (n) represents the number of egg masses parasitised by the indicated wasp species in each year. Bars without standard error lines represent single egg masses. The *Unknown* category represents egg masses in which parasitoid wasp emergence was confirmed, but no wasp specimens remained to confirm species identification.

Figure 4-3. Photo of female *Trissolcus japonicus* (FSCA 00090662), found in Salt Lake City, Site 1, on 17 June 2019. Key identifying characters include the episternal foveae occurring in a continuous line from the postacetabular sulcus to the mesopleural pit.

CHAPTER V

Comparison of Yellow and Blue Sticky Cards for Detection and Monitoring Parasitoid Wasps of the Invasive *Halyomorpha halys* (Hemiptera: Pentatomidae)[1,2]

Abstract

The invasive *Halyomorpha halys* (Stål) is a significant agricultural and urban nuisance pest in many parts of the world. In North America, biological control of *H. halys* by parasitoid wasps in the families Scelionidae and Eupelmidae has shown promise. An effective technique for detection and monitoring native and exotic parasitoids is deployment of yellow sticky cards; however, yellow cards also attract non-target arthropods, reducing efficiency and accuracy of parasitoid screening. This study sought to identify an alternative yet effective trapping technique by comparing the number of target parasitoid wasps [*Anastatus* spp. (Eupelmidae), *Telenomus* spp. (Scelionidae), and *Trissolcus* spp. (Scelionidae)] and arthropod bycatch on yellow and blue sticky cards deployed in urban, orchard, and vegetable landscapes in northern Utah from late May to early October in 2019 and 2020. Yellow sticky cards captured 54–72% more target parasitoids than blue cards from June through August in all three landscape types in both years; however, a positive correlation in parasitoid capture indicated blue cards detect target parasitoids, just in fewer numbers. Both card colors detected adventive *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) in initial findings of 2019, and in expanded locations of 2020. Furthermore, blue cards captured 31–48% less Diptera and non-target Hymenoptera than yellow cards in both years across all three landscapes, translating to reduced card processing time and impacts to beneficial insect

populations. Our results suggest that blue vs yellow sticky cards offer an alternative monitoring technique to survey for *H. halys* parasitoids.

Keywords

Anastatus spp., bycatch, parasitoid, survey, *Telenomus* spp., *Trissolcus* spp

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[2] Coauthored by Lori R. Spears and Diane G. Alston

Introduction

During the past two decades, *Halyomorpha halys* (Stål) has become a significant agricultural and urban nuisance pest in North America (Hoebeke and Carter 2003, Leskey et al. 2012, Rice et al. 2014, Lee 2015) as well as in many other parts of the world (Haye et al. 2015). Consequently, much research has focused on assessment of biological control agents available in its native range of Asia that offer effective population suppression, specifically parasitoid wasps (Yang et al. 2009, Lee et al. 2013). There has been particular emphasis on *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae), due to its efficiency in parasitizing *H. halys* eggs in its native range (Talamas et al. 2013, Zhang et al. 2017), and because adventive populations have been detected in North America (Talamas et al. 2015a, Milnes et al. 2016, Jarrett et al. 2019, Holthouse et al. 2020).

Monitoring efforts for the exotic *T. japonicus* and native parasitoid wasp species capable of parasitizing *H. halys* eggs have been conducted across North America and Europe using egg mass surveys (Herlihy et al. 2016, Abram et al. 2017, Dieckhoff et al. 2017, Stahl et al. 2019a, Zapponi et al. 2020) and yellow sticky cards (Lowenstein et al. 2019, Schumm et al. 2019, Peterson et al. 2021). Though both techniques are capable of parasitoid detection, yellow cards offer a more convenient approach to long-term and large-scale parasitoid detection and monitoring efforts (Quinn et al. 2019). The color yellow has been proven to attract some Scelionidae parasitoid wasp species (Ferreira Santos de Aquino et al. 2012), and sticky cards remain effective at detecting parasitoids in the field for longer durations than stink bug egg masses, as eggs may experience predation or decreased parasitoid attraction within just a few days (e.g., fresh eggs) (Qiu et al. 2007, Morrison et al. 2016). One downside to the convenience of yellow card deployment is the attraction and inadvertent capture of bycatch, or non-target arthropods (Yee et al. 2013a, 2013b, Horton et al. 2019). Bycatch is known to impede or slow the processing time of target taxa, increase trap processing costs, and can result in the undesired mortality of rare and beneficial insects (Weber and Ferro 1991, Cha et al. 2015, Spears and Ramirez 2015, Jorgensen et al. 2020). Many of the target Nearctic Scelionidae that parasitize *H. halys* eggs are 1-2 mm in length (Talamas et al. 2015b) and can be easily concealed or damaged by bycatch of larger arthropod taxa.

Exploring alternative trap lures, sizes, shapes, colors, and other features is critical to mitigation of bycatch, while facilitating accurate monitoring of target species (Yee 2013a, Spears et al. 2016, Grocock et al. 2020). It is known that Hymenoptera are most sensitive to light reflectance in the UV, blue, green, and yellow spectrums (Peitsch et al. 1992, Briscoe and Chittka 2001, Ferreira Santos de Aquino et al. 2012). The current study sets out to compare efficacy of blue and yellow sticky cards, assess bycatch rates, and develop alternative options for parasitoid detection and survey in diverse landscapes (urban, orchard, and vegetable) with known *H. halys* populations in northern Utah.

Materials and Methods

Card Deployment

Double-sided yellow and blue sticky cards (20 x 14 cm; Alpha Scents Inc., West Linn, OR, USA) were deployed for 14 d (± 1 d) intervals beginning 29–30 and 25–28 May in 2019 and 2020 respectively, and ending on 1 October in both years, resulting in nine deployment periods in each year. Cards were deployed at 24 sites in Cache, Davis, Salt Lake, Utah, and Weber counties of northern Utah. Sites represented eight replications of three landscape types: residential urban, vegetable row crops, and fruit orchards. At each site, one yellow and one blue card were placed at approximately 2 m height and 1 m apart. Cards were attached to tree branches or metal stakes using twist ties. Manufacturer wavelength reflectance specifications for the yellow and blue cards were 575.12 nm and 466.19 nm, respectively. After collection, biodegradable plastic straws (Evriholder, Anaheim, CA, USA) were placed as spacers between cards to prevent adherence, and stored at –13°C until processing. The duration of card storage was variable, from a few days to several months.

Card Processing

Each card was examined under a stereomicroscope (Leica Stereozoom S9E, Leica Microsystems Inc., USA) with 97.6x–880x magnification for the presence of target parasitoid genera, which included *Anastatus* spp. (Hymenoptera: Eupelmidae), *Telenomus* spp. (Hymenoptera: Scelionidae), and *Trissolcus* spp. (Hymenoptera: Scelionidae). These genera were selected because they have been observed parasitizing *H. halys* eggs in Utah (Holthouse et al. 2020) and elsewhere in the U.S. (Talamas et al. 2015a, Abram et al. 2017, Dieckhoff et al. 2017, Stahl et al. 2019b). Target wasps were removed from cards with a 10 mm diam. cork borer/punch (Cole-Parmer, Vernon Hills, IL, USA) to support convenient manipulation of specimens on small pieces of card stock. Wasps encased in the viscous adhesive were cleaned by soaking in Histo-Clear II histological clearing fluid (National Diagnostics, Atlanta, GA, USA) for ~5–7 min. After drying, wasps were point-mounted to an insect pin for identification. Wasps in the family Scelionidae were identified to genus using keys by Johnson (1984), Masner (1980), and Talamas (2015b); wasps in the family Eupelmidae were identified using an annotated key by Gibson et al. (1997) and a key on North American *Anastatus* spp. by Burks (1967). Species level identification was only performed for *Trissolcus* spp. (Talamas 2015b) since surveys were focused on detecting the exotic *T. japonicus*. Some *Trissolcus* specimens were unidentifiable beyond genus level due to physical damage. All intact parasitoid wasps were pinned, labelled, and stored in the Alston Lab, Department of Biology, Utah State University, Logan, UT. Voucher specimens were deposited in the USU Insect Collection.

The number of bycatch arthropods per card was recorded by order. Counts were capped at 100 individuals per order to support sustainable processing time. The time required to count bycatch was recorded for a subgroup of 66 blue and 64 yellow sticky cards deployed between late August and early September, 2020; a time period associated with moderate capture of target parasitoids and bycatch. Processing times to remove and identify target parasitoids was not included in this analysis.

Statistical Analyses

Linear mixed effects models were used to test the main and interaction effects of card color, landscape type, and deployment period for the mean number of target wasps and mean number of combined Diptera and non-target Hymenoptera per card. Square root and log transformations were used for the target wasp and bycatch models, respectively, and to meet model normality distribution assumptions. Contrasts using

Tukey's HSD method, adjusted for type one error, were implemented for post-hoc analysis of pairwise mean comparisons. For all tests, α was set to 0.05. Spearman's correlation coefficient tests between numbers of target wasp captures on yellow and blue sticky cards were conducted for each year and individual landscape type. All models were conducted using various functions from packages *lme4* (Bates et al. 2015), *car* (Fox and Weisberg 2019), *emmeans* (Lenth 2020), and *ggpubr* (Kassambara 2020) within R software (R version 4.0.2; R Core Team 2020). All figures were created using the ggplot2 package in R (Wickham 2016).

Deployment period 9, representing the last deployment date in late September, was removed from both 2019 and 2020 analyses because the mean number of wasps was at or near zero for all sites due to adverse weather conditions. One vegetable site in Salt Lake City was removed from 2019 analyses due to extremely high numbers of parasitoid wasps in the first two and very last deployment periods that year. This vegetable site was in close proximity to residential homes, contained a high diversity of plant species and was surrounded by several fruit trees; these factors likely contributed to the abnormally high number of parasitoid wasps found there. Excluding this site allowed for improved homogeneity of variance and normality of residuals in these models. Due to high winds and vandalism, four sticky cards were lost before collection in 2019 and eight in 2020 out of a total of 368 and 384 analyzed cards per year, respectively; these cards were excluded from statistical analyses.

Results

Target Parasitoids

In both years of the survey, there were approx. three times more target parasitoid wasps detected on yellow than blue sticky cards: 1,608 vs 560 in 2019, and 966 vs 301 in 2020. The majority of captured parasitoids belonged to the genus *Trissolcus* (72–88%), followed by *Telenomus* (11–28%). For both card colors, *Trissolcus* spp. were captured most frequently in urban landscapes, whereas *Telenomus* spp. were more common in vegetable sites. *Anastatus* spp. accounted for ≤ 2% of target wasps detected on all cards across all landscape types and years (Table 5-1).

The vast majority of *Trissolcus* spp. captured were *Trissolcus euschisti* (Ashmead), primarily in urban and orchard landscapes for both blue (63–66% of all *Trissolcus* captured) and yellow (65–67% of *Trissolcus*) cards. Capture of *T. japonicus* occurred most commonly in urban and orchard landscapes, but accounted for ≤ 9% of the total *Trissolcus* detected for any one card color and landscape type. *Trissolcus hullensis* (Harrington) was found most commonly within vegetable and orchard landscapes on blue (3–15% of *Trissolcus*) and yellow (7–10% of *Trissolcus*) cards. *Trissolcus utahensis* (Ashmead) occurred most commonly in vegetable landscapes on blue (18% of *Trissolcus*) and yellow (25% of *Trissolcus*) cards. There was a total of 648 unidentifiable *Trissolcus* spp. due to physical damage; approx. 1/4 of the captured wasps in all landscape types for blue (27–29%) and yellow (19–25%) cards (Table 5-2).

Higher numbers of target parasitoids were captured on yellow compared to blue cards from late June through August in 2019 (Fig. 5-1A) resulting in a significant card color by deployment period interaction (Table 5-3). In contrast, in 2020, this interaction was not significant (Table 5-3); however, that year more parasitoids were captured on sticky cards deployed in late May through early July (Fig. 5-1B; significant main effect for deployment, Table 5-3). Further, the number of parasitoids on yellow cards was greater than blue in urban, orchard, and vegetable landscapes in both years (Table 5-3, Fig. 5-2AB). Yellow cards in urban landscapes captured more parasitoids than yellow cards in vegetable landscapes in both years (Fig. 5-2AB). In 2019, parasitoid captures on yellow cards in orchards were also greater than those in vegetable landscapes (Fig. 5-2A). The mean number of parasitoids captured by blue cards did not differ among landscape types (Fig. 5-2AB). Overall, more target parasitoids were captured in 2019 than 2020 (Figs. 5-1 and 5-2).

Target parasitoid captures on yellow cards were positively correlated with captures on blue cards in 2019 ($r = 0.43$, df = 182 $P < 0.001$) and 2020 ($r = 0.62$, df = 190, $P < 0.001$). In 2019, there was a positive correlation between parasitoid captures on blue and yellow cards in urban ($r = 0.42$, df = 62, $P <0.001$) and orchard ($r = 0.31$, df = 62, $P = 0.01$) landscapes, but not for vegetable ($r = 0.23$, df = 54, $P = 0.08$) landscapes. However, in 2020, there was a correlation in parasitoid captures on blue and yellow cards within all three landscape types (urban: $r = 0.67$, df = 62, $P <0.001$; orchard: $r = 0.49$, df = 62, $P <0.001$; vegetable: $r = 0.62$, df = 62, $P <0.001$).

Bycatch

There were 1.8 and 1.6 times more total bycatch individuals caught on yellow than blue cards in 2019 (45,844 vs 25,920) and 2020 (48,594 vs 30,888). The highest bycatch captures occurred in vegetable landscapes for both card colors (1.5–2.6 and 1.3–1.9 times more in vegetable than orchard and urban for blue and yellow, respectively). The vast majority of bycatch belonged to the Orders Diptera, Thysanoptera, Hymenoptera, and Hemiptera. Other bycatch was in the Orders Araneae, Coleoptera, Dermaptera, Ephemeroptera, Lepidoptera, Neuroptera, and Odonata. The mean assessment time per card required to count bycatch individuals was 3 minutes and 54 seconds for blue cards and 5 minutes and 40 seconds for yellow cards (assessment times measured in late August and early September, 2020, only), a 1.5 times increase in processing time for yellow cards.

Diptera were the most abundant bycatch taxa in urban and orchard landscapes accounting for 50% and 38% of the bycatch, respectively, on blue cards, and for 42–48% on yellow cards. Thysanoptera were the most abundant bycatch order on blue cards in vegetable landscapes (41% of the bycatch), with Diptera and Thysanoptera each accounting for 31% of bycatch on yellow cards in vegetable landscapes.

