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Status and Enhancement of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) for Biological Control of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) in Northern Utah

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STATUS AND ENHANCEMENT OF *Trissolcus japonicus* (Ashmead)

(HYMENOPTERA: SCELIONIDAE) FOR BIOLOGICAL CONTROL

OF *Halyomorpha halys* (Stål) (HEMIPTERA:

PENTATOMIDAE) IN NORTHERN UTAH

by

Kate V. Richardson

A thesis submitted in partial fulfillment

of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

Diane G. Alston, Ph.D. Major Professor	Lori R. Spears, Ph.D. Committee Member
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UTAH STATE UNIVERSITY
Logan, Utah

2023

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ABTRACT

Status and Enhancement of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) for Biological Control of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) in Northern Utah

by

Kate V. Richardson, Master of Science

Utah State University, 2023

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

The invasive stink bug *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) is an urban nuisance and severe agricultural pest in North America causing significant economic loss. This pest has a wide host range of over 300 plant species, reduced susceptibility to insecticides, and strong flight capacity making it extremely difficult to manage. In its native range of Asia, populations are controlled primarily by parasitoid wasps. *Trissolcus* spp. (Hymenoptera: Scelionidae) native to the U.S. have demonstrated modest suppression of this pest and low rates of successful emergence. The first U.S. adventive population of *Trissolcus japonicus* (Ashmead) was detected in 2014 and has since been detected in Utah (2019) demonstrating effective biological control potential of *H. halys* despite suboptimal climatic conditions. This research focuses on the status and enhancement of *T. japonicus* and native *Trissolcus* in the Intermountain West.

Chapter II explores the range of exotic and native *Trissolcus* spp. in northern Utah's urban-agricultural interface and factors affecting their abundance. Though *T. japonicus* accounted for a small proportion of total *Trissolcus* detections, it exhibited a strong association with *H. halys*, following its patterns of seasonality, orchard groundcover preference, and reliance on urban landscape resources. Groundcover was a significant factor in abundance of native *Trissolcus* spp. with higher abundance in orchards with floral resources. Chapter III assesses the potential of kairomone rubber septa lures to attract and retain *T. japonicus* in the field and in a lab-based mesocosm system. *Trissolcus japonicus* attacked sentinel *H. halys* egg masses at almost an equal proportion to the native *Trissolcus euschisti* (Ashmead) but showed a much greater ability to successfully emerge. Mesocosm trials demonstrated two kairomone blend lures were significantly attractive to *T. japonicus* in a small-scale environment. Finally, Chapter IV investigates the occurrence of *Trissolcus* in southwestern Idaho which was previously unsurveyed for the exotic *T. japonicus* and potential native *H. halys* parasitoids. Reported is the first record of *T. japonicus* in the state of Idaho and details of its associated locality and abundance. Overall, abundance was low, but collection of egg masses demonstrate *T. japonicus* is taking an active role in the suppression of *H. halys* populations.

(177 pages)

PUBLIC ABSTRACT

Status and Enhancement of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) for Biological Control of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) in Northern Utah

Kate V. Richardson

The invasive brown marmorated stink bug (BMSB) is a major insect pest that invades human structures causing nuisance issues and attacks numerous fruit and vegetable crops in Northern America. As this pest threatens $23 billion worth of specialty and agricultural crops in the U.S. and is difficult to manage due to insecticide resistance, control practices such as the use of biological control through egg parasitoid wasps are critical. In its native range of Asia, BMSB populations are controlled primarily by members of the *Trissolcus* genus such as the samurai wasp, but U.S. native wasps have demonstrated low success of BMSB egg parasitism. An introduced population of the samurai wasp was detected in Utah in 2019, and early research suggests this wasp may provide effective biological control of BMSB. This research focuses on the status and enhancement of the samurai wasp and native parasitoids in northern Utah.

Chapter II explores the range of the exotic samurai wasp and native parasitoids in northern Utah's urban and agricultural areas and factors affecting their prosperity. The samurai wasp exhibited a strong association with BMSB, following its patterns of seasonality, orchard groundcover preference, and reliance on urban landscape resources. Samurai wasps accounted for only a small proportion of total *Trissolcus* parasitoid detections, and more native wasps were captured in orchards with floral groundcover as compared to those with non-floral groundcover. Chapter III assesses the attractiveness of kairomone lures to the samurai wasp in field and laboratory conditions. In the field, samurai wasp attacked lab-reared BMSB egg masses at almost an equal rate to a native *Trissolcus* species but had much higher emergence success from egg masses. Laboratory trials compared specific chemical blends for attractiveness to the samurai wasp. Finally, Chapter IV investigates the role of BMSB parasitoids in a state previously unsurveyed for the samurai wasp. Reported is the first record of samurai wasp in the state of Idaho and details about its population size and geographic locations. Overall, population sizes were very low, but collection of wild egg masses proved samurai wasp is taking an active role in the suppression of BMSB populations.

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CHAPTER I

INTRODUCTION: STATUS AND ENHANCEMENT OF *Trissolcus japonicus* (Ashmead) FOR BIOLOGICAL CONTROL OF Halyomorpha halys (Stål) IN NORTHERN UTAH

Invasion of *Halyomorpha halys*

The brown marmorated stink bug, (BMSB) *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive agricultural and urban nuisance pest originating from Asia (Lee et al. 2013). In its native range, it has one to two generations per season and a minimum and maximum developmental threshold of 14.14° C and 35.76° C, respectively (Nielsen et al. 2008, Lee et al. 2013). It was first discovered in the U.S. in Allentown, Pennsylvania in 1996, and has since spread to 47 U.S. states and 4 Canadian provinces (Fogain and Graff 2011, StopBMSB.org 2023) demonstrating great potential for rapid range expansion (Zhu et al. 2012). The majority (32) of these states have reported *H. halys* to be a problem ranging from small residential nuisances to severe agricultural and urban issues (StopBMSB.org 2023; Fig. I-1) In addition to North America, *H. halys* has invaded parts of South America (Chile) (Faundez and Rider 2017) and large parts of continental Europe (Haye, Fischer, et al. 2015, Gariepy and Talamas 2019). Additionally, multiple interceptions of *H. halys* have been made at ports of entry in New Zealand and Australia (Horwood et al. 2019). *Halyomorpha halys* was first detected in Utah in 2012 with the first injury to tree fruit and vegetable crops reported in 2017 (Spears et al. 2018); it is now established in six northern counties: Box Elder, Cache, Davis, Salt Lake, Utah, and Weber with detection in two central and southern counties: Carbon and Kane (Holthouse et al. 2017).

The rapid spread of *H. halys* can be attributed to its numerous life history traits common in successful invasive species (Sakai et al. 2001). The first trait is polyphagy; *H. halys* utilizes more than 300 host plant species including field and specialty crops (Haye, Gariepy, et al. 2015, Bergmann et al. 2016, Leskey and Nielsen 2018, Schumm et al. 2020, Holthouse et al. 2021a) to which it can cause severe damage and economic loss (Haye, Gariepy, et al. 2015). In addition to utilizing agricultural crops, *H. halys* has demonstrated the ability to survive and reproduce on urban and suburban ornamental plants (Holthouse et al. 2021a). This ability, coupled with its overwintering congregational behavior on and within human-made structures has led to nuisance issues throughout the U.S.; in places with established populations, they can be found in the hundreds to thousands when entering and exiting structures (Zhu et al. 2012, Inkley 2016).

Additionally, *H. halys* has an incredibly strong ability to disperse within and across landscapes resulting in convenient access to agricultural sites from urban overwintering sites and vice versa. Flight mill studies have found adults are able to fly more than 117 km (Lee and Leskey 2015, Wiman et al. 2015); nymphs also demonstrate an impressive dispersal capacity of covering more than 20 m on grassy ground within 12 hrs (Lee et al. 2014). This vagility allows *H. halys* of various life stages to move easily among local host plants, escape insecticide application, and recover in an untreated area, leading to insecticide residue tolerance (Kuhar and Kamminga 2017).

Pest Status and Management of *Halyomorpha halys*

In Utah, over 53 species of plants have been documented to sustain two or more life stages of *H. halys* (Holthouse et al. 2021a). Common ornamental hosts known to harbor large populations of *H. halys* in the U.S. include northern catalpa (*Catalpa speciosa* Warder ex Engelm.), tree of heaven (*Ailanthus altissia* Mill.), and empress tree (*Paulownia tomentosa*) (Acebes-Doria et al. 2016, Holthouse et al. 2021a) due to their abundant fruiting structures and large leaves which provide ample underside oviposition surfaces for. While tree of heaven remains the most significant host plant of *H. halys* in the eastern U.S. (Acebes-Doria et al. 2016, Quinn et al. 2019, Dyer et al. 2022), a host plant utilization study in northern Utah found that 91% of all *H. halys* detections were on northern catalpa (Holthouse et al. 2021a). These host plants offer significant feeding and reproduction opportunities, contributing to the insect's urban nuisance status for property owners and land managers where *H. halys* overwinters. In addition, along the Wasatch Front in northern Utah, urbanized areas with high populations of *H. halys* are often in close proximity to agricultural production areas where specialty crops are at particular risk of damage.

In the U.S., *H. halys* agricultural hosts of primary concern are apple (*Malus domestica* (Suckow) Borkh), peach (*Prunus persica* (L.) Batsch), cherry (tart: *Prunus cerasus* L. and sweet: *Prunus avium* L.), bean (*Phaseolus* spp.), hazelnut (*Corylus* *avellana* L.), corn (field and sweet; *Zea mays*), tomato (*Solanum lycopersicum* L.), pepper (*Capsicum* spp.), and soybean (*Glycine max* L.) (StopBMSB.org 2021). In fact, Mid-Atlantic apple growers reported a $37 million loss in apple production due to *H. halys* damage in just one outbreak year (Leskey, Hamilton, et al. 2012) and the loss of >90% fruit crop in some orchards (Leskey, Short, et al. 2012). In Utah specifically, apple, corn, peach, and tart cherry are vulnerable to *H. halys* and are some of the state's largest fruit and vegetable commodities (Holthouse et al. 2017, Schumm et al. 2020). Utah is the second largest producer of tart cherry in the U.S.; a recent study found that tart cherry fruits are highly susceptible to *H. halys* feeding injury (Schumm et al. 2020) causing high rates of early fruit abscission and great concern to fruit growers in the state.

All life stages of *H. halys* (apart from the egg) can feed and damage stems, leaves, flowers, fruits, and nuts. This pest uses a proboscis (stylet) to penetrate host plant structures, and symptoms of damage present as cat-facing, scarring, corking, discolorations, and deformities (Spears et al. 2018). Complete abortion of fruit development can occur if fed on during early season stages (Nielsen and Hamilton 2009, Kim et al. 2015, Schumm et al. 2020). Additionally, stylet feeding can transmit bacteria and lead to fruit rot (Rice et al. 2014). *Halyomorpha halys* damage may take up to two weeks to become visually evident after feeding injury occurs (Spears et al. 2018), delaying possible management tactics until after significant damage has occurred.

Though broad-spectrum insecticides are the most common management strategy, they are only moderately effective against *H. halys* due to the insect's strong flight capability and tolerance to insecticide residues. Studies have shown relatively low effectiveness of some chemical classes, and only temporary knockdown of adults resulting in up to 4-times more frequent insecticide applications to mitigate the immediate economic threat posed by this invasive insect (Leskey, Short, et al. 2012, Holthouse et al. 2017). However, frequent insecticide applications are incompatible with long-term sustainable management approaches because of their financial and economic infeasibility coupled with health risks for workers and the environment. In addition, insecticides cause major disruption of integrated pest management (IPM) programs by killing beneficial insects and natural enemies, including pollinators and biological control agents, and contributing to insecticide resistance and secondary pest outbreaks. Therefore, it is important to transition away from insecticides in favor of tactics that maintain or restore IPM programs.

Biological Control of *Halyomorpha halys*

In response to the challenges of managing *H. halys*, suppression strategies have shifted to include biological control programs (Ogburn et al. 2016, Dieckhoff et al. 2017). Some opportunistic predators have been observed attacking *H. halys* adults in the U.S., including mantids (Mantodea), spiders (Araneae), and assassin bugs (Hemiptera: Reduviidae), but these predators are scarce and do not provide adequate suppression (Ogburn et al. 2016). Of more value to control programs are predators and parasitoids that attack the highly vulnerable egg stage. Egg predators with sucking and chewing mouthparts such as true crickets and katydids

(Orthoptera), earwigs (Dermaptera), jumping spiders (Araneae: Salticidae), and ground beetles (Coleoptera: Carabidae) are capable of quickly consuming eggs (Rice et al. 2014, Pote and Nielsen 2017, Morrison et al. 2018), but are generalist predators with many other food sources. Parasitoids, on the other hand, tend to be highly host specific increasing the likelihood of a targeted and successful biological control effort.

In its native range, *H. halys* populations are controlled primarily by parasitoid wasps that attack the egg stage (Arakawa and Namura 2002, Yang et al. 2009). In the U.S., three families of Hymenopteran parasitoids have been found to sting (use ovipositor to lay eggs within) *H. halys* eggs—Scelionidae, Eupelmidae, and Encyrtidae (Abram et al. 2017). The only species that have demonstrated the ability to sting, complete development, and emerge from *H. halys* eggs are *Anastatus reduviid* (Howard), *A. mirabilis* (Walsh & Riley), *A. persalli* (Ashmead), *Trissolcus brochymenae* (Ashmead), *T. euschisti* (Ashmead), *T. hullensis* (Harrington), and *Telenomous podisi* (Ashmead) (Abram et al. 2017, Schumm et al. 2019, Richardson et al. 2023a). These native parasitoids have consistently resulted in less than 14% *H. halys* mortality and less than 5% of parasitized eggs have supported emergence of viable adults (Cornelius et al. 2016, Ogburn et al. 2016). In Utah specifically, native parasitoids have demonstrated only modest suppression of *H. halys* to-date with rates of successful emergence of only 0.5-3.7% (Schumm et al. 2019, Holthouse et al. 2020, Richardson et al. 2023a).

Due to the overall low efficacy of native parasitoids, *H. halys* control efforts shifted focus to classical biological control options. In Asia, *H. halys* is attacked by a similar suite of egg parasitoids to those in the U.S. including those of the *Anastatus, Telenomus*, and *Trissolcus* genera (Arakawa and Namura 2002, Yang et al. 2009, Lee et al. 2013). Specifically, species of *Trissolcus* have shown promise as potential biological control agents and *Trissolcus japonicus* (Ashmead) has been identified as a key natural enemy of *H. halys*.

Life History of *Trissolcus japonicus*

Trissolcus japonicus (Ashmead), commonly called the samurai wasp, is a solitary endoparasite of pentatomid eggs. In its native range of Asia, it is the predominant parasitoid of *H. halys* with parasitism rates up to 60-90% (Zhang et al. 1993, Yang et al. 2009). A female wasp will sting and deposit a single egg within each *H. halys* egg when parasitizing an egg mass. *Trissolcus japonicus* is generally thought to be a synovigenic species and is able to mature additional eggs after emergence (Sabbatini-Peverieri et al. 2020, Wong et al. 2021). Females with an initial full egg load (~31 eggs) are able to fully exploit an *H. halys* egg mass of ~28 eggs and can resynthesize an egg load of around 24 eggs by seven days after oviposition (Paul et al. 2022) allowing them to attack multiple egg masses. In addition to its high production of progeny, *T. japonicus* has few stink bug hosts, a short development time of ~18 days from egg laying to adult emergence (Lara et al. 2019), up to ten generations per year (Qiu et al. 2007), and a female-biased ratio of approximately 6:1 (Yang et al. 2009); these characteristics make it a promising candidate for classical biological control of *H. halys*.

Trissolcus japonicus is a temperate to subtropical species that is known to overwinter as an adult (Nystrom Santacruz et al. 2017, Zhang et al. 2017) and geographic modeling predicts that Mediterranean, temperate and subtropical climates are suitable for *T. japonicus* while semi-arid and cool-subarctic climates have only marginal suitability or are unsuitable (Avila and Charles 2018). It has been estimated that *T. japonicus* has a minimum threshold for development of 12.2° C (Qiu et al. 2007). However, recent research on genetic differences of populations (Chen et al. 2021, Personal Communication, Marie Bon Claude) may shed light on possible physiological differences, such as climate tolerance, among genotypes.

Range of *Trissolcus japonicus*

Though native to Asia, *Trissolcus japonicus* has been under study in U.S. quarantine facilities since 2007 to evaluate its efficacy as a biological control option for *H. halys* and to assess its possible negative effects on native stink bugs (Talamas, Herlihy, et al. 2015). However, an adventive population of *T. japonicus* was detected in Beltsville, Maryland in 2014 (Talamas, Herlihy, et al. 2015), and additional recoveries have been made in 15 states (StopBMSB.org 2023) and other countries outside its native range: Canada (Abram et al. 2019, Gariepy and Talamas 2019), Switzerland (Stahl et al. 2019), Italy (Peverieri et al. 2018), and Germany (Dieckhoff et al. 2021) (StopBMSB.org 2023; Fig. I-1).

Northern Utah consists of dry, semi-arid, and desert climates with average lows below 12.2° C for up to 8 months of the year (“Utah Climate Center - Utah State

University" 2022) which makes it an unlikely and unique climate for both *H. halys* and *T. japonicus,* especially compared to other areas of establishment in the U.S. Yet, *T. japonicus* was detected in Salt Lake City, Utah in 2019 (Holthouse et al. 2020) and has consistently overwintered and expanded its distribution in northern Utah (Holthouse et al. 2021b, K. Richardson, unpublished data). Climatic modeling and laboratory experiments determined temperature thresholds cannot possibly account for all behavioral aspects of habitat suitability. Regardless of its unlikely establishment, early research indicates parasitism rates of *H. halys* have increased since the discovery of *T. japonicus*, and lends support to the parasitoid's capacity for biological control of *H. halys* (Holthouse et al. 2020).

The state of Idaho has had little to no research on the invasive *H. halys* and its parasitoids. *Halyomorpha halys* has been detected in the state, but no significant damage or presence problems have been reported thus far (Personal communication, Jennifer Reibe and Paul Castrovillo). However, *H. halys* continues to threaten agricultural commodities in the U.S. and research predicts that climate change will likely expand geographic areas of high suitability (Streito et al. 2021; Illán et al. 2022). The Treasure Valley in southwestern Idaho is specifically expected to experience further spread of *H. halys* and increased negative impacts on agriculture (Illán et al. 2022).

With detections of *T. japonicus* on the West Coast in Washington in 2015 (Milnes et al. 2016), again in Oregon in 2017 (Hedstrom et al. 2017) and most recently Utah in 2019 (Holthouse et al. 2020), the potential for the wasp's presence is high, but no surveys have been conducted for this exotic parasitoid. As the risk to

Idaho's agriculture from *H. halys* continues to increase, it is important to document if this key biological control agent has established in the area.

Monitoring for *Trissolcus japonicus*

Common methods of parasitoid monitoring include deployment of sentinel (lab-reared) *H. halys* egg masses, collection and rearing of wild *H. halys* egg masses, and yellow sticky card (YSC) deployments. Many studies have used sentinel egg masses as a survey method for *T. japonicus* and other parasitoid wasps (Jones et al. 2014, Abram et al. 2017, Dieckhoff et al. 2017, Holthouse et al. 2020). This method provides important information on *Trissolcus* spp. incidence and *H. halys* parasitism rates. However, recent studies have shown that lab-reared egg masses underestimate parasitism rates and attract fewer wasps than wild egg masses (Jones et al. 2014, Abram et al. 2019, Holthouse et al. 2020) due to the removal and/or alteration of semiochemical cues used for host location during the handling of egg masses (Hedstrom et al. 2017). In addition, the use of sentinel egg masses requires labor-intensive rearing of *H. halys* (Medal et al. 2012) as eggs must be used within 72 hr to be most effective (Qiu et al. 2007). If not used within 72 hr, egg masses are typically frozen for use in field studies but this has been shown to reduce parasitism rates and delay parasitoid adult emergence (McIntosh et al. 2019).

Collecting and rearing wild egg masses can also contribute to information on *T. japonicus* and other *Trissolcus* spp. populations. Wild egg masses have the benefit of intact semiochemicals and provide a more accurate assessment of *Trissolcus* host location in conjunction with measures of parasitism rates. In fact, in Utah, *T. japonicus* was first detected emerging from two wild *H. halys* egg masses collected in parasitoid surveys in 2019 (Holthouse et al. 2020). Unfortunately, wild egg masses collected after parasitoid emergence lack species-specific information, though PCR advancements may provide a future solution to this issue (Chen et al. 2021).

While YSC do not have the advantage of providing parasitism rate information, they are an efficient alternative for gathering presence, abundance, and range expansion information of adventive *T. japonicus* populations (Quinn et al. 2019). Traditionally, YSC have been used in monitoring efforts and research of *T. japonicus* behavior (Lowenstein, Andrews, Hilton, et al. 2019, Schumm et al. 2019, Holthouse et al. 2021b, Peterson et al. 2021, Dyer et al. 2022). For example, Holthouse et al. (2021b) compared the use of yellow and blue sticky cards and found YSC captured significantly higher numbers of *Trissolcus* spp., but that both colors were effective in detecting *T. japonicus* in multiple habitat types of northern Utah. The majority of *T. japonicus* detections (79%) in this study were in urban landscapes as compared to fruit orchards (16%) and vegetable fields (5%), supporting results observed in other studies (Hedstrom et al. 2017, Peverieri et al. 2018, Lowenstein, Andrews, Hilton, et al. 2019, Holthouse et al. 2021b).

Floral Resources for *Trissolcus japonicus*

Current detections of *T. japonicus* across the U.S. often have the shared attribute of occurring in urban areas or in proximity to ornamental trees (Hedstrom et al. 2017, Peverieri et al. 2018, Lowenstein, Andrews, Hilton, et al. 2019, Holthouse et al. 2021b). One possible reason for this is the 'parasitoid nectar provision hypothesis' which asserts that biological control by parasitoids will be increased by the availability of nectar resources (Heimpel 2019). In simple agricultural habitats, parasitoids tend to be sugar-limited; however, this limitation can be alleviated by providing nectar, which in turn increases parasitoid longevity, fecundity, and their ability to suppress herbivorous pests (Lee et al. 2006). Urban areas often have increased ornamental plant resources and diversity that provide essential nectar and pollen resources for *T. japonicus.*

Furthermore, research has shown that non-crop host plants in agricultural settings can be critical in providing essential food and habitat resources not only to parasitoids, but also to beneficial insects, such as predators and pollinators (Hickman and Wratten 1996, Baggen and Gurr 1998). Some recent studies have demonstrated that parasitoids of leafrollers (Araj and Wratten 2015) and other Lepidopterans (Lee et al. 2006, Chau et al. 2019) utilize floral resources, particularly those of buckwheat (*Fagopyrum esculentum* Moench) and sweet alyssum (*Lobularia maritima* (L.) Desv.) to increase their longevity and parasitism rates. These benefits lead to increased efficacy in controlling agricultural crop pests.

Similar effects of floral resources have been observed in *Trissolcus* spp. Research by Rahat et al. (2005) demonstrated significant enhancement of longevity in *Trissolcus basalis* (Wollaston) adults from only 2-3 days to 33 days when provisioned with floral resources. In another study, *T. basalis* was attracted to buckwheat (*Fagopyrum esculentum* Moench) and basil (*Ocimum basilicum* L.) flowers which increased parasitoid offspring (Foti et al. 2017). In a follow-up study, egg parasitism of the southern green stink bug, *Nezara viridula* (Linnaeus), correlated positively with proximity to the buckwheat margin (Foti et al. 2019). Research specific to *T. japonicus* explored the impact of eight flowering plant species on survival in the laboratory and found buckwheat, cilantro (*Coriandrum sativum* L.), and dill (*Anethem graveolens* L.) provided nectar sources that improved survival (McIntosh et al. 2020). In addition to nutritionally sustaining parasitoids, non-crop plant resources may provide essential overwintering protection for *T. japonicus* and other parasitoids (Moya-Raygoza and Becerra-Chiron 2014, Ramsden et al. 2015, Gillespie et al. 2016).