Results from the linear mixed effects model considering the mean number of Diptera and non-target Hymenoptera revealed no interactions among card color, landscape type, or deployment in 2019; yet significant main effects revealed that more Diptera and non-target Hymenoptera were captured by yellow than blue cards, and sticky cards deployed mid-season, specifically late June through late August, captured more Diptera and non-target Hymenoptera (Tables 5-4 and 5-5). However, in 2020, all two-way interactions were significant (Table 5-4). More Diptera and non-target Hymenoptera were caught on yellow compared to blue cards across all deployment periods (Table 5-4, Fig. 5-3A). Further, yellow cards captured significantly more Diptera and non-target

Hymenoptera than blue within all landscapes and blue cards captured fewer bycatch in urban compared to vegetable landscapes; however, bycatch numbers on blue cards were similar in urban and orchard landscapes (Table 5-4, Fig. 5-3B). Diptera and non-target Hymenoptera captures were highest in vegetable and orchard landscapes in the early part of the season, and in vegetable landscapes later in the season; urban landscapes captured the fewest Diptera and non-target Hymenoptera across almost all deployment periods (Table 5-4, Fig. 5-3C).

Discussion

Both yellow and blue sticky cards detected a similar complex of target parasitoid wasps; however, yellow cards captured significantly higher numbers compared to blue cards across all landscape types and during most deployment periods. Both yellow and blue cards effectively detected peaks in wasp abundance in July and early August, likely correlated with warmer temperatures and increased stink bug host (e.g., *H. halys*) egg abundance (Nielsen et al. 2016, Holthouse et al. 2021). The relatively low target wasp capture in late May to early June of 2019, as well as early September of both years was likely the result of lower temperatures (mean minimum daily temperature May 25 to June 10 in Salt Lake City, Utah: 2019 = 8.94°C, 2020 = 12.17°C) or shorter photoperiods which can result in diminished wasp development and activity (Arakawa and Namura 2002, Hance et al. 2007, Stahl et al. 2019b, Cordeiro and Bueno 2021, climate.usu.edu).

The majority of target wasps captured on sticky cards belonged to the genus *Trissolcus*, specifically the native species *T. euschisti*. This species has been documented in previous parasitoid surveys in northern Utah (Schumm et al. 2019, 2020b), and is known to successfully complete development and emerge from *H. halys* eggs (Abram et al. 2019, Jarrett et al. 2019, Holthouse et al. 2020). *Trissolcus euschisti* and *T. japonicus* were most commonly detected in residential urban, followed by orchard landscapes. Both species prefer arboreal habitats where their primary stink bug hosts occur (Okuda and Yeargan 1988, Talamas et al. 2015a, Cornelius et al. 2016, Jones et al. 2017, Kaser et al. 2018, Peterson et al. 2021, Quinn et al. 2021). *Trissolcus hullensis* and *T. utahensis* were detected most commonly in vegetable landscapes, where their stink bug hosts (e.g., *Euschistus* spp.) are known to commonly feed and oviposit (Pease and Zalom 2010, Ganjisaffar et al. 2020).

Very importantly, the first detection of *T. japonicus* in Utah was documented in this study. *Trissolcus japonicus* was detected on both card colors in Salt Lake and Weber counties in 2019 (Holthouse et al. 2020), and expanded to Utah County in 2020. This study represents the first documentation of blue sticky cards being used to effectively monitor for *T. japonicus*.

Both card colors captured a large proportion of unidentifiable *Trissolcus* spp. due to physical damage caused by the sticky adhesive. These damaged specimens can result in false negatives of important parasitoid species. Fortunately, future sticky card monitoring and detection efforts will be less reliant on the morphological integrity of specimens for identification, as a new species-specific molecular identification technique for *T. japonicus* was recently created by Chen et al. (2021).

Telenomus was the second most commonly detected genus on both blue and yellow cards, indicating that these parasitoids are either less attracted to yellow and blue cards than *Trissolcus* or have smaller wild populations in the areas surveyed. Other similar sticky card surveys have documented higher numbers of *Telenomus* over *Trissolcus* species on yellow cards, indicating the observed density of genera in this study may be regionally specific (Peterson et al. 2021). The abundance of *Telenomus* varied across landscapes, but orchard and vegetable landscapes had proportionally higher detections, as noted in other research on *Telenomus podisis* Ashmead (Okuda and Yeargan 1988, Ogburn et al. 2016). This species can successfully parasitize *H. halys* eggs, but usually at low levels (Dieckhoff et al. 2017, Holthouse et al. 2020), and has been documented on yellow cards in other *H. halys* parasitoid surveys (Quinn et al. 2021). We did not identify *Telenomus* to species and it is possible that captured individuals represent species incapable of stinging or successfully parasitizing *H. halys* (Peterson et al. 2021).

Similar to the results of Quinn et al. (2021), relatively few *Anastatus* were detected on cards in this study, with no apparent card color or landscape type preference. Based on the low number of individuals captured in this genus, wild and sentinel egg mass surveys may be more effective than sticky cards at detecting species of *Anastatus* capable of attacking *H. halys* eggs (Jones et al. 2014, 2017, Dieckhoff et al. 2017).

Although valuable information can be gained through examination of bycatch (Buchholz et al. 2011, Spears and Ramirez 2015), Diptera and non-target Hymenoptera captures contributed to greater processing times, especially for yellow cards where bycatch captures were 1.5–2 times greater than on blue cards. Numerous bycatch individuals were similar in size, morphology, or color to the target parasitoid wasps. Diptera regularly covered large portions of the sticky card surface, sometimes obscuring other specimens (Fig. 4). Though Thysanoptera and Hemiptera were also captured in high numbers, they were generally smaller or easier to distinguish from target parasitoid wasps and therefore not considered as disruptive to card processing. Because of this, bycatch analyses were focused on combined Diptera and non-target Hymenoptera captures. These insects were captured in high abundances from June through August when target parasitoids were also at their peak abundance; this observation was also noted by Quinn et al. (2021). The higher captures of Diptera and non-target Hymenoptera during this period may outweigh the benefit of increased captures of target parasitoids for yellow cards. In contrast, blue cards also detected target parasitoids during this peak activity time, but with substantially reduced bycatch. Further, monitoring efforts hoping to capitalize on higher *T. japonicus* detections in July and August may want to target residential urban and orchard landscapes, which capture less Diptera and non-target Hymenoptera during this peak time period compared to vegetable landscapes. It is also important to note that this study only accounted for the first 100 specimens per order encountered on each card, which means our results underestimate bycatch, especially for Diptera and Thysanoptera which often exceeded this upper limit.

Insects in the Order Hymenoptera provide important ecosystem services (Noriega et al. 2018). Many are pollinators (Southwick and Southwick 1992, Klein et al. 2007), some of which are experiencing population declines due to habitat loss, pathogens and pests, improper management practices, and other anthropogenic factors (Watanabe 1994, Colla and Packer 2008, Brown and Paxton 2009, Potts et al. 2016). It is unknown if sticky cards impact non-target Hymenoptera populations; however, we demonstrated that the use of blue vs yellow cards would reduce non-target captures, as was similarly noted by Atakan et al. (2016). Interestingly, blue cards in 2020 caught almost as many Hymenoptera as yellow cards in vegetable landscapes, likely due to the greater diversity of angiosperm plant species present in these landscapes (Hülsmann et al. 2015, Lanner et al. 2020). However, some Hymenoptera, such as *Bombus* spp., are highly attracted to the color blue (Stephen and Rao 2005), so blue cards may need to be avoided in vegetable landscapes.

The current study only addresses the disparity between target parasitoid and bycatch captures on yellow and blue sticky cards. This difference may have been due to the use of a suboptimal blue card color or other physical properties. Work done by Yee (2013a, 2015) found that different color shades, transparency properties, and direction of ambient lighting of yellow traps can elicit varying levels of response in the fruit fly *Rhagoletis indifferens* Curran, and this may also apply to different blue colors as well. Future studies may therefore seek to compare other traps with different properties to determine the most effective approach for attracting target parasitoids and minimizing bycatch. Different types of sticky card adhesives have demonstrated differing levels of effectiveness in insect capture, but both blue and yellow sticky cards in this study contained the same type of adhesive, so this is likely not a factor in these observed differences (Kaloostian 1961, Davidson et al. 2015).

Although relatively unselective trap types like yellow cards are sometimes necessary for novel or adventive insect monitoring programs where only a few potential target organisms are present (Marchioro et al. 2020), future *H. halys* parasitoid monitoring efforts may look to adopt slightly less attractive card colors in the pursuit of decreased bycatch or target species specificity. Blue cards offer low, but consistent season-long captures of target parasitoids in urban and orchard landscapes. Blue cards documented similar seasonal parasitoid population trends as yellow cards, similar to a study that compared efficacy of different trap types for *H. halys* (Acebes-Doria et al. 2018, 2020). As compared to yellow cards, blue cards enable faster processing times and reduced impact on beneficial insect populations. Importantly, blue cards successfully documented the first detection of *T. japonicus* in northern Utah, which is a primary target of *H. halys* biological control surveys in North America (Peterson et al. 2021, Quin et al. 2021). Since blue cards have faster processing times, producers and pest managers can deploy more cards, allowing for greater spatial and temporal coverage. More testing is necessary to fully appreciate the practical use of blue cards in monitoring for parasitoids of *H. halys*, but in light of the nearly global pest status of this invasive insect, this study offers the first look into an alternative sticky card monitoring technique.

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Tables and Figures

Figure 5-1. Interactions for card color (yellow and blue) by deployment period (14±1-d intervals late May to September) for mean number of target parasitoid wasps (± SE) in 2019 (A) ($P < 0.001$) and 2020 (B) ($P = 0.06$). * represent significant differences between yellow and blue sticky card mean wasp capture within a deployment period (Tukey HSD; $P < 0.05$). The interaction between color and deployment was not significant in 2020.

Figure 5- 2. Interactions for card color (yellow and blue) by landscape type (urban, orchard, and vegetable) for mean number of target parasitoid wasps (± SE) captured from May to September 2019 (A) and 2020 (B). Lowercase letters represent significant differences between card colors within a landscape type. Uppercase letters represent significant differences in parasitoid capture among landscapes for yellow cards (Tukey HSD; $P < 0.05$). There were no differences in parasitoid detection on blue cards among landscape types ($P > 0.05$).

Figure 5-3. **(A)** Interactions for card color and deployment period (14±1-d intervals late May to September) for the mean number of Diptera and non-target Hymenoptera (± SE) bycatch in 2020. * represent significant differences between yellow and blue sticky card mean capture within a deployment period. **(B)** Card color by landscape type (urban, orchard, and vegetable) interactions for mean number of Diptera and non-target Hymenoptera (± SE) captured from May to September 2020. Lowercase letters represent significant differences between card colors within a landscape type. Uppercase letters represent significant differences in bycatch capture among landscapes for blue cards. There were no differences in bycatch on yellow cards among landscape types ($P > 0.05$). **(C)** Landscape type by deployment period interaction for the mean number of Diptera and non-target Hymenoptera (± SE) in 2020. * represent significant differences between landscape mean captures within a deployment period. (Tukey HSD; $P < 0.05$).

Figure 5-4. Blue (left) and yellow (right) sticky cards collected from the same site 14 days after deployment. Black circles on the yellow card represent locations where target parasitoids were removed from the card in order for species identification.

Table 5-1**.** The number of target parasitoid wasps by genus captured on blue and yellow sticky cards in urban, orchard, and vegetable landscapes in 2019 and 2020 combined. Proportional abundance of each genus by card color and landscape type is shown in parentheses.

Color	Landscape	*Anastatus*	*Telenomus*	*Trissolcus*	Total
Blue	Urban	2 (0.01)	53 (0.15)	300 (0.85)	355
	Orchard	1 (0.00)	65 (0.28)	169 (0.72)	235
	Vegetable	5 (0.02)	62 (0.23)	204 (0.75)	271
Yellow	Urban	5 (0.00)	129 (0.11)	1,007 (0.88)	1,141
	Orchard	3 (0.00)	127 (0.15)	710 (0.85)	840
	Vegetable	0	145 (0.24)	448 (0.76)	593

Table 5-2**.** The number of *Trissolcus* spp. identified on blue and yellow sticky cards in urban, orchard, and vegetable landscapes in 2019 and 2020 combined. *Trissolcus* wasps that were unidentifiable below the genus level due to damage or obstruction of view are presented as *Trissolcus* spp. Proportional abundance of each species by card color and landscape type is provided in parentheses.

Color	Landscape	*T. japonicus*	*T. euschisti*	*T. hullensis*	*T. utahensis*	*Trissolcus* spp.	Total
Blue	Urban	10 (0.03)	199 (0.66)	5 (0.02)	5 (0.02)	81 (0.27)	300
	Orchard	3 (0.02)	106 (0.63)	5 (0.03)	8 (0.05)	47 (0.28)	169
	Vegetable	2 (0.01)	75 (0.37)	31 (0.15)	37 (0.18)	59 (0.29)	204
Yellow	Urban	87 (0.09)	679 (0.67)	6 (0.01)	24 (0.02)	211(0.21)	1,007
	Orchard	16 (0.02)	458 (0.65)	48 (0.07)	52 (0.07)	136 (0.19)	710
	Vegetable	4 (0.01)	174 (0.39)	46 (0.10)	110 (0.25)	114 (0.25)	448

Table 5-3. Results from the linear mixed effects model for mean target parasitoids by sticky card color, landscape, deployment period, and subsequent interactions in 2019 and 2020.

Year	Treatment	*F*	Df	*P*
2019	Color	95.96	1, 300	< 0.001*
	Landscape	7.29	2, 20	0.004*
	Deployment	11.23	7, 300	< 0.001*
	Color x Landscape	6.55	2, 300	0.002*
	Color x Deployment	5.48	7, 300	< 0.001*
	Landscape x Deployment	1.29	14, 300	0.21
	Color x Landscape x Deployment	1.51	14, 300	0.10
2020	Color	104.86	1, 315	< 0.001*
	Landscape	3.63	2, 21	0.04*
	Deployment	19.36	7, 315	< 0.001*
	Color x Landscape	5.40	2, 315	0.01*
	Color x Deployment	1.95	7, 315	0.06
	Landscape x Deployment	1.64	14, 315	0.07
	Color x Landscape x Deployment	0.60	14, 315	0.87

* indicates a significant difference amongst treatment group means ($P < 0.05$)

Table 5-4. Results from the linear mixed effects model of mean Diptera and non-target Hymenoptera by sticky card color, landscape type, deployment period, and subsequent interactions in 2019 and 2020.

Year	Treatment	*F*	Df	*P*
2019	Color	232.44	1, 296	< 0.001*
	Landscape	2.81	2, 20	0.08
	Deployment	9.32	7, 296	< 0.001*
	Color x Landscape	0.41	2, 296	0.67
	Color x Deployment	0.86	7, 296	0.54
	Landscape x Deployment	1.66	14, 296	0.06
	Color x Landscape x Deployment	0.30	14, 296	0.99
2020	Color	0	1, 303	< 0.001*
	Landscape	0	2, 303	0.03*
	Deployment	0	7, 303	< 0.001*
	Color x Landscape	0	2, 303	0.01*
	Color x Deployment	0	7, 303	< 0.001*
	Landscape x Deployment	0	14, 303	0.001*
	Color x Landscape x Deployment	0	14, 303	0.48

* indicates a significant difference amongst treatment group means ($P < 0.05$)

Table 5-5. Mean ($\bar{x}$) and standard error (± SE) of Diptera and non-target Hymenoptera captured in 2019 listed by color and deployment period.

Independent Variables	$\bar{x}$ (± SE)
<u>Color</u>	
Blue	56.6 (4.24)^{b}
Yellow	110.3 (8.28)^{a}
<u>Deployment (Date)</u>	
1 (29 May)	59.0 (5.49)^{d}
2 (10 June)	70.0 (6.43)^{bcd}
3 (24 June)	78.6 (7.27)^{bc}
4 (8 July)	89.4 (8.21)^{ab}
5 (22 July)	106.0 (9.74)^{a}
6 (7 Aug)	82.7 (7.60)^{abc}
7 (20 Aug)	90.1 (8.28)^{ab}
8 (5 Sept)	66.3 (6.14)^{cd}

Letters represent significant differences between mean bycatch capture between colors and deployment periods (Tukey HSD; $P<0.05$).

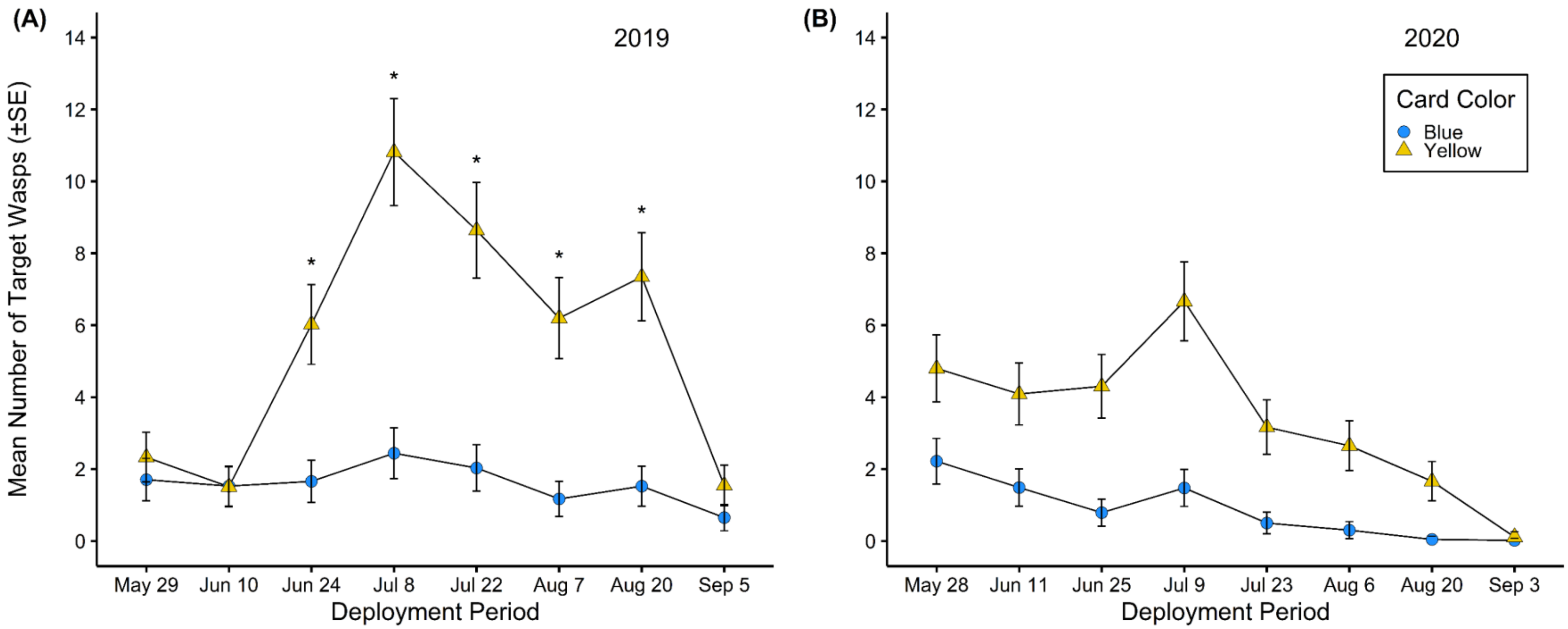
(A)
2019
Mean Number of Target Wasps (±SE)
14
12
10
8
6
4
2
0
*
May 29
Jun 10
Jun 24
Jul 8
Jul 22
Aug 7
Aug 20
Sep 5
Deployment Period
(B)
2020
Card Color
Blue
Yellow
May 28
Jun 11
Jun 25
Jul 9
Jul 23
Aug 6
Aug 20
Sep 3
Deployment Period

Fig. 5-1.

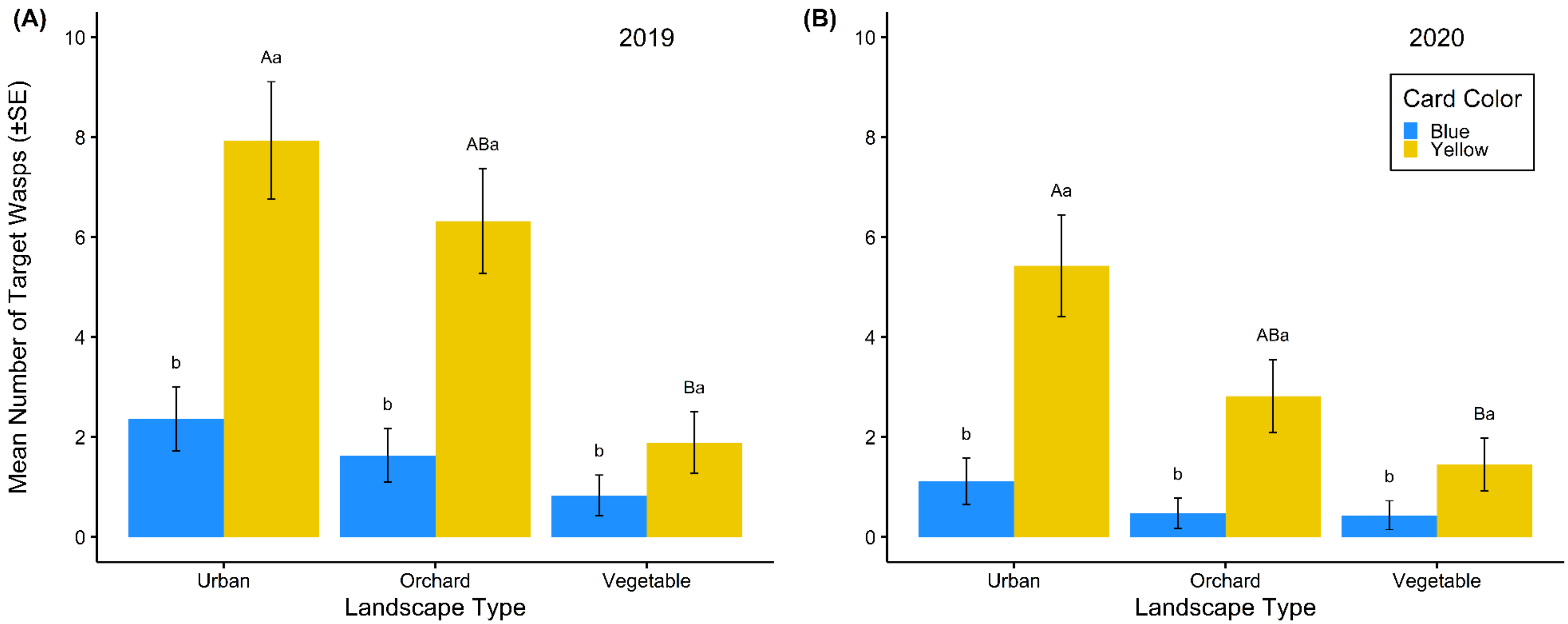
(A)
2019
Mean Number of Target Wasps (±SE)
10
8
6
4
2
0
Aa
ABa
Ba
b
b
b
Urban
Orchard
Vegetable
Landscape Type
(B)
2020
Card Color
Blue
Yellow
Aa
ABa
Ba
b
b
b
Urban
Orchard
Vegetable
Landscape Type

Fig. 5-2.

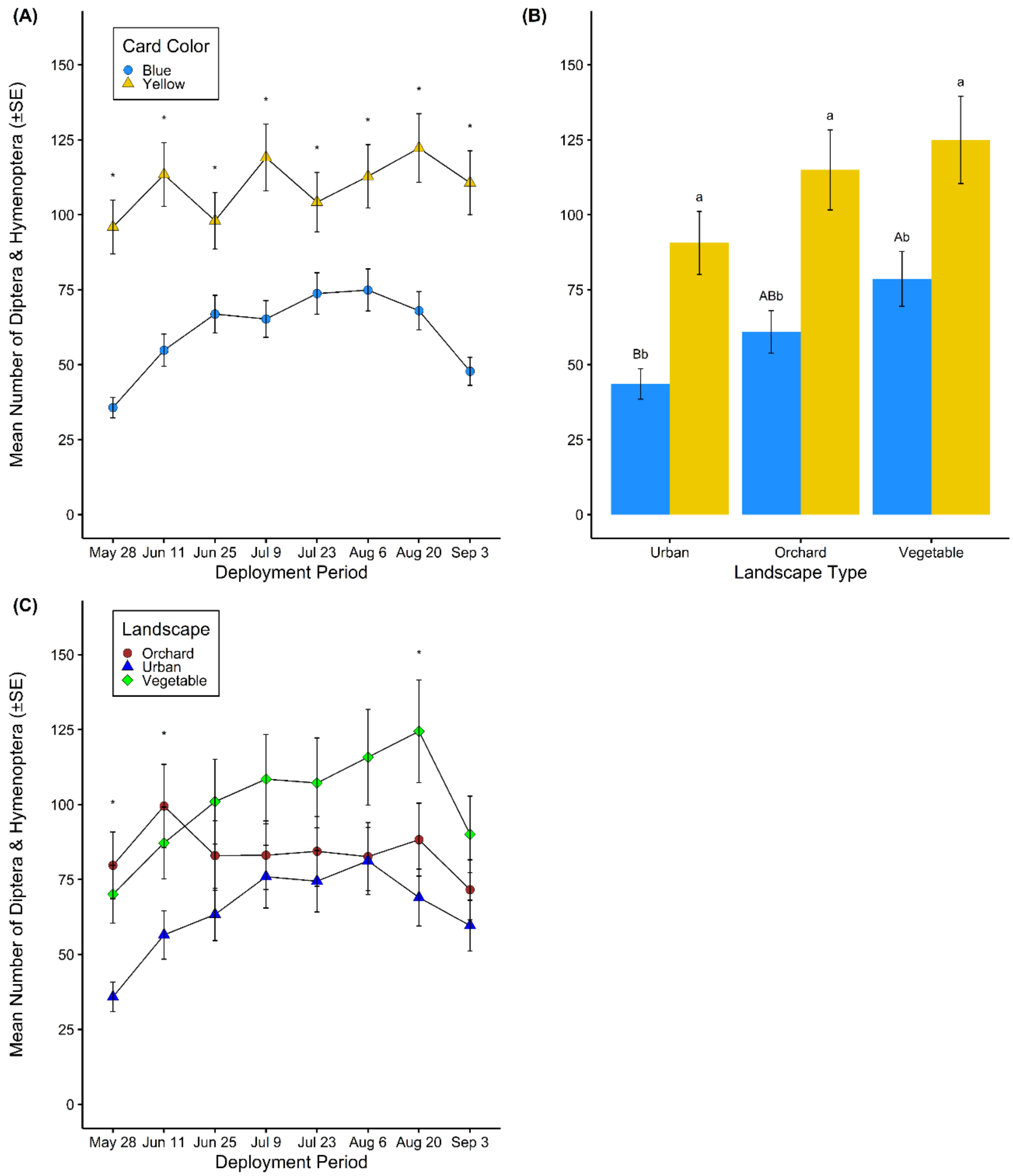
(A)
Card Color
Blue
Yellow
Mean Number of Diptera & Hymenoptera (±SE)
0
25
50
75
100
125
150
May 28
Jun 11
Jun 25
Jul 9
Jul 23
Aug 6
Aug 20
Sep 3
Deployment Period
(B)
a
a
a
Bb
ABb
Ab
Urban
Orchard
Vegetable
Landscape Type
(C)
Landscape
Orchard
Urban
Vegetable
Mean Number of Diptera & Hymenoptera (±SE)
Deployment Period

Fig. 5-3.

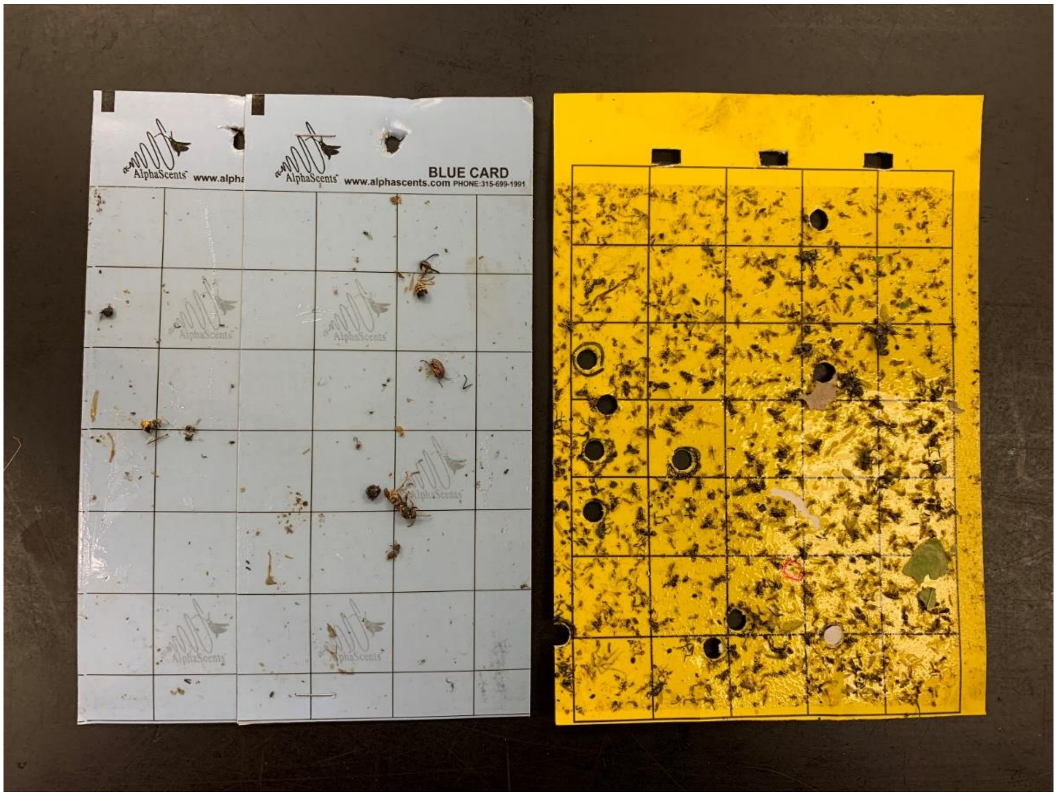
BLUE CARD
AlphaScents
www.alphascents.com PHONE:315-699-1991

Fig. 5-4.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The suite of studies presented in this dissertation highlight the host plant range, seasonal phenology, and biological control agents of *H. halys* in northern Utah, a region that presents unique geography and climatic conditions compared to other invaded regions of North America and Europe where *H. halys* is established. These three topics were explored herein to support development of timely pest management information for this invasive insect in Utah. The goal was to develop resources to inform management decisions that emphasize prevention and encourage less dependence on chemical controls which are primary aims of integrated pest management programs.