The benefits of floral resources can be taken advantage of in orchard settings in several ways. Some examples include strip cropping, border cropping, cover crops, or even leaving crop areas unmanaged. Mele et al. (2022) found that semi-natural habitats with large patches of unmanaged vegetation promote biological control of *H. halys* by *Trissolcus mitsukurii* (Ashmead) in kiwifruit orchards. Incorporating non-crop plants provide many benefits and are appropriate to agricultural production systems, particularly those focused on IPM tactics. Many growers already use non-crop plants for the benefits of soil conditioning, weed and erosion management, and attraction of beneficial insects. Floral resources may be an underutilized approach to the conservation of *T. japonicus* populations; their use may extend wasp longevity and fecundity and will likely enhance their efficacy as a biological control agent.

Host Kairomone use by *Trissolcus japonicus*

In many biological control systems, chemical residues left by host insects can attract parasitoid wasps, elicit parasitoid arrestment, stimulate parasitoid search behavior, and result in increased parasitism (Peri et al. 2006, Mansour et al. 2010, Murali-Baskaran et al. 2018). This strategy of exploiting kairomones from hosts is common in stink bug parasitoids. For example, in Y-tube experiments, *T. basalis* was attracted to volatiles from adults of its host, *Nezara viridula* (Colazza et al. 1999, 2004), and *Trissolcus brochymenae* (Ashmead) showed increased attraction to gravid females of its host (Conti et al. 2004).

Similar research demonstrated that under experimental conditions, female *T. japonicus* exhibited positive behavioral responses to *H. halys* stimuli such as herbivory and oviposition (Bertoldi et al. 2019). In addition, it has been well documented that *T. japonicus* females are responsive to the "footprints" or tarsal residues left by *H. halys* adults on various plant and artificial materials (Boyle et al. 2020, Arif et al. 2021, Malek et al. 2021). These chemical cues are highly host-specific; *T. japonicus* can distinguish between *H. halys* and native pentatomid semiochemicals (Arif et al. 2021), increasing its ability to target hosts effectively and avoid non-target effects. One study found that the bioactive volatile n-tridecane significantly attracted *T. japonicus* and reduced its host search time, while (E)-2-decenal acted as a repellent (Zhong et al. 2017). Subsequent research by Malek et al. (2021) found that a combination of 80% n-tridecane and 20% (E)-2-decenal performed better than n-tridecane alone in a Y-tube olfactometer experiment. A more recent study used a combination of 90% n-tridecane and 10% (E)-2-decenal during field trials, but had little success, likely due to inadequate release rates from filter paper sources (J. Kaser, personal communication). These chemicals have proven attractive in a laboratory setting, but more research is needed to understand how they perform in a field setting.

Traditionally, rubber septa are a standard chemical release device used in pest management (e.g., pheromone lures) (Knight and Light 2005, Stelinski et al. 2005, Charles et al. 2015). Septa can be loaded with kairomone compounds to attract beneficial parasitoids and enhance stink bug parasitism (Bakthavatsalam and Tandon 2006, Vieira et al. 2014). Thus far, this strategy has not been used to benefit the control of *H. halys;* therefore, the identification of effective techniques to deploy kairomone attractants could increase the accuracy of parasitism rate estimates, especially for early detection of *T. japonicus* when populations are low. In addition, the creation of a highly attractive lure for *T. japonicus* has the potential for use in field sites to increase parasitism, thereby reducing *H. halys* populations and subsequent crop damage.

Research Justification

Halyomorpha halys has proven to be a highly successful invasive species with a strong likelihood of continuing to expand its establishment in many areas outside of its native range. *Trissolcus japonicus* has thus far demonstrated the ability to expand alongside its native host without any documented non-target effects due to its high host-specificity. As adventive populations of *T. japonicus* increase both within North America and globally, it is essential to understand the potential impact they may have on *H. halys* populations as *T. japonicus* releases are being considered by pest managers as a control option.

Many IPM programs use the strategy of augmentative biological control by inundative releases (mass-reared natural enemies in large numbers) with the goal of obtaining immediate suppression of the pest (van Lenteren 2012, Perez-Alvarez et al. 2019). However, this approach is not always sustainable because it requires continued input and can distract research foci from more sustainable objectives (Michaud 2018). In fact, recent release and establishment efforts of *T. japonicus* in Oregon and several other states have shown low success (Nystrom Santacruz et al. 2017, Lowenstein, Andrews, Hilton, et al. 2019). Utah is a unique climate for *T. japonicus,* and the geography presents additional obstacles to establishment due to its extreme climate and high elevation, yet *T. japonicus* has successfully overwintered and expanded its distribution in northern Utah (Holthouse et al. 2021b, K. Richardson, unpublished data). Therefore, promoting and conserving *T. japonicus* populations already established in the Intermountain West appears to be a viable tactic to contribute to the sustainable management of *H. halys*.

This thesis aims to understand the geographic range of *T. japonicus* in northern Utah and southwestern Idaho and identify sustainable approaches to facilitate the recruitment and persistence of *T. japonicus*. In Chapter 2, the spatial distribution of *T. japonicus* and native *Trissolcus* spp. in Utah is examined along with factors affecting habitat suitability including urban surroundings, *H. halys* presence, and seasonality. Specifically, the effects of groundcovers of floral plants, bare ground, and turfgrass on the abundance of *T. japonicus* and native *Trissolcus* spp. are compared in agricultural orchards in northern Utah. In Chapter 3, the potential use of kairomone-infused rubber septa is explored in field settings and controlled mesocosm experiments to determine the attraction of *T. japonicus* to various ratios of chemical components as well as optimal septa load rates. In Chapter 4, the occurrence of native and exotic *Trissolcus* spp. and their potential for control of *H. halys* in southwestern Idaho, which was previously unsurveyed for parasitoids of *H. halys,* is discussed. As a whole, this research focuses on key strategies for the conservation and enhancement of *T. japonicus* as a biological control agent of *H. halys*.

Objectives

Objective 1 (Chapter 2). Report the current range of *T. japonicus* in northern Utah and assess the effects of urbanness, orchard groundcover, and *H. halys* presence on the abundance of *T. japonicus* and native *Trissolcus* spp.

Objective 2 (Chapter 3). Determine the viability of *H. halys* host chemical cues (kairomones) in attracting *T. japonicus* and increasing egg parasitism rates in a field and mesocosm setting.

Objective 3 (Chapter 4). Survey southwestern Idaho for adventive populations of *T. japonicus* and native *Trissolcus* parasitoids of *H. halys*.

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Figures

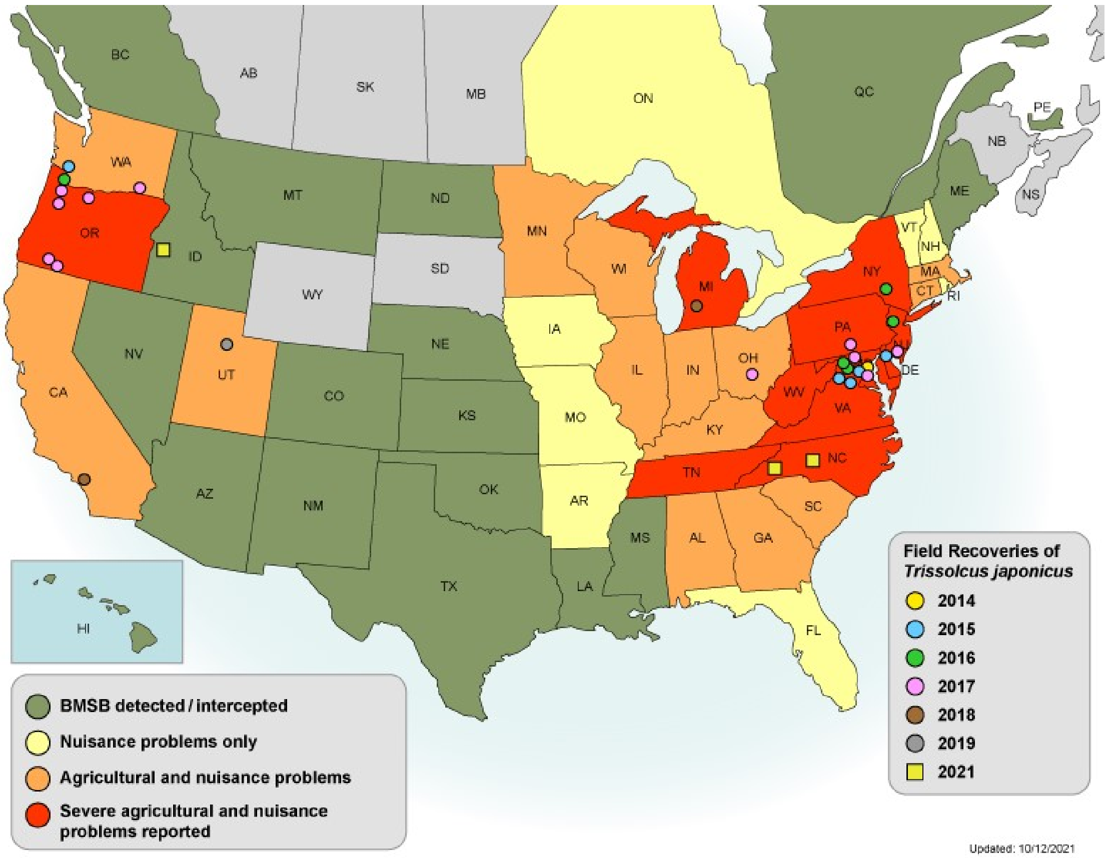

Figure I-1. Map of *H. halys* (colored states) and *T. japonicus* (colored points) distribution in the U.S. and Canada (Updated 10/12/2021, https://www.stopbmsb.org/biological-control/samurai-wasp-trissolcus-japonicus/).

CHAPTER II

LANDSCAPE EFFECTS ON NATIVE AND EXOTIC TRISSOLCUS SPP. (HYMENOPTERA: SCELIONIDAE) IN NORTHERN UTAH[1]

Abstract

The invasive stink bug *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) causes severe economic loss to specialty crops in North America. *Trissolcus* (Hymenoptera: Scelionidae) parasitoids native to Utah have demonstrated only modest suppression of this pest. However, adventive populations of the exotic *Trissolcus japonicus* (Ashmead) detected in Utah (2019) have demonstrated the potential to provide effective biological control of *H. halys*. To assess the abundance of *T. japonicus* and native *Trissolcus* species in northern Utah and their response to landscape resources, yellow sticky card surveys were conducted from May through September, 2019-2021 with expansion in 2021 to assess effects of orchard understory and *H. halys* presence. Mean captures of *T. japonicus* increased each year despite accounting for only a small proportion of total *Trissolcus* detections. Sites with a high proportion of urban land cover in a 1 km site radius significantly increased abundance of *T. japonicus*; native *Trissolcus* were not associated with urbanization. Significantly higher season-long *T. japonicus* captures occurred in bare groundcover orchards than turfgrass and floral. *Halyomorpha halys* presence was highest in bare orchards and was a highly significant factor influencing *T. japonicus* abundance, but not native *Trissolcus* abundance. No significant season-long groundcover trends were observed for native *Trissolcus* spp.; however, during the

time of greatest abundance (900 to 1400 $DD_{12°C}$), significantly higher captures occurred in orchards with floral groundcovers. Our results support that floral resources provided by orchard groundcover and urban land cover may increase abundance of native and exotic *Trissolcus* spp. in northern Utah.

Keywords

Samurai wasp, brown marmorated stink bug, biological control, parasitoid, floral resources, urban landcover

[1]Coauthored by Mark Cody Holthouse, Diane G. Alston, and Lori R. Spears

Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive agricultural and urban nuisance pest originating from East Asia with the ability to utilize more than 300 different host plants (Hoebeke and Carter 2003, Lee et al. 2013, Holthouse et al. 2017, Schumm et al. 2020) to which it can cause severe damage and economic loss (Haye, Gariepy, et al. 2015). Since its first detection in Utah in 2012 and subsequent injury to tree fruit and vegetable crops starting in 2017 (Spears et al. 2018), *H. halys* has been of significant concern to Utah specialty crop producers. Schumm et al. (2020) found that tart cherry fruits (*Prunus cerasus* L.) are highly susceptible to *H. halys* feeding injury causing high rates of early fruit abscission, which is particularly concerning as Utah is the second largest producer of tart cherry in the U.S. (UDAF 2021).

Though broad-spectrum insecticides are a common management strategy of *H. halys*, they are only moderately effective due to the insect's tolerance to insecticide residues, propensity to disperse among multiple hosts within a season, strong adult flight capability, and the ability of all life stages to feed and develop on a range of host plants (Leskey et al. 2012). In response to the challenges of managing *H. halys*, suppression strategies have shifted to include biological control programs (Ogburn et al. 2016, Dieckhoff et al. 2017).

In its native range, *H. halys* populations are controlled primarily by parasitoid wasps that attack the egg stage (Arakawa and Namura 2002, Yang et al. 2009). Several species of parasitoid wasps, *Trissolcus* spp. (Hymenoptera: Scelionidae), are reported to attack *H. halys* eggs; however, those native to Utah have demonstrated only modest suppression of *H. halys* to-date with rates of successful emergence of only 0.5-3.7% (Schumm et al. 2019, Holthouse et al. 2020, Richardson et al. 2023a). *Trissolcus japonicus* (Ashmead) has been identified as a key biocontrol agent of *H. halys* with egg parasitism rates up to 60-90% in their native Asian range (Zhang et al. 1993).

Adventive populations of *T. japonicus* have been detected in the U.S. since 2014 (Talamas, Herlihy, et al. 2015, Milnes et al. 2016) with current detections in 15 states (StopBMSB.org 2022). The first detection in Utah occurred in 2019 (Holthouse et al. 2020). Geographic and ecoclimatic models suggest that the high elevation, arid Intermountain West is only marginally suitable for this parasitoid (Avila and Charles 2018). In Utah, research indicates *H. halys* egg parasitism rates increased in the two years following *T. japonicus* discovery, and the wasp has demonstrated the potential to provide biological control of *H. halys* (Holthouse et al. 2020, Richardson et al. 2023a). To facilitate biological control of *H. halys* and protect Utah's specialty crops, it is critical to determine key factors affecting the successful establishment and retention of *T. japonicus* and other potential egg parasitoids in agricultural and urban landscapes.

Locations with detections of adventive populations of *T. japonicus* in Utah, across the U.S., and in other countries are often urban or near urban areas (Hedstrom et al. 2017, Kaser et al. 2018, Peverieri et al. 2018, Lowenstein, Andrews, Hilton, et al. 2019, Richardson et al. 2023b). One possible reason is that parasitoids tend to be sugar-limited in simplified agricultural habitats (Lee and Heimpel 2008). Research has shown that non-crop host plants in agricultural settings can be critical in providing essential food and habitat resources to parasitoids, such as for aphids (Araj and Wratten 2015, Ribeiro and Gontijo 2017) and Lepidopterans (Lee et al. 2006, Chau et al. 2019).

Research specific to *Trissolcus* spp. has demonstrated increases in longevity (Rahat et al. 2005), fecundity (Foti et al. 2017), and stink bug egg parasitism (Foti et al. 2019) when wasps are provisioned with floral resources. A recent study found buckwheat, cilantro, and dill provided nectar sources that improved the survival of *T. japonicus* in a laboratory setting (McIntosh et al. 2020). While research has demonstrated the benefits of floral resources for parasitoids, no studies have explored the impact of groundcover resources in agricultural settings on the enhancement of the exotic *T. japonicus* and native *Trissolcus* spp. populations.

Comparing the effects of understory vegetation diversity on wasp abundance provides further insight into foundational resource needs for *T. japonicus* and native *Trissolcus* spp., and effective methods to enhance their establishment in urban-agricultural landscapes. We predict fruit orchards in northern Utah that provide floral resources (through weeds, wildflowers, and/or strip-cropping) may increase the prevalence of exotic and native *Trissolcus* spp., and therefore support the suppression of *H. halys*. Additionally, we demonstrate the distribution of *T. japonicus* in northern Utah and report the effects of urban proximity, seasonality, and *H. halys* presence on the abundance of *T. japonicus* and native *Trissolcus* spp.

Materials and Methods

2.1 Surveys

Yellow sticky cards (YSC) (20 x 14 cm; Alpha Scents Inc., West Linn, OR) were deployed at 24 and 31 sites in 2019 and 2020, respectively (Tables II-1 and II-2). Sites were located in Box Elder, Cache, Davis, Salt Lake, Utah, and Weber counties of northern Utah. YSC were deployed starting 21 May and 29 May in 2019 and 2020, respectively, and ending 1 October in 14 d (±1 d) intervals resulting in a total of nine deployment periods. At each site, a YSC was secured with two twist ties to a branch at approximately 2 m height on target ornamental and fruit trees based on past studies that support *H. halys* oviposition attraction to these hosts (Holthouse et al. 2021a).

In 2021, YSC surveys were conducted at 36 sites (Table II-3) including some sites monitored in 2019-2020 and 24 orchards with groundcover types of interest. Orchard sites were selected based on understory vegetation categories of bare soil (cultivated and herbicide-managed), turfgrass (managed), or floral (with wildflowers, weeds, or strip-cropped floral resources) with each understory type replicated eight times. Sites were monitored for consistency in groundcover categorization throughout the season and were assumed to have similar insecticide application patterns based on interviews of producers. A total of ten, 14 d (±1 d) YSC deployments were conducted from 19 May to 5 October as described for 2019-2020.

Surveys for *H. halys* were conducted over the same time period at the 24 orchard sites in 2021. Clear dual sticky panel traps (Trécé Inc., Adair, OK) attached to a wooden stake and positioned ~1.2 m above the ground were deployed at the orchard edge within 10 m of the YSC. *Halyomorpha halys* dual pheromone lures (Trécé Inc., Adair, OK) were secured to traps using twist ties with replacement after 12 wk. *Halyomorpha halys* (adults and nymphs) were recovered from traps every 14 d (±1 d).

2.2 Parasitoid Processing

Upon retrieval, YSC were examined under a stereomicroscope (Leica Stereozoom S9E, Leica Microsystems Inc.) with 98–880x magnification for the presence of *Trissolcus* spp. Wasps were initially removed by cutting out a small piece of YSC, then soaked in Histo-Clear II histological clearing fluid (National Diagnostics, Atlanta, GA) for ~5–7 min to dissolve the adhesive, and mounted on a white cardstock point with clear fingernail polish and insect pin to allow for species identification. Due to the capture of large numbers of *Trissolcus* spp. on 23 August to 11 October 2021, wasp specimens were directly identified on small pieces of YSC to reduce processing time, and only removed if required for species identification. All *Trissolcus* specimens were identified to species-level following the Key to Nearctic *Trissolcus* (Talamas, Johnson, et al. 2015). Some *Trissolcus* specimens were unidentifiable beyond the genus level due to physical damage. Intact parasitoid wasps were labeled and stored in the Alston Lab, Department of Biology, Utah State University, Logan, UT. Voucher specimens were deposited in the Utah State University Insect Collection.

2.3 Data Analyses

Mean hourly temperature data were obtained each year from weather stations representative of each site, and accumulated degree days using a linear method based on averaging the daily maximum and minimum temperatures, a 1 January biofix, and 12 °C lower development threshold (LDT) (Qiu et al. 2007) were calculated for the end date of each deployment period.

Following methods of Christman et al. (2022), land cover values each year were obtained from USDA National Agricultural Statistics Service (NASS) CropScape and Cropland Data Layer (CDL) (USDA NASS CDL, 2019-2021). Urban land cover included all types of developed land. To assess urbanness of each site, a 1 km boundary was established, the number of pixels of urban land cover within the boundary counted, and the proportion of urban land cover quantified. Sites with 0-0.33, 0.33-0.67, and 0.67-1.00 urbanness were considered low, medium, and high, respectively.

Abundance detection maps were built in ArcGIS Pro (version 3.0.2). To compare *T. japonicus* and native *Trissolcus* spp. captures among urbanness categories, data from each year were pooled across sample dates and analyzed using the Kruskal-Wallis test followed by the Bonferroni corrected Dunn's test. For the 2021 groundcover study, only the 24 sites with designated groundcover and monitored for *H. halys* were included in the analysis. Captures of *T. japonicus* and total native *Trissolcus* spp. were compared across groundcover types for both season-long data and peak season (900 to 1400 $DD_{12°C}$) using the Kruskal-Wallis test followed by the Bonferroni corrected Dunn's test and were separately analyzed by the Kruskal-Wallis test alone for the effect of the presence or absence of *H. halys.* All statistical comparisons were run using R software (R version 4.1.1; R Core Team 2021) and were considered significant at $p < 0.05$.

One bare ground orchard site in Box Elder County (Table II-3) was removed from all statistical analyses due to extremely high numbers of *T. euschisti* (Ashmead) uncharacteristic to this groundcover type and other sites in the study. This site was only surveyed in 2021 and was in close proximity to commercial berry fields which may have contained unusually high numbers of native stink bug hosts; thus, high numbers of *Trissolcus* wasps. Excluding this site allowed for improved rigor of statistical comparisons.

Results

3.1 Trissolcus japonicus Detections

In 2019, *T. japonicus* was detected in two of five counties surveyed (24 total sites; Salt Lake and Weber) throughout the sampling period. Seasonal detections occurred from 171 $DD_{12°C}$ to 1043 $DD_{12°C}$. In 2020, detections occurred in three of five counties surveyed (31 total sites; Davis, Salt Lake, and Utah) and from 262 to 1149 $DD_{12°C}$. Detections in 2021 were present in all six counties surveyed (36 total sites; Box Elder, Cache, Davis, Salt Lake, Utah, and Weber) and occurred throughout the entire sampling period (210 to 1367 $DD_{12°C}$). By the end of September 2021, *T. japonicus* was detected 85 km both north and south of the original 2019 detection site in Salt Lake City (Fig. II-1). In all years, detections began increasing around 600 $DD_{12°C}$. Detection peaks occurred in 2019 and 2020 from 700 to 1,000 $DD_{12°C}$

and in 2021 from 1,000 to 1,200 $DD_{12°C}$ (Fig. II-2). Mean *T. japonicus* captures increased each year with 1.61 (±0.58), 2.23 (±1.34), and 3.51 (±0.84) per YSC in 2019, 2020, and 2021, respectively.

3.2 Landscape Effects on Trissolcus japonicus Abundance

In the first two years of surveys, *T. japonicus* only occurred at sites with highly urban surroundings (Fig. II-3A). In 2021, 8% of detections were in low urban sites, 13% in medium urban sites, and 79% of captures occurred in high urban sites. Urbanness was a significant effect each year (2019: $\chi2 = 7.65$, df = 2, $p = 0.022$; 2020: $\chi2 = 7.38$, df = 2, $p = 0.025$; 2021: $\chi2 = 46.0$, df = 2, $p < 0.001$). Pairwise comparisons were not significant in 2019 and 2020. In 2021, *T. japonicus* was more abundant at high urban sites than low urban sites ($p < 0.001$). Across years there were no significant differences in *T. japonicus* abundance in low urbanness sites ($\chi2 = 3.41$, df = 2, $p = 0.182$). However, in medium and high sites the effect was significant (medium: $\chi2 = 12.1$, df = 2, $p = 0.002$; high: $\chi2 = 40.2$, df = 2, $p < 0.001$) and there were higher captures in 2021 than in 2019 (medium: $p = 0.023$; high: $p < 0.001$), and in 2021 than 2020 (medium: $p = 0.006$; high: $p < 0.001$) (Fig. II-3A).

Groundcover type significantly affected *T. japonicus* abundance in the 24 orchard sites in 2021 ($\chi2 = 6.96$, df = 2, $p = 0.031$), and there were significantly more captures in bare ground orchards than orchards with turfgrass cover ($p = 0.029$). Other pairwise comparisons were not significant. A total of 64 *T. japonicus* were captured; 31 (48%) in bare ground orchards, 24 (38%) in floral, and 9 (14%) in turfgrass (Table II-4). *Trissolcus japonicus* experienced a similar abundance peak at 1,000-1,300 $DD_{12°C}$ across all groundcover types (Fig. II-4B); however, peak season analysis did not demonstrate any significant differences in abundance across groundcover types ($\chi2 = 3.03$, df = 2, $p = 0.22$).