In Chapter II, I documented 53 host plant species with one or more life stage of *H. halys* present, and nine plant species that harbored two or more *H. halys* life stages. The most important host species across both years of survey was *Catalpa speciosa*, as the vast majority of egg masses, nymphs, and adults were found on this host. The large leaves, dense canopy, flowering structures, and large reproductive pods of this plant make it an ideal host for feeding and oviposition. This species has been deemed a sentinel host and should inform future monitoring and management efforts in Utah. More broadly, I found that the majority of host plants in northern Utah belonged to the families Fabaceae, Rosaceae, and Sapindaceae. Many of these species have been recorded in similar host plant surveys in the eastern U.S., but 29 species documented in Utah were novel hosts for *H. halys*. Three of note include *Populus tremuloides*, an important native plant in Utah that provides many key ecosystem services, *Acer ginnala*, and

Prunus virginiana ‘Schubert’. These three tree species are common urban and suburban landscape plants in northern Utah. This chapter also includes a list of non-host plant species, a great resource for those selecting plant species less likely to solicit *H. halys* establishment.

In Chapter III, *H. halys* trapping data from urban/suburban locations in Davis, Salt Lake, Utah, and Weber counties described the seasonal phenology of *H. halys* in northern Utah between 2017–2018 and in Salt Lake County in 2019–2020. Overall, adult trap captures revealed a primary spike in populations in May representing overwintered F0 adults emerging from winter diapause, a larger secondary peak in in July and early August representing development of the F1 adults, and a third increase in numbers in late September and early October, representing fall aggregation of F1 adults in preparation for winter diapause. Degree day (DD) modelling was based on daily maximum and minimum temperatures, lower (14.2°C) and upper (35.8°C) developmental thresholds for *H. halys*, and spring (~April 19) and fall (~August 22) biofix dates dictated by a critical photoperiod of 13.5 h; these methods and values were informed by primary literature as cited in Chapter III.

A biofix of 13.5 h photoperiod was validated by initial adult detections in spring of 2019 and 2020 within 2–8 days of critical photoperiods. Nymphs were first detected in traps June 16 to July 3 at 299–331 DD with peak numbers occurring in July and August (~500–1000 DD). Adult numbers displayed a mid-season increase in early July to early August (~400–600 DD) in 2017–2019 (trap catch was very low in 2020 and this trend was not observed). This increase in adults coincides with the established egg to adult maturation time of 537.6 DD (Nielsen et al. 2008), indicating the likely presence of both

F0 and F1 adults during these mid-season trap captures. Accumulation of DD for each *H. halys* life stage for 2017–2020 can be referenced for further detail in Figures 3-1AB and 3-2AB of Chapter III.

Voltinism of *H. halys*, or the number of generations possible within a single year, was addressed in Chapter III. Observations of wild caught adults confined to three susceptible host plants, *C. speciosa*, *Prunus cerasus, and Prunus persica,* revealed that *H. halys* is univoltine in northern Utah, with a partial second generation observed on *P. cerasus* in one year (2018). This partial second generation was likely due to the fact that 2018 exhibited higher heat units (1362.3 DD) than 2019 (1154.1 DD) by the time observations ended in early October (8 and 9 respectively) of both years. Cohorts of *H. halys* adults placed on *P. persica* or those transferred from *C. speciosa or P. cerasus* to *P. persica* upon development to the second instar in 2019, produced higher numbers of second and third instar nymphs than those confined to *C. speciosa or P. cerasus* alone. All host plants supported the production of F1 adults in both years except for those transferred *from P. cerasus* to *P. persica* in 2019. The cause for lower numbers (or the lack of) of mature F1 adults on transitional plant treatments is unknown, though it is suspected that human-mediated transfer of the insects to the second host may have induced stress.

Because *H. halys* is univoltine in northern Utah, control efforts targeting nymphs in the early season and adults in July and August should lower the likelihood for large populations of overwintering F1 adults and support more sustainable management of this invasive insect. This point is especially significant when comparing Utah to more southern regions of North America or Asia that experience at least two or more generations of *H. halys* per season, which makes timing control efforts more challenging due to overlapping generations. Because of this life history aspect, pest populations may be easier to predict and prevent in Utah relative to other invaded regions suffering from more significant pest pressure, especially considering decreasing captures in traps between 2017–2018 and 2019–2020 (Figures 3-1AB and 3-2AB of chapter III). Managers should remain alert to the potential for *H. halys* to complete a second generation in some years if summer temperatures increase as a result of climate change.

Chapter IV discussed the outcome of wild and lab-reared (sentinel) egg mass surveys in 2017–2019 that were used to detect parasitoid wasps of *H. halys* present in northern Utah. Seven native parasitoid species from the families Scelionidae and Eupelmidae were detected guarding *H. halys* eggs, with five of these species able to provide relatively low rates of parasitism (measured by adult wasp emergence from *H. halys* eggs). Importantly, *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) was detected in June 2019 in Salt Lake County on wild egg masses, with subsequent detections later that summer. This species is highly effective in exploiting *H. halys* eggs in its native home range of Asia and has already shown improved parasitism of wild egg masses in Utah when compared to native parasitoid species in the genera *Trissolcus* and *Anastatus.*

Additionally, studies revealed that wild egg masses displayed higher mean rates of parasitism compared to lab-reared egg masses deployed into the field. Wild egg mass parasitism was highest in 2019 compared to the two previous years due to the presence of *T. japonicus*. Most of the parasitized *H. halys* egg masses were found on *C. speciosa,* reaffirming this plant as a sentinel host in Utah (Chapter II).

Sticky card monitoring efforts in 2020 (Chapter V) detected *T. japonicus* in Davis Salt Lake, and Utah counties, indicating an established overwintering population in Utah. Discovery of established *T. japonicus* populations in Utah is encouraging for future sustainable biological suppression of *H. halys* and prevention of agricultural crop losses.

Additionally, in Chapter V, I explored card color for attraction of target parasitoid species and deterrence of non-target arthropods. Yellow sticky cards are effective in surveying for key parasitoid species like *T. japonicus*; however, they also capture large numbers of bycatch (non-target insects), reducing efficiency of target wasp identification and card processing. Side-by-side comparison of yellow and blue cards was evaluated in urban, orchard, and vegetable landscape types. Our prediction was that blue cards would be attractive to key parasitoid species, while capturing fewer bycatch. Results showed that overall, yellow captured 54–72% more target parasitoid wasps than blue cards in June–August across the three landscape types, but that parasitoid capture on blue was positively correlated with capture on yellow cards. This indicated that blue cards effectively captured target wasps and reflected trends on yellow cards, just in fewer numbers.

Blue cards captured 31–48% less bycatch than yellow cards, which reduced processing time and improved wasp identification rates. Most importantly, both blue and yellow sticky cards effectively detected *T. japonicus* in 2019 and 2020. These results indicate that blue sticky cards can be used as a viable alternative to the traditional yellow cards, especially in surveys focused on large-scale and long-term surveillance, where faster processing times and easier identifications of target wasps are of great importance. The alternative card color may prove a helpful tool in the years to come, as *H. halys* continues to spread into new regions of North America, Europe, and other parts of the world, and monitoring for adventive populations of *T. japonicus* expands into novel ranges.

An important component of this dissertation has been extension outreach to diverse communities and stakeholders. I have authored a fact sheet on the general biology and pest management of *H. halys* (Appendix C) and another on the identification of *H. halys* and other commonly encountered Pentatomidae species in Utah (Appendix D). I shared results on host plant preferences, phenology, and parasitoid wasps of *H. halys* in two Utah Pests newsletters (Appendix E). I have particularly enjoyed sharing lectures on the specific host plants and seasonal phenology of *H. halys* with extension specialists, university students, producers, and master gardeners at 10 speaking events in Utah. Public awareness and understanding are pivotal to the ultimate success of future monitoring and management efforts of *H. halys* in Utah. Overall, I believe that the research discussed in this document will help diverse audiences more effectively recognize important host plant species, improve timing of control efforts, and improve their understanding of the benefits of biological control agents (e.g., parasitoid wasps) in managing for *H. halys*. This is especially true going forward, as an educated public will be a vital part in preventing and managing potential pest outbreaks of *H. halys* in the future.

APPENDICES

APPENDIX A

AUTHORSHIP AND CITATIONS OF PUBLISHED CHAPTERS

Chapter II:

This is pre-copyedited, author-produced version of an article published by the journal NeoBiota following peer review. The version of record **Holthouse, M. C., Spears, L. R., & Alston, D. G. (2021)**. Urban host plant utilisation by the invasive *Halyomorpha halys* (Stål) (Hemiptera, Pentatomidae) in northern Utah. *NeoBiota*, *64*, 87–101. is available online at: https://doi.org/10.3897/neobiota.64.60050

Chapter IV:

This is pre-copyedited, author-produced version of an article published by the Biodiversity Data Journal following peer review. The version of record **Holthouse, M., Schumm, Z., Talamas, E., Spears, L., & Alston, D**. **(2020)**. Surveys in northern Utah for egg parasitoids of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) detect *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae). *Biodiversity Data Journal*, *8*, e53363. is available online at https://doi.org/10.3897/BDJ.8.e53363

Chapter V:

This is pre-copyedited, author-produced version of an article published by the Journal of Insect Science following peer review. The version of record **Holthouse, M. C., Spears, L. R., & Alston, D. G. (2021)**. Comparison of Yellow and Blue Sticky Cards for Detection and Monitoring Parasitoid Wasps of the Invasive *Halyomorpha halys* (Hemiptera: Pentatomidae). *Journal of Insect Science*, *21*(5). is available online at: https://doi.org/10.1093/jisesa/ieab062

APPENDIX B

LETTERS OF PERMISSION

Vincent Smith <vince@vsmith.info> Jun 4, 2020, 10:51 AM
to me, Pavel, Torsten, kristofer.helgen, Zach

Dear Mark,

Thanks for your e-mail. For all BDJ publications, authors retain the copyright to their article and can by default it is available under the terms of the Creative Commons Attribution License (CC-BY 4.0) or, if requested, of the Creative Commons CC-Zero Waiver (CC-0). Supplementary materials associated with an article will normally be made available under the Creative Commons CC-Zero Waiver (CC-0). So far as I can tell (and Pavel or others from Pensoft can correct me if I'm wrong), you or Zachary don't need any special permission to include the final paper in the masters thesis because you already have the right to do this under the BDJ's normal terms of publication. As far as I can tell the only people that need to give consent are the other co-authors.

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@vsmith.info (preferred), Skype: vsmithuk, Tel: +44 (0) 207 942 5127
Meeting Scheduling: http://doodle.com/vsmithuk

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Again in the spirit of open and collaborative research, authors are encouraged to post their work online (e.g., institutional repositories or their websites). Such practices trigger productive exchange, as well as earlier and greater citation of published work.

April 6, 2021

To whom it may concern:

I, Zachary Schumm, 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)” and “Common Stink Bugs of Utah” of which I am a coauthor, in the dissertation of Mark Cody Holthouse.

Sincerely,

Zachary Schumm
Arthropod Diagnostician, Utah State University
zach.schumm@usu.edu; 443-617-7327

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

May 24, 2021

To whom it may concern:

I, Kate Richardson, hereby grant my permission for the use of “Native and Exotic Parasitoid Wasps of BMSB in Utah” of which I am a coauthor, in the dissertation of Mark Cody Holthouse.

Sincerely,

Kate Richardson
Graduate Research Assistant, Utah State University
kate.vivian@aggiemail.usu.edu; 208-440-0400

10/12/2021

To the Journal of Insect Science Team,

I am in the process of preparing my dissertation in the Department of Biology at Utah State University.

The article "Comparison of Yellow and Blue Sticky Cards for Detection and Monitoring Parasitoid Wasps of the Invasive Halyomorpha halys (Hemiptera: Pentatomidae)" (https://doi.org/10.1093/jisesa/ieab062), of which I am first author, reports an essential component of my research. This article has been published by the Journal of Insect Science. I would like permission to print this article as a component of my dissertation. 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!

Kind Regards,
Mark Cody Holthouse (cody.holthouse@usu.edu) – Corresponding Author

---

I hereby give my permission to Mark Cody Holthouse to print the requested article in his dissertation:

"Comparison of Yellow and Blue Sticky Cards for Detection and Monitoring Parasitoid Wasps of the Invasive Halyomorpha halys (Hemiptera: Pentatomidae)"
with the following acknowledgement:

"We thank the Journal of Insect Science team for allowing the printing of this manuscript in this dissertation."

Signed: [signature]
Date: 10/12/2021
Fee: ———

JL Josh Lancette <JLancette@entsoc.org>
Wed 10/13/2021 2:49 PM
To: Cody Holthouse

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Hi Cody,

Please find the signed form attached. ESA and OUP allow for all articles to be reused in a dissertation or thesis, provided proper citation is given to the original publication.

Thanks!

Josh

Josh Lancette (he/him/his) | Managing Editor
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Phone: +1 301-731-4535 ext. 3023 | Direct Dial: +1 240-696-3743 | Email: jlancette@entsoc.org
insectscience.org
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APPENDIX C

BROWN MARMORATED STINK BUG [Halyomorpha halys (Stål)] (UTAH PESTS FACT SHEET PUBLISHED VERSION)

UTAH PESTS fact sheet EXTENSION UtahStateUniversity

Published by Utah State University Extension and Utah Plant Pest Diagnostic Laboratory Ent-144-17 July 2017

Brown Marmorated Stink Bug [*Halyomorpha halys* (Stål)]

Mark Cody Holthouse • Diane G. Alston • Lori R. Spears • Erin Petrizzo

Do You Know?

- Brown marmorated stink bug (BMSB) is an invasive insect pest from eastern Asia.
- In 2012, it was detected for the first time in Utah, in Salt Lake City; as of 2016, it is established and causing nuisance problems in northern Utah.
- BMSB has a broad host range that includes fruit, vegetable, ornamental, and field crop plants; in Utah, it has primarily infested ornamental deciduous trees and shrubs in urban and residential settings.
- In the late fall through spring, BMSB adults will aggregate on homes and buildings; they will seek shelter indoors, under roof eaves, and in attic spaces.
- In addition to nuisance problems, BMSB has caused severe economic plant damage in other regions of the U.S.; it was detected for the first time in commercial crops (peach orchards) in Utah in 2016 and crop damage was reported in 2017.