3.3 Native Trissolcus spp. Detections

Of the native *Trissolcus* spp. detected, *T. euschisti* was by far the most abundant species (70% of all *Trissolcus* specimens recovered), followed by *T. utahensis* (Ashmead) (9%), *T. hullensis* (Harrington) (4%), *T. ruidus* (Johnson) (<.1%), *T. strabus* (Johnson) (<.1%), and *T. parma* (Johnson) (<0.1%) (Table II-5). The exotic *T. japonicus* made up only 3-7% of *Trissolcus* spp. detected in northern Utah each year. An average of 13% of *Trissolcus* captures were unidentifiable beyond genus due to damaged specimens.

3.4 Landscape Effects on Native Trissolcus spp. Abundance

Urbanness was a significant effect in captures of native *Trissolcus* species in 2019 ($\chi2 = 8.42$, df = 2, $p = 0.015$) but not in 2020 ($\chi2 = 0.567$, df = 2, $p = 0.753$) or 2021 ($\chi2 = 4.68$, df = 2, $p = 0.096$). Only pairwise comparisons between high and low urbanness in 2019 were significant ($p = 0.015$); there were no clear trends across years (Fig. II-3B). Across years, there were no significant differences in *Trissolcus* abundance in low urbanness sites ($\chi2 = 3.91$, df = 2, $p = 0.142$). However, in medium urbanness sites the effect was significant ($\chi2 = 14.6$, df = 2, $p < 0.001$) with higher captures in 2021 than 2020 ($p < 0.001$). In high urbanness sites, there was also a significant effect of year ($\chi2 = 31.3$, df = 2, $p < 0.001$) with lower captures in 2020 than in either 2019 ($p < 0.001$) or 2021 ($p = 0.002$) (Fig. II-3B).

In 2021, orchard groundcover type did not influence captures of native *Trissolcus* spp. combined throughout the season ($\chi 2 = 2.07$, df = 2, $p = 0.356$); however, response of native *Trissolcus* did diverge after 900 $DD_{12°C}$. Significant effects occurred during peak abundance from 900 $DD_{12°C}$ through the end of sampling at 1400 $DD_{12°C}$ ($\chi 2 = 10.3$, df = 2, $p = 0.006$). A total of 1,688 *Trissolcus* were captured in the 24 orchard sites: 394 (23%) in bare ground, 386 (23%) in turfgrass, and 908 (54%) in floral (Table II-4). Pairwise comparison demonstrated that peak season native *Trissolcus* spp. abundance was significantly higher in floral than bare orchards ($p = 0.007$) and higher with borderline significance in floral than turfgrass orchards ($p = 0.0518$). *Trissolcus* spp. abundance was similar between bare and turfgrass groundcovers and showed no differences in pairwise comparisons. *Trissolcus* spp. proportions were similar across mean biweekly captures for each groundcover type (Fig. II-5).

3.5 Halyomorpha halys Presence and Effects

Mean captures of *H. halys* were low: 0.72 (±0.15), 0.23 (±0.08), and 0.06 (±0.03) adults per biweekly trapping period for bare, turfgrass, and floral, respectively (Table II-4A). *Halyomorpha halys* demonstrated similar patterns of peak abundance to *T. japonicus* (Fig. II-4A and 4B). Mean *T. japonicus* captures in commercial orchards where *H. halys* was present were significantly higher than in orchards without *H. halys* ($\chi 2 = 11.5$, df = 1, $p < 0.001$). In contrast to *T. japonicus*, peak total *Trissolcus* spp. captures were misaligned with *H. halys* detections (Fig. II-4A and 4C), and *H. halys* presence did not influence native *Trissolcus* captures ($\chi 2 = 0.779$, df = 1, $p = 0.377$).

Discussion

Despite the unique geographic challenges of severe climate and high elevation (> 1200 m), *Trissolcus japonicus* has successfully established in northern Utah since its initial detection in 2019 (Holthouse et al. 2020, Richardson et al. 2023a). Northern Utah consists of dry, semi-arid, and desert climates with average low temperatures below the estimated minimum threshold for *T. japonicus* development (12.2° C; Qiu et al. 2007) for up to eight months of the year (Utah Climate Center 2022). As adventive *T. japonicus* populations continue to persist in this harsh climate, it is crucial to understand its phenology in order to support conservation efforts in the Intermountain West.

The peak season of *T. japonicus* detections observed in this study falls in the months of July and August and is similar to the results Quinn et al. (2021) observed in the eastern U.S. In 2021, the peak season of *T. japonicus* was later than in previous years, possibly due to extreme drought conditions in Utah. The 18 months from January 2020 to June 2021 were the driest 18-month period on record for northern Utah (NCEI 2022). Some studies have shown that precipitation may play a greater role than temperature in some insect taxa occurrence in North America (Gutiérrez Illán et al. 2020), including the occurrence of *T. japonicus*' primary host *H. halys* (Illán et al. 2022). Future research on climatic variables other than degree days will help further elucidate the potential range and seasonality of the exotic *T. japonicus* in the Intermountain West. Regardless, the capacity to survive and expand its distribution in areas previously considered marginal or unsuitable in geographic models (Avila and Charles 2018) has implications for range expansion of the exotic species in North America.

Halyomorpha halys has demonstrated a notable ability to disperse and thrive outside of predicted ranges (Kriticos et al. 2017, Illán et al. 2022); it follows, therefore, that *T. japonicus* may demonstrate similar capabilities. Recent analysis of *H. halys* populations found that proximity to urban areas was one of the most important factors mediating *H. halys* occurrence and likely reflects human-assisted transport, the use of human structures for overwintering sites, and increased ornamental plant diversity (Illán et al. 2022). Our analysis demonstrates that *T. japonicus* presence is also highly affected by proximity to urban areas; this may be due to its direct reliance on its host and/or its sustainment from urban area resources.

This study focused on the resources provided by the habitat in a 1 km buffer around each site, and groundcover composition in 2021 surveys of commercial orchard sites. The significant influence of urban habitat in contrast to the nonsignificant factor of groundcover type during peak season may be evidence that *T. japonicus* populations are utilizing resources from a greater dispersion area than previously hypothesized. Further research utilizing increased buffer sizes around sites may demonstrate an even greater extent of the wasp's mobility to access floral and other resources. In contrast, this may indicate that urban ornamental plants provide resources more appropriate to the exotic *T. japonicus* as compared to those provided by strip-cropped flowering plants, weeds, or wildflowers naturally occurring in orchard settings.

Overall, orchards with bare soil had comparable captures of *T. japonicus* to floral sites, while turfgrass sites had few *T. japonicus*. The interval between cultivation events at bare soil sites may have given rise to forbs that were beneficial to parasitoids. In addition, frequent disruptions of turfgrass from mowing and other management practices may have been a detriment to *T. japonicus* populations (Horton et al. 2003). Though insecticide applications were assumed to be similar among orchards and groundcover types, application pattern variation may have contributed to biased results as *T. japonicus* is highly sensitive to certain insecticides and is unlikely to survive in settings with broad-spectrum insecticide applications (Lowenstein, Andrews, Mugica, et al. 2019).

A large underlying factor in the presence and abundance of *T. japonicus* is the presence and preferences of its host; the benefits floral understory provide are irrelevant without the insect host to support parasitoid populations. In 2021, we attempted to measure the effect of host presence on parasitoid abundance alongside groundcover by trapping for *H. halys*; however, the abundance of *H. halys* was low and these data were condensed to presence-absence format. The presence of *H. halys* adults was a significant factor for *T. japonicus* abundance, and the demonstrated alignment of seasonality between the host and its natural parasitoid provides strong support for the continued reliance of *T. japonicus* on its natural host rather than pentatomids native to North America.

While we did not measure the effect of crop type on *T. japonicus* abundance, of the orchard crops surveyed in this study (apple, peach, and tart cherry), peach is known to be a host of particular significance in supporting *H. halys* nymphal development and survivorship (Acebes-Doria et al. 2016). In this study, bare groundcover was more common in peach than apple or tart cherry orchards; thus, this association may have had a significant effect on *H. halys* abundance. Regardless of the cause, on average, sites with bare groundcover had higher abundance of *H. halys* which could have significantly skewed the comparative proportion of *T. japonicus* at those sites and biased the apparent effect of bare groundcover. Had there been equal abundance of *H. halys* between all groundcover types, the benefits of floral resources for *T. japonicus* may have been more distinct.

Trissolcus japonicus presence was significantly affected by groundcover over the course of the season, but captures were not significantly different among groundcover types during the peak season of abundance; thus, our prediction of increases due to floral resources was not supported. In addition to possible host bias, this may be due to overall low populations of *T. japonicus* in Utah as it is still in the establishment phase (Holthouse et al 2020). Research in Frederick County, VA demonstrated relatively few *T. japonicus* captures in the first few years of surveys after its initial detection in 2015 followed by subsequent increases in relative abundance in following years (Dyer et al. 2022). Additionally, the suboptimal climatic conditions of the Intermountain West may keep *T. japonicus* at relatively low densities as compared to locations with more suitable climate and availability of its host, *H. halys.* Surveys in this study likely represent *T. japonicus* still in its early establishment phase, and further investigation of this exotic parasitoid outside of its native range may yield more accurate assessments of its response to varying groundcovers.

Native *Trissolcus* species made up the majority of *Trissolcus* detected in agricultural and urban site surveys and provided a larger sample size to detect true differences due to groundcover. Native species increased in response to floral resources supporting our original hypothesis of parasitoid preference for floral groundcover, though this was only apparent during the peak season of wasp abundance, late in the growing season (900 to 1400 $DD_{12°C}$). Other studies have demonstrated the importance of floral resources for *Trissolcus,* particularly on fecundity (Hajirajabi et al. 2016, Foti et al. 2017), and foraging may be of increased priority to parasitoids as opportunities to reproduce increase alongside stink bug host abundance.

The results from this study continue to provide essential information on the presence and abundance of *Trissolcus* parasitoids native to northern Utah. *Trissolcus euschisti* was the most abundant *Trissolcus* spp. in northern Utah urban and orchard sites; over two-thirds of *Trissolcus* spp. detections on YSC and comparable to other YSC surveys in Utah (Holthouse et al. 2021b, Richardson et al. 2023a). While *T. euschisti* has demonstrated the ability to attack and successfully parasitize *H. halys*, rates of wasp emergence have been low and not shown sufficient evidence of effective *H. halys* suppression in Utah or elsewhere (Cornelius et al. 2016, Dieckhoff et al. 2017, Schumm et al. 2019, Costi et al. 2020, Holthouse et al. 2020, Konopka et al. 2020, Richardson et al. 2023a). In addition, our results suggest a seasonal misalignment of native *Trissolcus* abundance, the majority of which was *T. euschisti*, with that of *H. halys*. Conversely, *T. japonicus* demonstrated similar seasonality to its natural host in our study and has already shown the ability to suppress *H. halys* populations despite their low abundances (Holthouse et al. 2020).

The data presented have significant implications for *T. japonicus* as a biological control agent of *H. halys* in the Intermountain West and other similar regions. We present evidence of the importance of urban habitat to the presence and establishment of *T. japonicus* and suggest that the parasitoid is taking advantage of resources outside of resident orchards. In addition, the seasonality implications include improved timing precision for mass releases of wasps with optimal ability for successful establishment, avoidance of harmful pesticides, and for provision of beneficial floral resources. This study supports strategies for further research on an effective biological control agent of *H. halys* and advances our understanding of the establishment of *T. japonicus* and native *Trissolcus* spp. in northern Utah.

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Tables

Table II-1. Sites surveyed in 2019: county location, urbanness measure (proportion of surrounding 1 km habitat with developed land), latitude and longitude.

Site ID	County	Urbanness	Latitude	Longitude
BE1	Box Elder	0.029	41.73761	-112.28079
BE2	Box Elder	0.090	41.72079	-112.14402
DA1	Davis	0.327	41.06271	-112.01766
DA3	Davis	0.585	41.03606	-111.90633
DA4	Davis	0.925	41.02282	-111.93749
DA6	Davis	0.963	41.02065	-111.93025
DA9	Davis	0.629	40.97439	-111.90437
DA10	Davis	0.938	40.90257	-111.87136
SL1	Salt Lake	0.925	40.78039	-111.89626
SL2	Salt Lake	0.921	40.78004	-111.89545
SL3	Salt Lake	0.998	40.77311	-111.86849
SL4	Salt Lake	0.921	40.77078	-111.85519
SL5	Salt Lake	1.000	40.76951	-111.86596
SL6	Salt Lake	0.888	40.76735	-111.85298
SL7	Salt Lake	0.823	40.76367	-111.85029
SL8	Salt Lake	0.960	40.75231	-111.87353
SL9	Salt Lake	0.968	40.74897	-111.85457
SL11	Salt Lake	0.962	40.63577	-111.86400
UT1	Utah	0.989	40.34708	-111.71357
UT8	Utah	0.045	40.04023	-111.86118
UT13	Utah	0.152	39.99747	-111.82487
WE1	Weber	0.518	41.32905	-112.00984
WE2	Weber	0.904	41.31532	-111.95860
WE3	Weber	0.914	41.18553	-112.04079

Table II-2. Sites surveyed in 2020: county location, urbanness measure (proportion of surrounding 1 km habitat with developed land), latitude and longitude.

Site ID	County	Urbanness	Latitude	Longitude
BE1	Box Elder	0.029	41.73761	-112.28079
CA3	Cache	0.126	41.58166	-111.84779
DA1	Davis	0.327	41.06271	-112.01766
DA2	Davis	0.910	41.06028	-111.97000
DA3	Davis	0.585	41.03606	-111.90633
DA4	Davis	0.926	41.02282	-111.93749
DA5	Davis	0.961	41.02142	-111.93200
DA6	Davis	0.970	41.02065	-111.93025
DA7	Davis	0.939	41.02036	-111.93600
DA8	Davis	0.499	40.99549	-111.88500
DA9	Davis	0.628	40.97439	-111.90437
DA10	Davis	0.938	40.90257	-111.87136
SL1	Salt Lake	0.926	40.78039	-111.89626
SL2	Salt Lake	0.922	40.78004	-111.89545
SL3	Salt Lake	0.998	40.77311	-111.86849
SL4	Salt Lake	0.921	40.77078	-111.85519
SL5	Salt Lake	1.000	40.76951	-111.86596
SL5	Salt Lake	1.000	40.76951	-111.86600
SL6	Salt Lake	0.889	40.76735	-111.85298
SL7	Salt Lake	0.822	40.76367	-111.85029
SL8	Salt Lake	0.960	40.75231	-111.87353
SL9	Salt Lake	0.968	40.74897	-111.85457
SL10	Salt Lake	0.998	40.69306	-111.84800
SL11	Salt Lake	0.962	40.63577	-111.86400
UT4	Utah	1.000	40.31310	-111.71038
UT5	Utah	0.976	40.26861	-111.65600
UT6	Utah	1.000	40.22972	-111.66389
UT8	Utah	0.044	40.04023	-111.85337
UT13	Utah	0.156	39.99747	-111.75843
WE1	Weber	0.518	41.32905	-112.00984
WE2	Weber	0.904	41.31532	-111.95860
WE3	Weber	0.914	41.18553	-112.04079

Table II-3. Sites surveyed in 2021 by groundcover designation (bare, floral, turf, and unspecified). Twelve sites surveyed in 2021 were not included in the groundcover study and were not monitored for groundcover type (unspecified). County location, urbanness measure (proportion of surrounding 1 km habitat with developed land), latitude and longitude are provided.

Groundcover	Site ID	County	Urbanness	Latitude	Longitude
Bare	BE4	Box Elder	0.180	41.44748	-112.03740
	BE6	Box Elder	0.180	41.42223	-112.03153
	BE7*	Box Elder	0.399	41.41284	-112.03087
	DA3	Davis	0.605	41.03606	-111.90632
	UT3	Utah	0.983	40.33722	-111.71865
	UT4	Utah	0.999	40.31310	-111.71038
	UT7	Utah	0.050	40.04556	-111.86118
	WE2	Weber	0.920	41.31532	-111.95857
Floral	BE5	Box Elder	0.185	41.42383	-112.03349
	CA1	Cache	0.192	41.81379	-111.80955
	UT8	Utah	0.054	40.04023	-111.85337
	UT9	Utah	0.048	40.02905	-111.83839
	UT12	Utah	0.122	40.00388	-111.82487
	UT14	Utah	0.135	39.99692	-111.83255
	UT16	Utah	0.104	39.98245	-111.82606
	WE3	Weber	0.941	41.18553	-112.04066
Turf	BE3	Box Elder	0.004	41.69340	-112.00984
	CA2	Cache	0.616	41.72535	-111.80753
	CA3	Cache	0.149	41.58166	-111.84779
	DA5	Davis	0.961	41.02142	-111.93194
	UT10	Utah	0.082	40.02306	-111.70732
	UT11	Utah	0.105	40.01267	-111.77738
	UT15	Utah	0.141	39.99258	-111.76879
	WE1	Weber	0.542	41.32905	-112.00984
Unspecified	CA4	Cache	0.147	41.57325	-111.81705
	DA11	Davis	0.928	40.74598	-111.85400
	SL1	Salt Lake	0.931	40.78039	-111.89626
	SL4	Salt Lake	0.982	40.77078	-111.85519
	SL7	Salt Lake	0.976	40.76367	-111.85029
	SL8	Salt Lake	0.969	40.75231	-111.87353
	SL9	Salt Lake	0.974	40.74897	-111.85457
	DA11	Salt Lake	0.990	40.74598	-111.85400
	SL10	Salt Lake	1.000	40.69306	-111.84800
	UT2	Utah	0.997	40.34708	-111.71357
	UT13	Utah	0.001	39.99747	-111.75800
	UT17	Utah	0.275	39.98220	-111.80317

*Site was dropped from all statistical analysis.

Table II-4. The number of *H. halys* adults and *Trissolcus* spp. captured in orchards with bare, turfgrass, and floral understories. Proportional abundance of species captured in each groundcover type is provided in parentheses. Data were collected 19 May through 5 October 2021 at 24 commercial orchard sites in northern Utah.

		Trissolcus						
Groundcover	***H. halys* adults**	***japonicus***	***euschisti***	***utahensis***	***hullensis***	***ruidus***	**spp.***	**Total**
Bare	63 (0.72)	31 (0.48)	294 (0.22)	18 (0.44)	10 (0.19)	1 (0.50)	40 (0.29)	394 (0.23)
Turfgrass	20 (0.23)	9 (0.14)	301 (0.23)	22 (0.12)	24 (0.46)	1 (0.50)	29 (0.21)	386 (0.23)
Floral	5 (0.06)	24 (0.38)	720 (0.55)	78 (0.44)	18 (0.35)	0 (0.00)	68 (0.50)	908 (0.54)
Total	88	64	1315	118	52	2	137	1688

**Trissolcus* wasps that were unidentifiable below the genus level due to damage are presented as *Trissolcus* spp.

Table II-5. The number of *Trissolcus* spp. identified on yellow sticky cards in northern Utah, 2019-2021. Proportional abundance of each species by year is provided in parentheses.

		Trissolcus								
Year	**Sites**	***japonicus***	***euschisti***	***utahensis***	***strabus***	***hullensis***	***ruidus***	***parma***	**spp.***	**Total**
2019	24	37 (0.03)	690 (0.61)	117 (0.10)	0 (0.00)	47 (0.04)	0 (0.00)	0 (0.00)	247 (0.22)	1,138
2020	31	69 (0.07)	691 (0.69)	98 (0.10)	15 (0.02)	51 (0.05)	0 (0.00)	0 (0.00)	76 (0.08)	1,000
2021	36	123 (0.04)	2,462 (0.79)	206 (0.07)	4 (0.00)	50 (0.02)	5 (0.00)	1 (0.00)	261 (0.08)	3,112

**Trissolcus* wasps that were unidentifiable below the genus level due to damage are presented as *Trissolcus* spp.

Figures

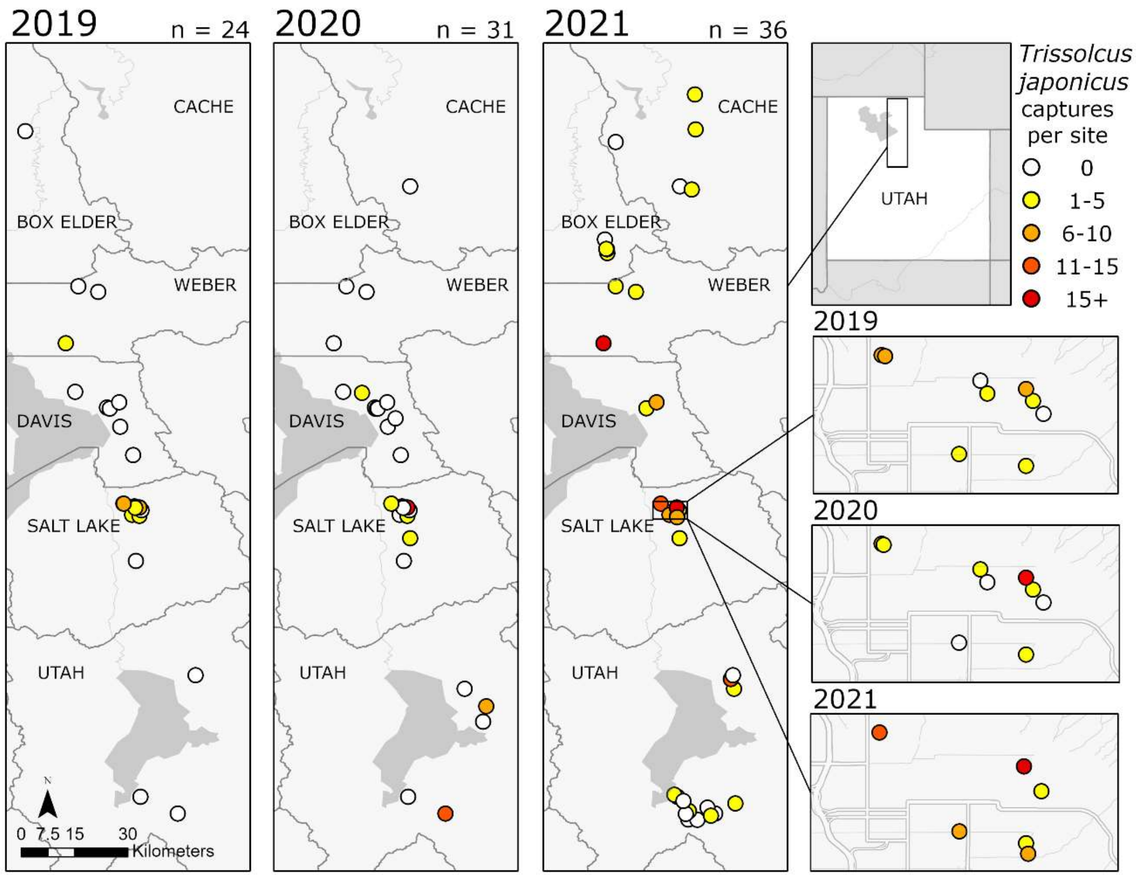

Figure II-1. *Trissolcus japonicus* captures from late May through early October in northern Utah 2019-2021. Number of sites surveyed per year is shown as *n* at the top of each map. The map insets by year depict *T. japonicus* captures at and near the original detection site in Salt Lake City.