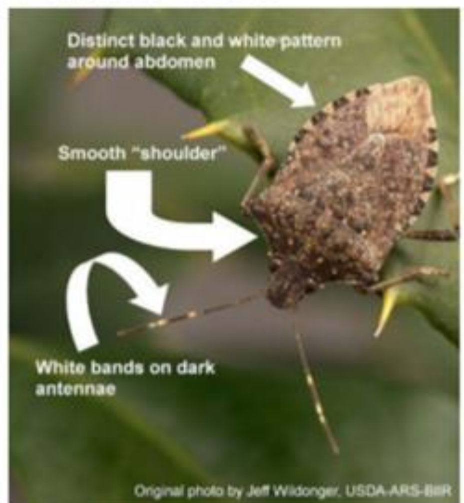

Fig. 1. Adult BSMB and three key identifying characteristics.

Fig. 2. Large numbers of adult BMSB congregate on the side of a home.

The brown marmorated stink bug (BMSB, *Halyomorpha halys* Stål) (Fig. 1) is a recent invasive insect to North America and is native to eastern Asia. Its first North American detection was in Pennsylvania in 1996. In the last decade, it has become a severe urban nuisance (Fig. 2) and agricultural pest (Fig. 3) in the mid-Atlantic and northwestern regions of the U.S. Since January 2017, 43 U.S. states and four Canadian provinces have reported BMSB occurrence (Fig. 4). BMSB was first detected in Utah in 2012; it is now established in four counties (Weber, Davis, Salt Lake, and Utah) and has been detected in two other counties (Cache and Box Elder). As an aggressive generalist herbivore, BMSB infests a broad range of plants and habitats, enabling its rapid spread across many regions of North America, including the Wasatch Front of Utah.

At present, Salt Lake County hosts the bulk of Utah's BMSB populations. Early establishment has been primarily on ornamental trees (mainly *Catalpa speciosa*) (Fig. 5) and shrubs. However, in 2016, it was detected in commercial peach orchards, its first detection in agricultural crops in Utah (see section titled "Agricultural Risk"). BMSB is classified as an urban nuisance pest due to its congregation behavior on and within buildings and homes from fall through spring. Damage to peach, apple, popcorn, and other crops was detected for the first time in 2017

HOST PLANTS

BMSB exploits a wide array of plants, contributing to its success as an invasive insect pest. Within its native range of eastern Asia, it feeds on more than 106 plant types, from trees and shrubs to smaller herbaceous and woody plants (Bergmann et al. 2016). In North America, BMSB has been documented on more than 100 species of plants (Rice et al. 2014); the majority are commodity crop plants and ornamental shrubs and trees.

Fig. 3. Internal damage to Bosc pear caused by BMSB feeding.

Fig. 4. Current distribution and status of BMSB in the U.S. and Canada (status as of September 20, 2017).
For updates, see http://www.stopbmsb.org/where-is-bmsb/).

Currently in Utah, BMSB is found primarily on ornamental trees and shrubs along the Wasatch Front. Some of the documented host plants in Utah are listed in Table 1. The greatest numbers of BMSB have been found on catalpa, making it a sentinel tree for detection and assessment of invasion risk (Fig. 5). Taller trees or shrubs are the likely places BMSB adults will fly to and congregate on.

Table 1. Click here for the most current list of BMSB host plants in Utah.

Current BMSB Host Plants in Utah	
Ornamental	
Amur maple	*Acer ginnala*
butterfly bush	*Buddleja* spp.
catalpa	*Catalpa speciosa*
eastern redbud	*Cercis canadensis*
European beech 'Tricolor'	*Fagus sylvatica*
honeysuckle	*Lonicera* spp.
Japanese maple	*Acer palmatum*
lilac	*Syringa* spp.
Norway maple 'Crimson King'	*Acer platanoides*
purple-leaf plum	*Prunus cerasifera*
purple robe black locust	*Robinia pseudoacacia*
quaking aspen	*Populus tremuloides*
Siberian pea shrub	*Caragana arborescens*
Tree Fruit	
apple	*Malus domestica*
chokecherry	*Prunus virginiana*
common plum	*Prunus domestica*
peach	*Prunus persica*

Initial invasion of BMSB is thought to be reliant on human structures for overwintering success and access to ornamental host plants. Initial populations have been along the I-15 corridor, radiating north and south from Salt Lake City.

Fig. 5. A mature catalpa tree with large seed pods; a common host for BMSB in Utah.

CROP INJURY AND PLANT DAMAGE

BMSB has straw-like mouthparts, called a proboscis or stylet, for piercing and sucking plant sap. BMSB can feed on many plant parts such as buds, leaves and stems, but prefers reproductive structures such as fruits and seed pods. Feeding on immature fruits can result in distorted development known as cat facing (Fig. 6). Feeding on mature fruits can cause sunken, corky lesions (Fig. 7) and discolored spots (Fig. 8). BMSB can feed on field and

Fig. 6. Distorted peach fruit growth caused by BMSB feeding called "cat-facing."

Fig. 7. BMSB feeding damage on 'Pink Lady' apple. Note the corky lesions.

Fig. 8. Discolored and sunken areas on tomato caused by BMSB feeding.

Fig. 9. Sweet corn ear with brown and sunken kernels due to BMSB feeding.

sweet corn through the husk, leaving brown and sunken kernels (Fig. 9). The winery and fruit juice industries are fearful of the impact of BMSB on grapes; injury causes berry collapse and release of noxious volatiles that can taint the wine and juice. BMSB damage has occurred in many other types of plants; for a greater description and photos of BMSB damage, see **www.stopbmsb.org.**

GENERAL DESCRIPTION

Adult: *Life stage associated with dispersal (flight), overwintering, plant damage, and reproduction.*

Adult BMSB are cryptically colored with marbled gray, brown, and black camouflage on their back and shoulder areas. The edges of the abdomen exhibit a black and white stripe pattern, antennae have two white bands, and the shoulder (pronotum) edges are smooth (Fig. 1). The underside of the body is light gray to off-white in color. Body shape resembles a five-pointed shield and is approximately 17 mm (5/8 inch) long.

BMSB adults congregate on host plants (Fig. 10) and buildings (Fig. 11). This aggregation behavior is controlled by pheromone cues released by adults. Adults are adept fliers and disperse readily. In late fall, adults move to buildings to seek shelter. These congregation events can be a nuisance to homeowners as the bugs cover surfaces in great numbers, and enter homes through cracks and crevices to exploit the warmer conditions (Fig. 11). BMSB are harmless to humans, but will release a defensive odor when disturbed (some have said it smells like cilantro). By late October, adults enter a winter diapause (similar to hibernation) in which activity slows and feeding ceases. Adults increase activity in the spring (April-May) to begin feeding, mating, and producing egg clusters 2 weeks later (Figs. 12-15). Females produce one egg mass at approximately weekly intervals, and can produce up to 400 eggs in a season with variation by geographical region.

Fig. 10. BMSB adults and nymphs aggregate on a crabapple leaf.

Fig. 11. Adult BMSB aggregate on residential buildings in the fall.

Egg: BMSB eggs are white or light green, and usually found on the underside of leaves in clusters of 20-30 eggs (Fig. 12). Individual eggs are barrel shaped; when nearing maturity, a black triangle, the egg burster, on the first instar's head can be seen through the egg shell. Eggs require 3-7 days to develop and hatch, depending on temperature.

Fig. 12. BMSB egg mass on the underside of a leaf. The triangular shaped egg burster on the head of developing nymphs is visible through the egg shell.

Nymph: *Immature life stage associated with plant damage.*

BMSB develops from egg to adult through five juvenile stages called instars (Fig. 13). Each instar sheds its exoskeleton (called molting) to increase its body size. Nymphs are wingless; thus confined to host plants on which they hatch or those within walking distance. Like adults, nymphs feed on plant hosts with their piercing-sucking mouthparts. First instar nymphs are red and black, and remain on the egg mass until their first molt (Fig. 14). Second through fifth instars are black and gray with dark bands across the back. Nymph size ranges from 2.4-12 mm (1/10-1/2 inch) in length.

Fig. 13. Developmental progression of BMSB, depicting the five nymphal stages (instars) between egg and mature adult.

Fig. 14. First instar nymphs remain near egg mass until their first molt.

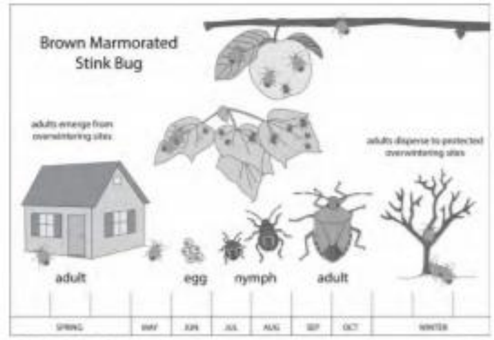

Fig. 15. BMSB life history; there is one generation per year in northern Utah.

AGRICULTURAL RISKS

The first signs of agricultural problems with BMSB in the U.S. came in 2008 when a variety of crops (apple, peach, sweet corn, pepper, tomato, soybean) in the mid-Atlantic region experienced significant damage. BMSB crop damage reached a crisis level in 2010 when $37 million was lost in the apple crop (Herrick 2011). Growers responded to BMSB damage by using broad-spectrum insecticides. In some cases, insecticide use has increased by four-fold (Leskey et al. 2012b). BMSB is a strong flier, has a high reproductive rate, lacks specialized natural enemies in North America, has effective overwintering strategies, feeds on a wide range of plants, and has piercing-sucking mouthparts that allow for partial avoidance of insecticide residues on plants. These factors all contribute to its high risk as an agricultural pest.

BMSB has been detected in fruit and vegetable fields in Utah, Salt Lake, Davis, Weber, and Box Elder counties. In addition, fruit growers have found BMSB at their urban fruit stands and in their freshly picked fruit bins. Damage has been reported on peach, apple, corn, squash, basil, and borage. Peach is just one of many fruits BMSB will attack, both in its Asian home range and in the U.S. Utah producers of stone and pome fruit, along with berry, vegetable and row crops, should be vigilant in scouting for BMSB, and intervening before crop damage occurs.

MONITORING

It is unlikely that BMSB will be eradicated in Utah and other regions of the U.S. due to its widespread distribution, broad host plant range, and high reproductive output. However, effective monitoring efforts should provide early warning for infestations to prevent significant crop loss.

Traps using BMSB-specific aggregation pheromone lures can provide effective detection and warning of BMSB populations. A few trap examples are Dead-Inn Pyramid Trap by AgBio Inc., Pherocon® Dual Panel Clear Sticky Trap by Trece Inc., the Rescue® Stink Bug Trap and Trapstik Trap by Sterling International Inc., and the Stink Bug Trap by Alpha Scents Inc. (Fig. 16). Traps should be baited with a lure, and for traps with a collection container, an insecticide strip should be included to kill stink bugs as they enter the trap. Trapping trials are underway in northern Utah to develop monitoring tools and economic thresholds to guide management decision-making.

BMSB can also be effectively monitored by visual observation. Use visual inspections during spring emergence (May), peak population spikes (July and August), and when BMSB seek overwintering sites (late September through November). For plant inspections, look up into a tree or shrub canopy against the lighted sky background to spot nymphs and adults on leaves, fruits and seedpods. Egg masses can be conspicuous on the underside of leaves (Fig. 12). Beating sheet sampling (using a beating stick and white catch sheet) can dislodge BMSB from tree or shrub branches for easier viewing on the sheet surface (Fig. 17).

Fig. 16. Different styles of BMSB traps are baited with a two-part pheromone lure to attract adults and nymphs. Clockwise from top left sticky trap, Rescue stink bug trap, Black pyramid trap, Alpha Scents trap.

Fig. 17. Beating sheet sampling.

MANAGEMENT

Exclusion

To reduce invasion of BMSB into homes and buildings, seal openings with weather stripping, screens, and caulking. Repair cracks and gaps in walls and foundations.

Stink bugs can be excluded from garden and small acreage crops by the application of floating row cover or fine-mesh netting over plants, sticky/adhesive bands on the trunks of trees (Tangle-Trap®), and wrapping fruit in breathable bags. Screens placed on orchard borders and cages are being explored as options to exclude BMSB from fruit and other crops.

Physical Removal

To remove BMSB within a home or workplace, a simple indoor trap can be constructed from a lamp with a bowl of soapy water placed just below the light. BMSB adults will be attracted to the light at night, drop into the soapy water, and drown. For removal of aggregations of BMSB on exterior walls and structures, sweep or vacuum (using waste bag inside) BMSB into a container and freeze before disposal.

Cultural Control

In agricultural settings, trap crops can offer an effective barrier of protection for the cash crop. BMSB primarily enters agricultural fields and orchards from surrounding wooded or residential areas where it overwinters. Planting a non-cash crop barrier around the edge of the crop can congregate invading BMSB and distract them from the cash crop. Farmers in the eastern U.S. have demonstrated effective trap cropping with triticale, sorghum, millet, buckwheat, and sunflower.

Biological Control

Regulating populations of invasive organisms can be challenging due to the "enemy release" effect. When an exotic pest like BMSB invades a new area such as Utah, it lacks the specific predators and parasitoids from its homeland that provide natural population regulation. Restoring natural enemies through introduction or exploiting similar native analogs is a prospect of great interest for BMSB management in the U.S. Surveys will be initiated in northern Utah in 2017 to identify native and introduced predators and parasitoids that may be regulating BMSB populations. Generalist predators found to prey on BMSB in other regions of the U.S. include praying mantid, robber fly, assassin bug, earwig, and spiders. Specific emphasis will be placed on surveying for parasitoid wasps (small wasps that parasitize BMSB eggs), as these provide significant suppression of BMSB in Asia. *Trissolcus japonicus*, commonly known as the samurai wasp, is an effective parasitoid from Asia that significantly limits BMSB egg survival (Fig. 18). It has been discovered parasitizing BMSB eggs on both the eastern and northwestern coasts of the U.S. The samurai wasp is thought to have come into the U.S. on its own through hitching a ride with BMSB.

The samurai wasp belongs to the Scelionidae family, of which there are several other effective *Trissolcus* wasps (e.g., *T. itoi*, *T. mitsukurii*, and *T. plautiae* of Japan; several other *Trissolcus* spp. in Korea and China) found to attack BMSB in Asia. In North America (primarily in the East), chalcid wasps (*Anastatus ruduvii* and *Anastatus mirabilis*) have been found to effectively parasitize BMSB eggs in the wild, though mostly in non-agricultural wooded areas. Eggs are not the only BMSB life stage at risk of parasitism; tachinid flies will attack adults. A few tachinid flies have been detected in the U.S., but successful development of the fly larva within BMSB has not been observed.

Fig. 18. Photo of Samurai Wasp from Asia, *Trissolcus japonicus*.

INSECTICIDES

BMSB adults can be difficult to kill with insecticides due to their strong flight capability (rapid dispersal to avoid treated sites) and tolerance to insecticide residues (avoid contact with residues through their piercing-sucking feeding habit). Studies have shown relatively low effectiveness of some chemical classes, and only temporary knock-down of adults. Because of this resiliency, BMSB chemical control has been focused on broad-spectrum insecticides applied at higher label rates. Carbamates (IRAC Class 1A*), organophosphates (IRAC Class 1B*), pyrethroids (Class 3A*) and neonicotinoids (Class 4A*) have generally shown the greatest efficacy against BMSB. To reduce the likelihood of resistance development in BMSB, it is important to rotate treatments among insecticide classes.