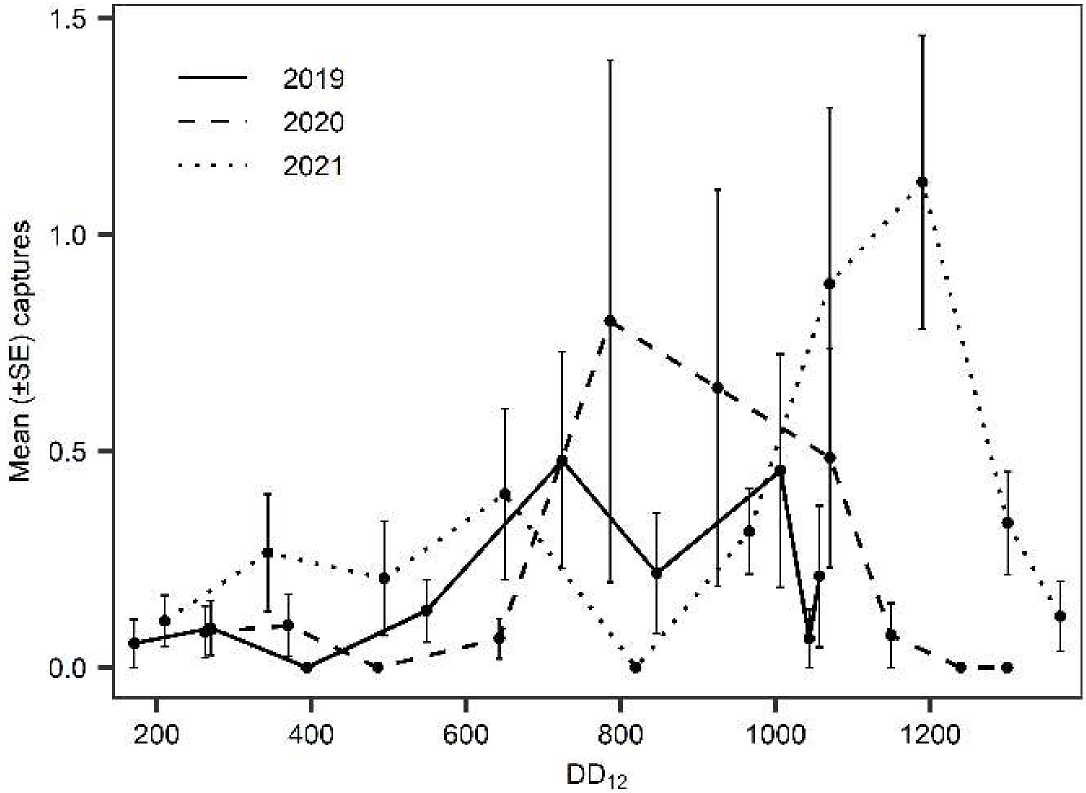

Figure II-2. Mean captures of *Trissolcus japonicus* on yellow sticky cards from late May through early October 2019-2021. Results are plotted by average degree days accumulated (DD12°C) at the end date of each 14 d (+1 d) deployment period.

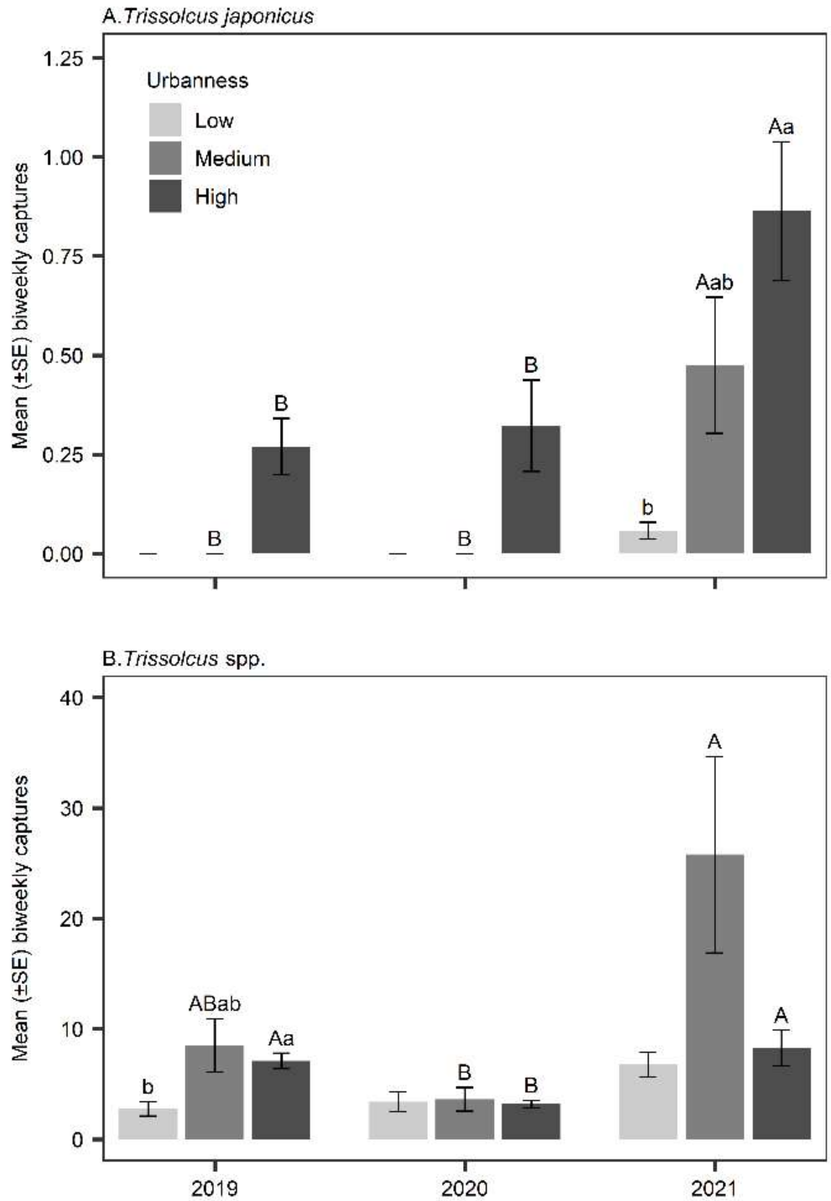

Figure II-3. Mean biweekly (per yellow sticky card) captures of *Trissolcus japonicus* (A) and native *Trissolcus* spp. (B) in sites with low, medium, and high proportions of urban land in the surrounding 1 km boundary of survey sites. Lowercase letters represent significant differences among urbanness categories within a year. Uppercase letters represent significant differences among years within urbanness categories (Kruskal-Wallis test and Bonferroni corrected Dunn's test, $p > .05$).

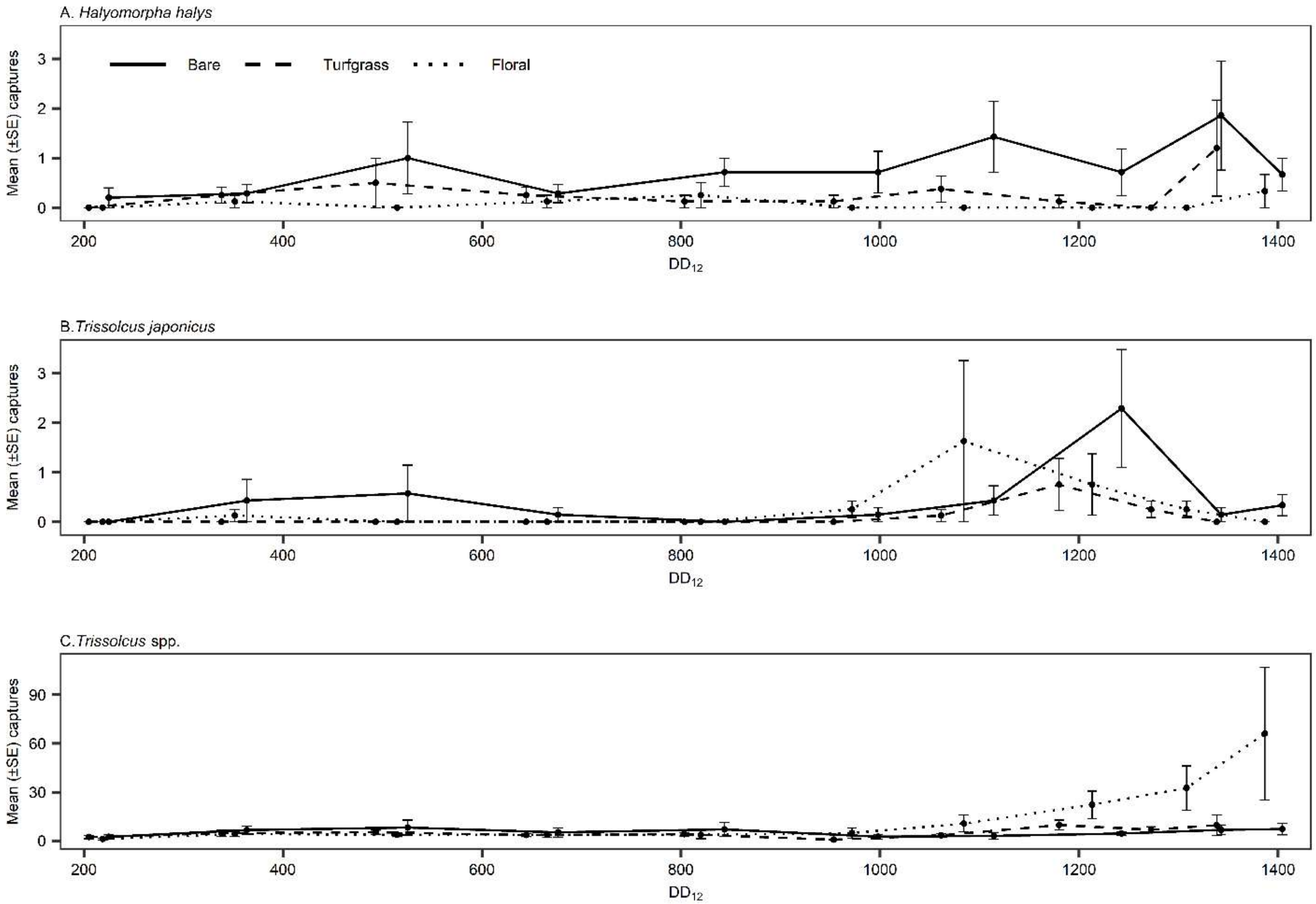

Figure II-4. Mean captures of *Halyomorpha halys* (A) per baited clear dual panel sticky trap, and *Trissolcus japonicus* (B) and native *Trissolcus* spp. (C) per yellow sticky card by average accumulated degree days of each deployment end date. Counts were averaged by groundcover designations of bare, turfgrass, and floral with eight sites of each designation from 19 May to 5 October, 2021.

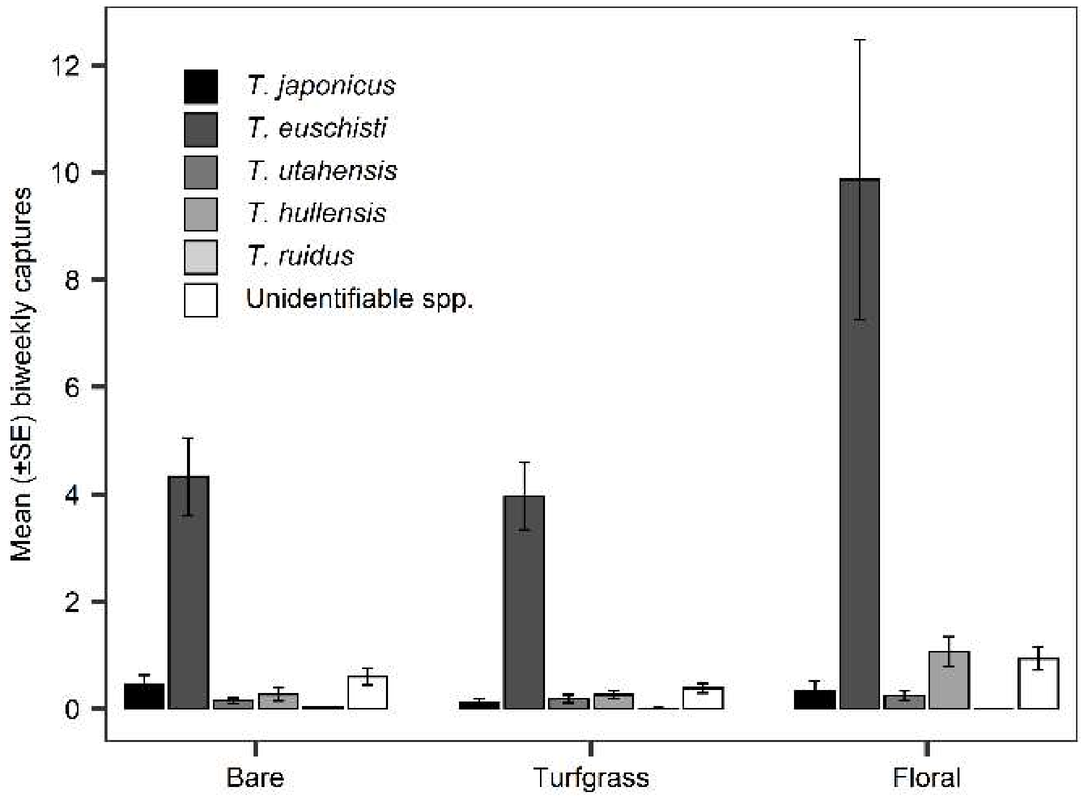

Figure II-5. Mean captures of *Trissolcus* species per biweekly yellow sticky card deployment from May-September 2021.Cards were deployed at eight sites of each groundcover designation (bare, turfgrass, and floral). "Unidentifiable spp." represents wasps that were unidentifiable beyond genus due to physical damage during capture.