Applications of insecticides to crop borders, where BMSB populations invade first and are typically highest, has been shown to be effective while reducing insecticide use by up to 85% (Leskey et al. 2012a). Insecticide treatments are recommended when BMSB are initially detected, and before populations reach a phase of rapid increase or establishment.

For commercial crops, methomyl (Lannate, other brands), chlorpyrifos (Lorsban), beta-cyfluthrin (Baythroid), bifenthrin (Brigade, many brands), cyfluthrin (Renounce, other brands), deltamethrin (Delta Gold), esfenvalerate (Asana, other brands), fenpropathrin (Danitol), gamma-cyhalothrin (Declare, other brands), lambda-cyhalothrin (Warrior, many brands), zeta-cypermethrin (Mustang Max), acetamiprid (Assail), clothianidin (Belay), dinotefuran (Scorpion), imidacloprid (Admire Pro, many brands), thiacloprid (Calypso), and thiamethoxam (Actara) have shown efficacy against BMSB.

For home fruit and vegetable production, bifenthrin (Ortho Bug B Gon), gamma-cyhalothrin (Spectracide Triazicide Insect Killer), and acetamiprid (Ortho Flower, Fruit and Vegetable Insect Killer) are the primary conventional insecticides available, while pyrethrins (Pyganic, other brands), azadirachtin/neem (Aza-Direct, other brands), and kaolin clay (Surround) are organically certified options.

For indoor/outdoor treatments made by a commercial applicator (with a valid Utah pesticide applicator license), chlorpyrifos (Vulcan) and bifenthrin (Menace, other brands) are registered in Utah. Homeowner products for treatment of buildings include bifenthrin, gamma-cyhalothrin, cyfluthrin (Bayer Vegetable and Garden Insect Spray), cypermethrin (Ortho Ant and Roach Killer), deltamethrin (Spectracide Stink Bug Killer), permethrin (Monterey Stink Bug Spray), imidacloprid (Ortho Dual-Action Bed Bug Killer) and azadirachtin (organic). For a more inclusive list of chemical insecticide options for BMSB, consult the Invasive Fruit Pest Guide for Utah.

*Insecticide Resistance Action Committee Mode of Action Classification

HAVE YOU SEEN BMSB?

Finding BMSB in your home or garden can be unsettling, but there are precautionary measures to help defend yourself against this invasive pest.

Reports of possible BMSB sightings are valuable to protect all Utah communities and property owners. The USU Cooperative Extension 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. Establishing whether or not you have found BMSB or a look-alike is a great first step.

For more information on brown marmorated stink bug, refer to:

Invasive Fruit Pest Guide for Utah

Cannon, C., D. Alston, and L. Spears. 2016. Chapter 4, Brown Marmorated Stink Bug (pp 45-64) in Invasive Fruit Pest Guide for Utah: Insect and Disease Identification, Monitoring and Management, C. Cannon and D. Alston, ed. (102 pp). Utah State University Extension, Logan, UT.

First Detector Guide to Invasive Insects

Spears, L., R. Davis, D. Alston, and R. Ramirez. 2016. First Detector Guide to Invasive Insects: Biology, Identification, and Monitoring (53 pp). Utah State University Extension, Logan, UT.

USU Extension Invasive Insect Look-Alikes Fact Sheet

Spears, L., R. Davis, and R. Ramirez. 2015. Invasive Insect Look-Alikes: Mistaken Insect Identity (6 pp). Utah State University Extension Fact Sheet Ent-175-15-PR, Logan, UT.

USU Extension BMSB Rack Card

A brief information card on BMSB.

Stopbmsb.org

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

ADDITIONAL RESOURCES

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APPENDIX D

COMMON STINK BUGS OF UTAH (UTAH PESTS FACT SHEET PUBLISHED VERSION)

UTAH PESTS fact sheet EXTENSION UtahStateUniversity

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Common Stink Bugs of Utah

Mark Cody Holthouse • Zachary R. Schumm • Diane G. Alston • Lori R. Spears

Do You Know?

- There are over 300 species of stink bugs in North America.
- Stink bugs only fly as adults and not in the juvenile or 'nymph' stage.
- When feeding on plants, stink bugs release tissue dissolving enzymes that cause scarring and cat-facing on leaves, stems, and fruiting structures.
- Though most are herbivorous (plant feeding), some stink bugs are predatory and help control pest insect populations, including other stink bugs.

Background

The term "stink bug" most commonly refers to a group of insects in the Family Pentatomidae, within the Order Hemiptera (the "true bugs"). As the name suggests, stink bugs exude foul smelling odors from glands on their thorax as a means of defense. Pentatomidae comes from the Greek terms pente- meaning "five" and –tomos, or "section". They have five antennal segments and five major body partitions (pronotum, scutellum, two hemelytra, and exposed wing membrane) in a shield-like shape that is easily recognizable when these insects are viewed from above (referred to later as dorsal view; Fig. 1). Stink bug hemelytra (singular hemelytron), or partial wing covers on their dorsal side, differentiate them from beetles which have full wing coverings called elytra. Stink bugs are also equipped with a piercing and sucking straw-like mouthpart called a proboscis, which is tucked under the ventral side (underside of body) of their abdomen. Stink bugs are hemimetabolous, meaning they develop from egg, to nymph (stage made up of multiple juvenile stages lacking wings), to the adult stage gradually without undergoing a pupal stage (Fig. 2), unlike beetles or butterflies whose development requires a pupal stage to reach full maturity.

Stink bugs are both herbivores and carnivores so understanding how to identify them as a plant pest or a beneficial predator is a critical skill for a home gardener, commercial grower, or insect enthusiast. They are found in most climates around the world and many species feed on economically significant agricultural crops. Plant-feeding stink bugs commonly target reproductive structures, but also feed on vascular tissues in leaves and stems. Plant damage is often observed as necrotic lesions, cat-facing on fruit, dimpling, sunken areas below the plant cuticle, and corking below the skin in pome fruits.

Below is information on some of Utah's commonly encountered stink bugs, including what they look like, where to find them, and other key identifying characteristics.

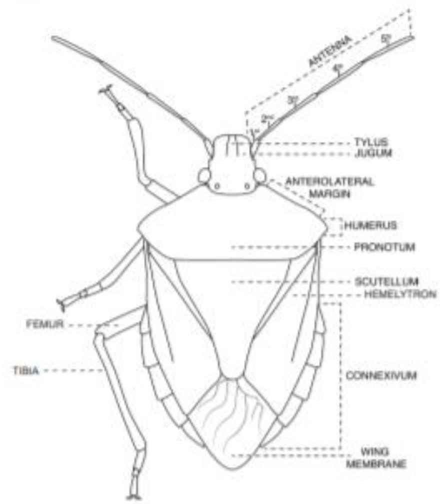


Fig. 1 Anatomy of an average adult stink bug. Refer to this image and associated terms throughout this fact sheet.

Fig. 2 Stink bugs hatch from eggs typically laid on leaves into wingless nymphs before developing into winged adults.

PLANT FEEDING STINK BUGS

Brown Marmorated Stink Bug

Latin Name: *Halyomorpha halys* **Status:** Invasive

Size: 12-17 mm (0.5-0.7 inch)

Description: Adults have a marbled brown and gray dorsum (top portion of body; Fig. 3), and a light gray/cream ventral surface (Fig. 4). Note that ventral coloration can vary depending on diet and sexual maturity. Antennae display two interspersed white bands, a unique trait not found in native stink bugs. The anterolateral margin of the pronotum (leading edge of shoulder plate) is smooth and entire. The connexivum (outer edge of abdomen) displays a white and black banding pattern.

Habitat: This invasive pest can be found on a wide variety of ornamental trees and shrubs, fruit, nut, and vegetable plants. It will also invade buildings in fall and winter months. Learn more about how to monitor and control this pest here and here.


Fig. 3


Fig. 4

Conchuela Bug

Latin Name: *Chlorochroa ligata* **Status:** Native

Size: 12-17 mm (0.5-0.7 inch)

Description: This species displays variability in coloration, but in Utah most are either dark gray/charcoal (Figs. 5 and 6) or a lighter brown/burgundy (Figs. 7 and 8) in the adult stage. Their connexivum is a pale yellow or cream color and this color faintly highlights the entire margin of the thorax as well. The tip of the scutellum (triangular plate between wings) is lighter in color and both the antennae and legs are uniformly dark in color.

Habitat: These stink bugs are found on ornamental shrubs and trees, especially those in the Family Fabaceae. Some agriculturally significant host plant species include sorghum, cotton, alfalfa, and hemp.


Fig. 5


Fig. 6


Fig. 7


Fig. 8

Green Stink Bug

Latin Name: *Chinavia hilaris* **Status:** Native

Size: 13-19 mm (0.5-0.75 inch)

Description: The green stink bug is one of the largest in Utah and is easily recognized by its uniform green body coloration. Adults have yellow and black notches/bands on the connexivum (Fig. 9). The ventral body coloration is also entirely green (Fig. 10). The wing membrane is clear and lacks any markings.

Habitat: Ornamental trees and shrubs are their most common hosts. Some economically significant host plants include cotton, corn, tobacco, and some specialty fruit crops. This species is problematic in the southern U.S.


Fig. 9


Fig. 10

PLANT FEEDING STINK BUGS

Onespotted Stink Bug

Latin Name: *Euschistus variolarius* **Status:** Native

Size: 11-15 mm (0.4-0.6 inch)

Description: The dorsal side of the body is primarily light brown with a dark speckling pattern. The wing membrane is entirely dark brown in color (Fig. 11). Adults are also recognized by their cinnamon colored ventral side, antennae, and legs (Fig. 12). Though the connexivum pattern is similar to other stink bugs with its display of black bands, the alternating cinnamon/brown color is unique to this species.

Habitat: These stink bugs are found on ornamental shrubs and trees.


Fig. 11

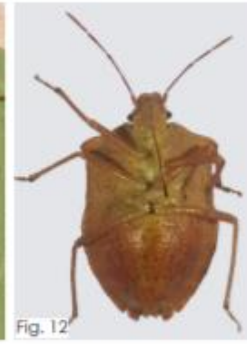


Fig. 12

Rough Stink Bug

Latin Name: *Brochymena sulcata* **Status:** Native

Size: 12-16 mm (0.5-0.6 inch)

Description: This stink bug species has cryptic coloration and texture, resembling a piece of bark or lichen on a tree. The entire body is is spotted and has light gray and black/brown coloration (Figs. 13 and 14). Each leg has two light colored bands and the connexivum has alternating black and light gray/tan bands. The anterolateral margin of the pronotum has saw-like serrations (Fig. 13).

Habitat: Rough stink bugs are found on many different ornamental shrubs and trees. Though they are primarily herbivorous, there are documented cases of them feeding on soft bodied juvenile insects like caterpillars or beetle larvae.


Fig. 13


Fig. 14

Say Stink Bug

Latin Name: *Chlorochroa sayi* **Status:** Native

Size: 12-17 mm (0.5-0.7 inch)

Description: The Say stink bug is usually green (varies between light to dark green) both in body and leg coloration (Figs. 15 and 16). The yellow/cream color on the connexivum and outer margin of the thorax is prominent. The scutellum and hemelytra display speckling or patches of lighter colored markings. Unlike the Conchuela bug, which displays only one light colored patch on the rear tip of the scutellum (Figs. 5 and 7), Say stink bug displays multiple light patches on its scutellum (Fig. 15).

Habitat: These stink bugs are found on ornamental shrubs and trees.


Fig. 15


Fig. 16

PLANT FEEDING STINK BUGS

Menecles insertus

Latin Name: *Menecles insertus* **Status:** Native

Size: 8-14 mm (0.3-0.6 inch)

Description: The pronotum is prominent and wraps around the posterior portion of the head. A lightly colored line runs from the anterior margin of the pronotum to the middle of the scutellum (Fig. 17). Adult coloration is primarily brown with tiny light colored spots uniformly distributed over the entire body and legs (Figs. 17 and 18). The connexivum has only a faint brown and black pattern and the antennae are entirely brown.

Habitat: These stink bugs are found on ornamental shrubs and trees.


Fig. 17


Fig. 18

Red-Backed Stink Bug

Latin Name: *Banasa dimidiata* **Status:** Native

Size: 7-10 mm (0.3-0.4 inch)

Description: The adult stage exhibits a brilliant lime green color on the legs, scutellum (Fig. 19), and ventral side of the abdomen and thorax (Fig. 20). The hemelytra and posterior portion of the pronotum is burgundy, along with the head and antennae (Fig. 19). The outer surface of the body displays a metallic sheen under direct light.

Habitat: These stink bugs are found on ornamental shrubs and trees.


Fig. 19


Fig. 20

Jade or Juniper Stink Bug

Latin Name: *Banasa euchlora* **Status:** Native

Size: 7-10 mm (0.3-0.4 inch)

Description: Adults dsiplay a deep green coloration over their entire body, with faint light green or yellow markings on the hemelytra, anterolateral margin of the pronotum, and corners of the scutellum (Fig. 21). The ventral side has both dark and light green markings (Fig. 22). The connexivum has alternating dark and light green bar patterning (sometimes hard to view). The antennae are entirely green.

Habitat: These stink bugs are most commonly found feeding on *Juniperus* spp. or plants in the Family Cupressaceae.


Fig. 21


Fig. 22

PLANT FEEDING STINK BUGS

Thyanta spp.

Latin Name: *Thyanta spp.* **Status:** Native

Size: 10-16 mm (0.4-0.6 inch; Most species)

Description: Most local *Thyanta* species are green with certain species displaying black or red markings on the pronotum in either a line or band of color on the posterior or anterior margins. Most *Thyanta* have black speckling on their wing membrane (Fig. 23). Some less common species are pale brown or gray in body color. *Thyanta* may be confused with the green stink bug, but are generally smaller than the green stink bug and lack yellow and black alternating markings on the connexivum (Figs. 23 and 24).

Habitat: These stink bugs inhabit ornamental shrubs and trees.


Fig. 23


Fig. 24

Cosmopepla uhleri

Latin Name: *Cosmopepla uhleri* **Status:** Native

Size: 4-5 mm (0.2 inch)

Description: This species is unique in its smaller size relative to other stink bugs found in Utah. The defining characteristic for this species lies in the mottled yellow/orange coloration on the anterior portion of the pronotum, along with the outer margin of the abdomen and connexivum. The ventral portion of the stink bug is completely black in color, along with a majority of the hemelytra and wing membrane.

Habitat: This species is commonly found on Columbine (*Aquilegia* spp.).


Fig. 25


Fig. 26

Holcostethus abbreviatus

Latin Name: *Holcostethus abbreviatus* **Status:** Native

Size: 6-9 mm (0.2-0.4 inch)

Description: At first glance, this species may look similar to the brown marmorated stink bug, but has a smaller body size, solid brown antennae, and a white spot at the posterior tip of the scutellum (Fig. 27). The angle of the humerus is more rounded when compared to other stink bugs that display this gray marbled coloration (Fig. 28). The head structure is also unique, with the tylus (nose-like indent on head) being completely enclosed by the jugum (front of head) (Fig. 27).

Habitat: These stink bugs are found on ornamental shrubs and trees.


Fig. 27


Fig. 28

BENEFICIAL PREDATORY STINK BUGS

Spined soldier bug

Latin Name: *Podisus maculaventris* **Status:** Native

Size: 8.5-13 mm (0.3-0.5 inch)

Description: Adults have a marbled brown body with solid brown antennae. The wing membranes protrude beyond the abdomen with black markings down the center (Fig. 29). The mouthparts are thicker than those of herbivorous stink bugs (Fig. 30). The humerus is acutely angled into a spine-like projection. The connexivum has alternating light brown and black bands (Fig. 29). The hind legs have black dots on the distal region of the femur (Fig. 30).

Habitat: Spined soldier bugs are often found in residential gardens and on ornamental plants (e.g., goldenrod, yarrow, or bishop's weed). They feed on a variety of small arthropods such as caterpillars and beetle grubs.


Fig. 29


Fig. 30

Podisus placidus

Latin Name: *Podisus placidus* **Status:** Native

Size: 8.5-13 mm (0.3-0.5 inch)

Description: As with other stink bugs in this genus, *P. placidus* displays a brown-black alternating band pattern on the connexivum and has a marbled brown dorsal coloration (Fig. 31). Note the absence of black spots on the femur (Fig. 32) and black markings on its wing membranes (Fig. 31). In Utah, individuals are commonly described as having hints of orange-brown coloration in direct sunlight.

Habitat: These stink bugs are found on ornamental shrubs and trees and feed on small insects.


Fig. 31


Fig. 32

Twospotted stink bug

Latin Name: *Perillus bioculatus* **Status:** Native

Size: 8.5-11 mm (0.3-0.4 inch)

Description: Adult coloration can vary between pale tan, orange, and red depending on diet. Black markings cover most of the body and their patterns are fairly uniform between color variants, displaying two black bars or spots on the anterior portion of the pronotum and a thick black bar pattern on the posterior portion (Figs. 33 and 34). The scutellum has two concentric color markings that resemble the capital letter Y or a lock keyhole. Each leg has a white band on the middle portion of the tibia (Fig. 35). The color patterns on the hemelytra can vary.

Habitat: These stink bugs are found on ornamental shrubs and trees. They are also commonly found on potato plants where they prey on Colorado potato beetle larvae.


Fig. 33


Fig. 34

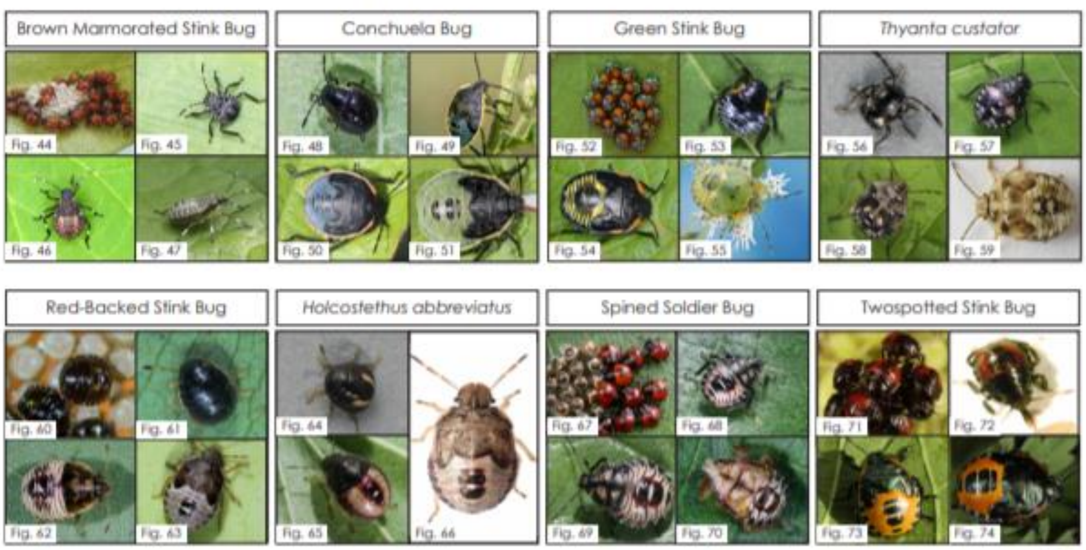

Fig. 35

COMMONLY ENCOUNTERED STINK BUG EGGS

Stink bug eggs are generally round or barrel-shaped in appearnce and laid in a mass of multiple eggs. The average number of eggs per egg mass varies by species. Eggs generally require between 4-8 days to fully develop and hatch depending on temperature, photoperiod, and species. As the eggs mature, their color may change and "egg bursters" (small triangular markings) used to pierce through the egg cap during hatch, will begin to appear on the top of the eggs. Some egg caps will have ornate spines protruding outward (Fig. 42). Some eggs may appear abnormally dark or exhibit damage caused by parasitoids.

COMMONLY ENCOUNTERED STINK BUG NYMPHS

Photographs below depict a selection of nymphal instars for the stink bug species described above. Most Pentatomidae have five nymphal instars before reaching the mature adult stage. The first instar nymphs feed on the egg mass and leave only after the second instar molt. Note color and morphological differences between develpmental stages. Stink bug species that look very different as adults may look nearly identical in early development.



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Schumm, Z. R., Holthouse, M. C., Mizuno, Y., Alston, D. G. and Spears, L. R. 2019. Parasitoid wasps of the invasive brown marmorated stink bug in Utah (6 pp.). Utah State University Extension Fact Sheet Ent-198-19, Logan, UT.

Spears, L.R., Davis, R., and Ramirez, R. 2015. Invasive insect look-alikes: mistaken insect identity (6 pp). Utah State University Extension Fact Sheet Ent175-15-PR, Logan, UT.

Stopbmsb.org
A comprehensive website on BMSB identification, management, and new research.

APPENDIX E

UTAH PESTS NEWSLETTERS

GUEST AUTHOR SPOTLIGHT

Native and Exotic Parasitoid Wasps of BMSB in Utah

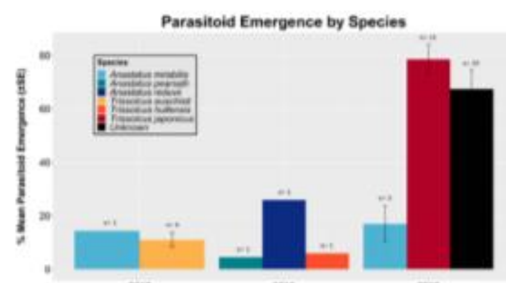
Kate Richardson and Cody Holthouse are graduate students in the USU Department of Biology working with Drs. Diane Alston and Lori Spears. Richardson is pursing a master's degree and Holthouse a doctorate. Both are studying parasitoid wasps of the brown marmorated stink bug.

The brown marmorated stink bug (BMSB, *Halyomorpha halys*) is a significant agricultural and urban nuisance pest in many regions of North America. In Utah, BMSB is established in six counties (Box Elder, Cache, Davis, Salt Lake, Utah, and Weber), and has been detected in Carbon and Kane counties. It feeds on a variety of ornamental and agriculturally significant plants, including specialty fruit crops like peach, tart cherry, and many vegetables. Managing BMSB with insecticides is challenging due in part to their strong dispersal capacity and their waxy, water-repellent cuticle that protects them from insecticide applications. Efforts have therefore emphasized biological control of BMSB eggs by small parasitoid wasps in the families Scelionidae and Eupelmidae (Order Hymenoptera). The most effective parasitoid of BMSB in both its native and invaded ranges is the samurai wasp, *Trissolcus japonicus*, a parasitoid native to southeast Asia that has also been found in some U.S. states.

In surveys for the samurai wasp and other native parasitoid species capable of parasitizing BMSB eggs in Utah, wild- and lab-reared BMSB egg masses were placed on outdoor hosts in 2017, 2018, and 2019. Five native parasitoid species were found: *Anastatus mirabilis, A. pearsalli, A. reduvii, Trissolcus euschisti,* and *T. hullensis.* On average, native adult wasps emerged from less than 26% of eggs within parasitized masses.

In 2019, the exotic samurai wasp was first detected in Utah, and our team found adults emerging from 21 egg masses that summer. On average, 78% of eggs within masses parasitized by the samurai wasp that year gave rise to adult wasps, shown in the figure above. These results suggest that the samurai wasp is a more effective egg parasitoid of BMSB than native wasps.

Sticky cards are a useful tool to detect local populations of parasitoid wasps. Yellow is the most popular color for this purpose; however, blue sticky cards appear to attract fewer non-target arthropods.



Percent parasitism of eggs in wild and lab-reared egg masses with adult wasp emergence in northern Utah, 2017–2019. Sample size (n) represents the number of egg masses parasitized. Bars without standard error lines represent single egg masses. The Unknown results represent parasitized egg masses where wasps were not present for identification. Given the large number of unknown wasps in 2019, many were likely *T. japonicus*.

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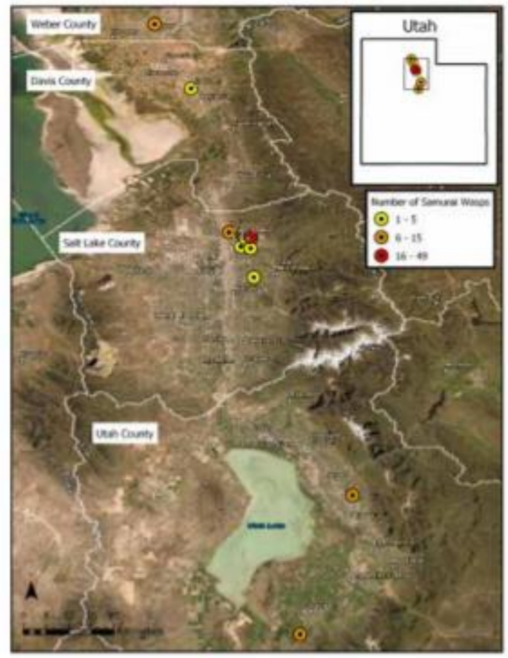
The samurai wasp, native to eastern Asia, is a promising biocontrol for BMSB (top). Stink bug eggs parasitized by a wasp turn black (bottom).

The search for parasitoid wasps in Utah also included sticky card traps in urban and agricultural landscapes along the Wasatch Front (shown at top of prior page). Easily installed sticky have been used across the U.S. to monitor parasitoid wasps of BMSB. Yellow is the most commonly used color due to its known attractiveness to many wasp species. However, yellow cards also attract numerous non-target species that reduces screening efficiency.

Our research team is comparing blue and yellow sticky cards as attractants of parasitoid wasps and non-target arthropods such as bees. Preliminary results show blue cards attract fewer target wasps and non-target arthropods than yellow cards, while representing a similar target wasp species complex. These results support the potential for increased screening efficiency with blue cards, and their use in parasitoid wasp surveys.

Yellow and blue sticky card traps deployed in 2019 and 2020 detected the samurai wasp in Davis, Salt Lake, Utah, and Weber counties (see map). Since 2019, we have observed reduced BMSB in certain areas, such as the University of Utah campus and neighborhoods in The



Map of samurai wasp detections in northern Utah on yellow and blue sticky card traps between late May and late September 2019–2020.

Avenues of Salt Lake City. In fact, over just a three-week period, 11 Samurai wasps were caught in catalpa trees in The Avenues area in August 2020.

Adult parasitoid wasps are nutritionally dependent on nectar and pollen. To support establishment and enhancement of samurai wasp in Utah, upcoming research at USU will investigate the degree to which certain cover crops attract wasps. The studies will assess plants, such as buckwheat (*Fagopyrum esculentum*) and alyssum (*Lobularia maritima*), that attract and enhance the parasitism rates of the samurai wasp on BMSB egg masses, as well as those that extend the wasp's life span. These results will support the development of guidelines for specialty crop producers to encourage samurai wasp establishment and to better manage BMSB.

— Kate Richardson, M.S. graduate student,
Cody Holthouse, PhD graduate student,
Diane Alston, Entomologist, and
Lori Spears, Invasive Species Coordinator

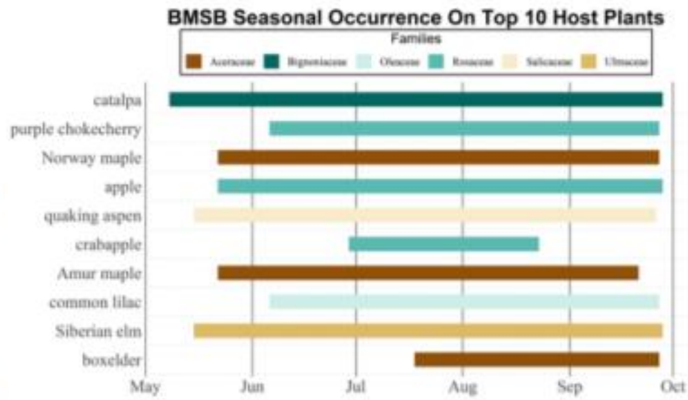
Seasonal Development and Occurrence of Brown Marmorated Stink Bug in Utah

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 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 insect pest in many U.S. states, feeding on hundreds of different host plants and adapting to a wide array of climatic conditions.

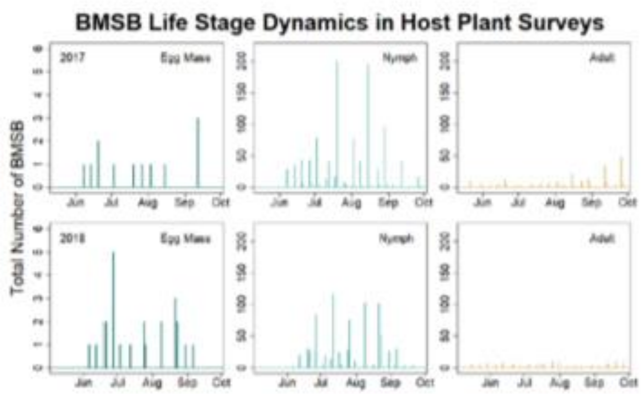
In Utah, BMSB has slowly built in population size since its discovery in 2012, with highest concentrations in and around urban and suburban neighborhoods. BMSB is commonly found on many ornamental shrubs and trees, especially catalpa. The first reports of BMSB damaging crop plants in Utah occurred in 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 arid, 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



BMSB observations on the top 10 most common host plants from May to Oct., 2017 and 2018. Each color corresponds to a plant family.



Total number of BMSB observed on plants, by life stage, in the summer of 2017 (top) and 2018 (bottom). Observations were made by visual inspection and beat sheet sampling of 300 plants of varying species on 15 sites in Davis, Salt Lake, Utah, and Weber counties.

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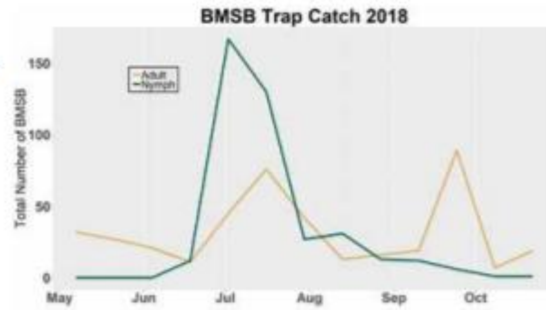
in early to mid-May and can continue through September. They lay eggs in masses of roughly 28, and a single female can produce an average of 224 eggs in her lifetime. Nymphs are first present in June and then reach peak numbers in mid-July. Adult BMSB numbers peak in early July, with a second peak occurring 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.



Total of number of BMSB found in traps from May to October 2018. Traps were spread across Davis, Salt Lake, Utah, and Weber counties.

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 Schumm (USU Biology Graduate Students), Lori Spears (Invasive Species Specialist), and Diane Alston (Entomologist)

For more information:

Skillman, V. P., & Lee, J. C. (2017). Nutrient Content of Brown Marmorated Stink Bug Eggs and Comparisons Between Experimental Uses. Journal of Insect Science, 17(6).

See utahpests.usu.edu/caps/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 hardiness 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

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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.

Parasitoid Wasp Species Currently Found in Utah

Species	Family	Collection Method	Actual Size	Can Emerge from BMSB?
Anastatus mirabilis	Eupelmidae	BMSB Eggs	▬	Yes*
Anastatus persalli	Eupelmidae	BMSB Eggs	▬	Yes*
Anastatus reduvii	Eupelmidae	BMSB Eggs	▬	Yes*
Telenomus podisi	Scelionidae	BMSB Eggs / Sticky Cards	-	No*
Trissolcus erugatus	Scelionidae	BMSB Eggs / Sticky Cards	-	No*
Trissolcus euschisti	Scelionidae	BMSB Eggs / Sticky Cards	-	Yes*
Trissolcus hullensis	Scelionidae	BMSB Eggs / Sticky Cards	-	Yes*
Trissolcus parma	Scelionidae	Sticky Cards	-	Unknown
Trissolcus thyante	Scelionidae	Sticky Cards	-	Unknown
Trissolcus strabus	Scelionidae	Sticky Cards	-	Unknown
Trissolcus utahensis	Scelionidae	BMSB Eggs / Sticky Cards	-	No*

*Based on current surveys in Utah

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. persalli, A. reduvii.* Two are in the family Scelionidae, and specialize only on stink bug eggs: *Trissolcus euschisti*, and *T. hullensis*. Unfortunately, none of these species have shown high efficacy, with only 3-18% of wasps completing development and emergence as adults.

Trissolcus erugatus, a stink bug parasitoid native to Utah has been found stinging BMSB eggs, but cannot develop and emerge properly from them.

We have additionally tested the efficacy of a parasitoid wasp species native to Utah, *Trissolcus utahensis*, 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. utahensis*, 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.

Yellow sticky cards were placed in trees to attract various parasitoids.

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.

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

APPENDIX F

Curriculum Vitae

Mark Cody Holthouse
Biology Department
Utah State University
5305 Old Main Hill, Logan, Utah 84322 USA
Email: cody.holthouse@usu.edu Cell Phone: 530-306-2313

EDUCATION

Utah State University Biology Department, Logan, Utah 2016–present

PhD Ecology

Dissertation: Host plant use, phenology, and biological control of the brown marmorated stink bug (Hemiptera: Pentatomidae; Halyomorpha halys) in northern Utah

Advisors: Drs. Diane Alston and Lori Spears

Pacific Union College Biology Department, Angwin, California 2011–2016

BS Biology

PUBLICATIONS

Research Publications

Holthouse, M.C., Spears, L.R., & Alston, D.G. (2021). Comparison of yellow and blue sticky cards for detection and monitoring parasitoid wasps of the invasive Halyomorpha halys (Hemiptera: Pentatomidae). *Journal of Insect Science*. 21(5), 1; 1-10. https://doi.org/10.1093/jisesa/ieab062

Holthouse, M.C., Spears, L.R., & Alston, D.G. (2021). Urban host plant utilisation by the invasive *Halyomorpha halys* (Stål) (Hemiptera, Pentatomidae) in northern Utah. *NeoBiota*. 64: 87–101. https://doi.org/10.3897/neobiota.64.60050

Holthouse, M.C., Schumm, Z.R., Talamas, E.J., Spears, L.R., & Alston, D.G. (2020). Surveys in northern Utah for egg parasitoids of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) detect *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae). *Biodiversity Data Journal*, *8*, e53363. https://doi.org/10.3897/BDJ.8.e53363

Schumm, Z.R., Alston, D.G., **Holthouse**, M.C., & Spears, L.R. (2020). Non-sib male guarding behavior observed in *Trissolcus euschisti* (Hymenoptera: Scelionidae). *Matters Select*, *6*(4), e202004000005. https://sciencematters.io/articles/202004000005

Hayes, F.E., **Holthouse**, M.C., Turner. D.G., Baumbach, D.S., & Holloway, S. (2016). Decapod crustaceans associating with echinoids in Roatán, Honduras. *Crustacean Research*, *45*(0), 37–47. https://doi.org/10.18353/crustacea.45.0_37

Extension Publications

Richardson, K., **Holthouse**, M.C., Alston, D., and Spears, L. (2020). Native and exotic parasitoid wasps of brown marmorated stink bug in Utah. Utah Pests News, Utah State University Extension. Vol 14: Fall edition. https://extension.usu.edu

Holthouse, M.C., Spears, L.R., Schumm, Z.R., & Alston, D.G. (2019). The samurai wasp brings new hope in the fight against brown marmorated stink bug in Utah. Paper 2045. Utah State University Extension and Utah Plant Pest Diagnostic Lab, Logan, UT. https://digitalcommons.usu.edu

Holthouse, M.C., Schumm, Z.R., Alston, D.G., & Spears, L.R. (2019). Common stink bugs of Utah. ENT-209-19. Utah State University Extension and Utah Plant Pest Diagnostic Lab, Logan, UT (8 pp.). https://digitalcommons.usu.edu.

Holthouse, M.C., Schumm, Z., Spears, L., & Alston, D. (2019). Seasonal development and occurrence of brown marmorated stink bug in Utah. Utah Pests Quarterly Newsletter. Vol. XIII. https://extension.usu.edu

Schumm, Z.R., **Holthouse**, M.C., Mizuno, Y., Alston, D.G., & Spears, L.R. (2019). Parasitoid Wasps of the invasive brown marmorated stink bug in Utah. ENT-198-19. Utah State University Extension and Utah Plant Pest Diagnostic Lab, Logan, UT (6 pp.). https://digitalcommons.usu.edu

Holthouse, M.C., Alston, D.G., Spears, L.R., & Petrizzo, E. (2017). Brown marmorated stink bug in Utah. ENT-144-17. Utah State University Extension and Utah Plant Pest Diagnostic Lab, Logan, UT (8 pp.). https://extension.usu.edu

GRANTS

Holthouse, M.C., Alston, D.G., Spears, L.R. Brown marmorated stink bug in Utah's Intermountain West. USDA Western SARE Graduate Student Grant. **Awarded funds ($24,999)** — 2018–2020

AWARDS

First place graduate student poster competition: Entomological Society of America Joint Annual Meeting in Vancouver, BC Canada — 2018

Utah State University Office of Graduate Studies Travel Awards ($900) — 2017–2019

Utah State University Ecology Center Travel Award ($400) — 2017

SEMINARS AND PRESENTATIONS

Invited Seminars

Orchard Pest and Disease Management Conference — 2021

Holthouse, M.C., Spears, L., & Alston, D. Effectiveness of yellow and blue sticky cards for monitoring parasitoid wasps of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae). Virtual presentation.

Utah Urban and Small Farms Conference — 2020

Holthouse, M.C., Spears, L., & Alston, D. Natural enemies of the invasive brown marmorated stink bug. 47 participants

Utah Pests In–Service Training — 2020

Holthouse, M.C., Spears, L., & Alston, D. Stink bug identification and management. 13 participants

First Detector Training — 2019

Holthouse, M.C., Spears, L., & Alston, D. Stink bug identification and management. 45 participants.

Invasive Insect Identification Workshop 2019

Holthouse, M.C., Schumm, Z., Spears, L., & Alston, D. Invasive and native stink bug identification. 50 participants.

Utah State Horticultural Association 2019

Holthouse, M.C., Spears, L., & Alston, D. Pest status of the brown marmorated stink bug: Host plants and phenology. 40 participants.

Weber State University, Biology Department Seminar 2018

Holthouse, M.C., Spears, L., & Alston, D. Tracking brown marmorated stink bug in Utah's Intermountain West. 25 participants.

First Detector Trainings 2016, 2018

Holthouse, M.C., Spears, L., & Alston, D. Pest status of the brown marmorated stink bug: Host plants, phenology, and biological control agents. One lecture each year. 90 total participants.

Utah State In–Service: Invasive Insect Training 2017

Holthouse, M.C., Spears, L., & Alston, D. Pest status of the brown marmorated stink bug: Host plants, phenology, and biological control agents. 14 participants.

Utah County Expanded Tree Fruit Grower Meeting 2017

Holthouse, M.C., Spears, L., & Alston, D. Current trapping methods and host plants species associated with the brown marmorated stink bug. 21 participants.

Scientific Conference Presentations

Oral Presentations

Entomological Society of America (Annual Meeting): Student 10-minute Paper Competition. Virtual Meeting. 2020

Holthouse, M.C., Spears, L., & Alston, D. Effectiveness of yellow and blue sticky cards for monitoring parasitoid wasps of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål).

Entomological Society of America (Annual Meeting): Student 10-minute Paper Competition. St. Louis, MO. 2019

Holthouse, M.C., Schumm, Z., Spears, L., & Alston, D. Voltinism and parasitoids of brown marmorated stink bug in Utah.

Entomological Society of America (Pacific Branch Meeting): Student 10-minute Paper Competition. Reno, NV. 2018

Holthouse, M.C., Spears, L., & Alston, D. Brown marmorated stink bug in the urban landscape: Host plants, trap efficacy, and biological control.

Entomological Society of America (Pacific Branch Meeting): Student 10-minute Paper Competition. Portland, OR. 2017

Holthouse, M.C., Spears, L., & Alston, D. Brown marmorated stink bug host plant use and phenology in northern Utah.

Poster Presentations

Entomological Society of America (Annual Meeting): Student Poster Competition. Virtual. 2020

Richardson, K.V., Holthouse, M.C., Spears, L., & Alston, D. Status and enhancement of *Trissolcus japonicus* (Ashmead), for biological control of *Halyomorpha halys* (Stål) in Utah.

Utah State University Undergraduate Research Symposium. Logan, UT. 2019

Mizuno, Y., Holthouse, M.C., Spears, L., Alston, D. Inhabitation status of egg parasitoid wasps of brown marmorated stink bug, *Halyomorpha halys* (Stål) in Utah.

Entomological Society of America (Joint Annual Meeting): Student Poster Competition. Vancouver, BC, Canada. (President's Prize Winner) 2018

Holthouse, M.C., Spears, L., & Alston, D. Tracking brown marmorated stink bug in Utah's urban-agriculture landscapes.

Utah State University Undergraduate Research Symposium 2018

Withers, J., Linford, L., Holthouse, M.C., Alston, D. Detection of microsporidia (*Nosema maddoxi sp. nov.*) and nematode pathogens in the invasive brown marmorated stink bug (*Halyomorpha halys* (Stål)) of northern Utah.

Community Outreach

Wendover High School: Intro the Arthropods and Insect Orders 2021

Great Basin National Park: Hemiptera Bioblitz 2020

Video recordings, virtual meetings with community members, insect collection, and iNaturalist project coordination.

Utah State University Entomology Club Insect Tours 2017–2019

Tours were focused on teaching young people basic insect facts and showing them the USU insect collection. (>5 tours).

Utah State University Cooperative Extension: Wheeler Historic Farm Market 2017–2019

I fielded questions from citizens and master gardeners about common insect pests and management options. (2 markets).

Utah State University Research Farm: Fruit and Vegetable Field Day 2018

I spoke in front of specialty fruit crop producers and extension agents at the USU Kaysville, research farm about pest status of the brown marmorated stink bug

Utah State University Cooperative Extension: Logan Farmer's Market 2017

I fielded questions from citizens and master gardeners about common insect pests and management options.

Utah State University Cooperative Extension: Ogden Famer's Market 2017

I fielded questions from citizens and master gardeners about common insect pests and management options.

TEACHING

Utah State University

Instructor: Applied Entomology (BIOL 4500/6750: 3 credits) 31 students enrolled (undergraduate and graduate), two lectures per week, and two lab sections. Spring 2021

Teaching Assistant: Applied Entomology Laboratory (BIOL 4500/6750: 3 credits) 30 students enrolled (undergraduate and graduate students), two lab sections. Spring 2019, Spring 2020

Pacific Union College

Teaching Assistant: General Physiology Laboratory (Human Physiology) 20 students, two lab sections. Spring 2014, Fall 2015

ACADEMIC AND OUTREACH LEADERSHIP ROLES

Utah State University Entomology Club

Club President 2017-2018: I organized club fundraisers, presented several insects for club meetings, organized guest speakers for club meetings, lead out in insect tours for elementary school students from the local school districts, and organized a club team for the Entomology Games at the Entomological Society of America Pacific Branch Meeting in Reno, NV in 2018.

Great Basin National Park

BioBlitz Video Series and Identification Guide to Hemiptera: I was invited by Park Ecologist Gretchen Baker to participate in the 2020 Hemiptera Bioblitz where I shared family level identification information with over 30 students through YouTube and iNaturalist. Students submitted specimens by mail or iNaturalist photos and I helped identify them. The event was 4 days long and I continued to identify all collected specimen after the event.
Link to BioBlitz webpage: **https://www.nps.gov/grba/learn/nature/great-basin-bioblitz.htm**

COMPUTER SKILLS

Data analysis and visualization in R
Mapping and data visualization using ArcGIS Pro
Adobe InDesign
Microsoft Office: Word, Excel, PowerPoint

EDUCATIONAL CLINICS AND WORKSHOPS

Empowering Teaching Excellence **2019**

Utah State University academic and instructional services hosted a day of seminars focused on innovative teaching techniques. There was specific information on interacting with students on Canvas or other online platforms, along with tips on curriculum development.

Parasitoid Wasp Identification Workshop **2018**

Elijah Talamas (USDA ARS, University of Florida, Gainesville, FL), Matt Buffington (USDA ARS, Smithsonian Institution, Washington, DC), and Kim Hoelmer (USDA ARS, Beneficial Insects Introduction Research Unit, Newark, DE) hosted an identification workshop focused on Nearctic Scelionidae and Eupelmidae parasitoid wasps that effectively parasitize brown marmorated stink bug eggs. I was able to attend the two-day workshop and learned to identify many wasp species from their provided collection and my own specimens collected in Utah.