CHAPTER III

EFFICACY OF KAIROMONE LURES TO ATTRACT PARASITOIDS OF Halyomorpha halys[1, 2]

Simple Summary: The brown marmorated stink bug, *Halyomorpha halys*, is an invasive pest of agricultural crops, ornamentals, and human structures. In its native range, populations are suppressed primarily by parasitoid wasps that attack the egg stage. A promising adventive parasitoid, the samurai wasp, *Trissolcus japonicus*, has become established in the U.S., including Utah. According to ecological models, Utah is marginally suitable for the samurai wasp and poses unique challenges to its establishment from extreme climates and high elevation. Biological control enhancement efforts, such as deploying stink bug kairomones to attract parasitoids, may lead to the enhanced suppression of the brown marmorated stink bug. To evaluate the efficacy of this approach, experimental lures loaded with varying blends and release rates of stink bug kairomones were tested in field and mesocosm trials. This study found low parasitism in the field, while mesocosm trials demonstrated the efficacy of a single- and dual-compound blend at the 10 mg load rate for the attraction of the samurai wasp. These results support the validity of using rubber septa as a release device for kairomones of stink bugs and provide a baseline for future work on attracting samurai wasps with lures in a field environment.

Abstract: In its native range, *Halyomorpha halys* (Stål) is suppressed by parasitoids in the genus *Trissolcus* (Hymenoptera: Scelionidae). *Trissolcus* native to Utah have demonstrated low parasitism of *H. halys*, while adventive *Trissolcus japonicus* (Ashmead) have shown parasitism of up to 20%. Custom rubber septa lures containing stink bug kairomones, n-tridecane (attractant), and (E)-2-decenal (repellent), at 100%, 90%, and 80% levels of attractant (10 mg load rate), were placed adjacent to sentinel *H. halys* egg masses in northern Utah field trials. Egg masses were evaluated for the presence and intensity (proportion of parasitized eggs) of parasitism. Parasitism by *T. japonicus* and *T. euschisti* (Ashmead) was low; however, the 100% lure showed double the parasitism of the control and more than three times that of the 90% and 80%. Two-way choice mesocosm trials in the laboratory evaluated previous lures and a lower load rate of 5 mg—100% attractant treatment. Lures of 10 mg at 100% and 80% were more attractive to *T. japonicus* than the control, while 5 mg at 100% and 10 mg at 90% showed no significant attraction. Our results support a proof-of-concept of rubber septa as release devices for kairomones to attract *T. japonicus* and provide a baseline for future field-based studies.

Keywords: Scelionidae; *Trissolcus*; Pentatomidae; invasive species; parasitoid; kairomone; chemical ecology; biological control

[1]We thank the Insects team and the director of publications for allowing the reprinting of this publication in this thesis.

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

1. Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is an invasive pest originating from East Asia. *H. halys* was first detected in Utah in 2012, with the first injury to tree fruit and vegetable crops reported in 2017 [1]. The rapid spread of *H. halys* can be attributed to its ability to utilize more than 300 different host plants including fruits, vegetables, field crops, and ornamentals [2–4] upon which it can cause economic damage [5]. In addition to causing mild to severe damage to agricultural crops, *H. halys* is an urban nuisance due to its overwintering congregation behavior on and within human structures [6].

In its native range, *H. halys* populations are suppressed primarily by parasitoid wasps that attack the egg stage [7,8]. The wasp genus *Trissolcus* (Hymenoptera: Scelionidae) contains species that attack *H. halys* eggs; however, those native to Utah have demonstrated only modest parasitism rates of *H. halys* to date [9,10]. *Trissolcus japonicus* (Ashmead), or the samurai wasp, has been identified as a key biocontrol agent with parasitism rates of *H. halys* eggs up to 60–90% in Asia [11]. Adventive populations of *T. japonicus* have been detected in the U.S. since 2014 [12,13], with the first detection in Utah in Salt Lake City in June 2019 [9]. Early surveys found *H. halys* egg masses parasitized by *T. japonicus* on *Catalpa speciosa* (Warder) Warder ex Engelm. (Lamiales: Bignoniaceae) trees [9]; thus, northern catalpa has been a focus for *H. halys* and *T. japonicus* surveys in northern Utah [14].

Utah is a unique geographic location and climate for both *H. halys* and *T. japonicus* with high elevation (>1200 m in northern Utah), substantial snowfall in winter, and hot, arid summers. For up to eight months of the year, average low temperatures fall below the minimum threshold for the development of *T. japonicus* (12.2 °C) [15,16], and current climatic modeling suggests only marginal suitability in the state [17]. A contributing factor may be insect behavioral aspects unaccounted for in laboratory studies and geographic models [17]. Early research in northern Utah indicates *H. halys* egg parasitism rates have increased in the two summers since *T. japonicus* was discovered, thus demonstrating the potential to provide biological control of *H. halys* [9]. Promoting and conserving Utah's adventive populations of *T. japonicus* may be a viable option for the sustainable management of *H. halys*.

Though lab-reared sentinel *H. halys* egg masses are a common way to assess wasp parasitism rates, many studies have shown that they underestimate parasitism rates and attract fewer wasps than wild egg masses [9,18,19]. It is thought that *T. japonicus* utilizes volatile cues associated with *H. halys* oviposition and feeding during host location. One study found that the bioactive volatile n-tridecane significantly attracted *T. japonicus* and reduced its host search time, while (E)-2-decenal acted as a repellent [20]. Subsequent research by Malek et al. [21] found that combining these kairomone compounds at a ratio of 4:1 n-tridecane to (E)-2-decenal, or 80% attractant, performed better than n-tridecane alone in a Y-tube olfactometer experiment. A more recent study used a ratio of 9:1 (90% attractant) during field trials, but with little success, likely due to inadequate release rates from filter paper sources [22]. The kairomone compounds have proven attractive in small-scale experiments, but more research is needed to understand how they perform in larger settings.

Traditionally, rubber septa are a standard chemical release device used in pest management (e.g., pheromone lures) [23–25]. Septa can be loaded with kairomone compounds to attract beneficial parasitoids and enhance target pest parasitism [26,27]. Our objective was to determine the viability of synthetic kairomone-loaded septa lures to increase *T. japonicus* parasitism rates of *H. halys* egg masses in field and laboratory mesocosm settings. This research will contribute to the identification of effective techniques to deploy stink bug kairomones to attract parasitoids and may contribute to increased accuracy in estimates of *H. halys* parasitism rates and enhance early detection of *T. japonicus*. Future research could lead to the creation of a highly attractive lure for *T. japonicus* with the potential for use in field sites to increase parasitism, thereby reducing *H. halys* populations and subsequent crop and nuisance damage.

2. Materials and Methods

2.1. Field Trials

To assess the attractiveness of kairomone chemicals in a field setting, custom gray rubber septa lures loaded with 10 mg of test compounds were developed by Trécé, Inc., (Adair, OK, USA). This field study included four lure treatments with varying ratios of n-tridecane to (E)-2-decenal: 100% n-tridecane, 90% n-tridecane, 80% n-tridecane, and hexane(control). Lab-reared *H. halys* sentinel egg masses were deployed adjacent to kairomone lures as hosts for parasitoid wasps.

Trials (n = 6) were conducted from 24 June to 27 August 2021 in a strip of residential Catalpa speciosa trees in Salt Lake City, UT (40.772480, −111.854975). Catalpa trees were selected due to consistent and relatively high populations of *H. halys* observed on leaves and pods. Treatments were replicated in four trees (three in the final deployment due to a lack of egg masses) with a blank buffer tree between each treatment tree. Each replicate tree (3 m wide canopy) contained four *H. halys* egg masses and one of each lure treatment with one mass and lure placed approximately 2 m laterally from the trunk of the tree at each cardinal direction. Egg masses of *H. halys* were attached to small rectangles of white cardstock (2 cm by 3 cm) and clipped with a lure to the underside of tree leaves (Figure III-1). Treatments were placed at approx. a 2 m height above the ground with cardinal direction of treatments randomized for each tree in each deployment.

Egg masses (n = 92) were ∼48 h old and produced from an *H. halys* laboratory colony at the Oregon Department of Agriculture (Salem, OR, USA). Sentinel egg masses were deployed with kairomone treatment lures in the field for approximately 96 h and returned to the laboratory for evaluation. Any wasps found guarding egg masses were collected into a 9-dram plastic vial (Thornton Plastics, Salt Lake City, UT, USA) using a WHO (World Health Organization) in-line tube aspirator (Bioquip, Compton, CA, USA) for later identification. After eggs were incubated at 25–27 °C for 14 days in the laboratory, they were evaluated for parasitism incidence and intensity (proportion of parasitized eggs per mass), and emerged wasps were identified to species using the key to Nearctic *Trissolcus* [28]. Egg masses were observed again 14 days later (4 weeks after collection) to identify late-emerging wasps or eggs with partially developed wasps or stink bugs. Individual egg fate was recorded as emerged or undeveloped parasitoid, hatched or unhatched *H. halys* nymph, predated, sunken, empty, or missing.

2.2. Mesocosm Trials

In order to mitigate multiple uncontrollable factors in a field setting, a second experiment was conducted in a mesocosm-scale lab-based experimental system in 2022. In a 0.5 m height × 0.5 m depth × 0.8 m length plexiglass observation cage with a mesh lid, a clear panel trap (Alpha Scents, Inc., Canby, OR, USA, 30.5 cm × 30.5 cm) and lure attached via a clothespin to the upper portion of the card were hung at either end of the cage (1 m apart). Four to five 1–20 day post-emergence (according to colony availability), honey-fed, female *T. japonicus* from the Utah State University *T. japonicus* colony (originating from females collected in 2019 from Salt Lake City, UT, USA) were introduced to the center, bottom of the cage via a small access hole (stoppered by a cork) and allowed up to 30 min to select between the control and treatment lure by landing on the adjacent clear panel sticky trap (2-way choice). Treatments consisted of four combinations of chemical attractant to repellent ratios and load rates: 5 mg–100% n-tridecane, 10 mg–100% n-tridecane, 10 mg–90% n-tridecane, and 10 mg–80% n-tridecane.

Each treatment was tested against a hexane control lure and trials were replicated until each treatment had a minimum of 32 individuals make a choice. Wasps that did not make a choice within the 30 min experimental period were not included in the analyses. The observation cage was cleaned with laboratory detergent and allowed to air dry between lure types and treatment vs. control lures were rotated every other trial to account for side bias. Trials were conducted in a temperature-controlled rearing room at 21–27 °C and 30–50% RH.

2.3. Statistical Analysis

To analyze field trial results, data were pooled across sample dates and each egg fate category was analyzed using the Kruskal-Wallis test to compare differences across treatment lure types. In mesocosm trials, the null hypothesis that *T. japonicus* showed no preference between the control and treatment lure (an overall choice of 50:50) was analyzed with a Chi-square goodness of fit test. All statistical comparisons were run using R software [29] and were considered significant at $p < 0.05$.

3. Results

3.1. Field Trials

Of 92 total egg masses containing 2472 eggs deployed in the field, only 13 masses had evidence of parasitism (14.1%; guarding female present or eclosed parasitoids) of which 6 masses supported successful emergence of adult parasitoids (6.5%). The lure treatments in order of highest proportion of eggs with successfully emerged parasitoids were 100% n-tridecane (10.6%), hexane control (5.2%), 80% n-tridecane (2.9%), and 90% n-tridecane (0.0%) (Figure III-2). Though the 100% lure showed double the parasitism of the control and more than three times that of the 90% and 80%, the analysis of all egg fate categories did not support statistical differences ($p > 0.05$; Table III-1).

T. japonicus attacked 5.4% of deployed egg masses. This included one egg mass in each of the control and 80% attractant treatments and three in the 100% attractant treatment. Of the 129 *H. halys* eggs *T. japonicus* parasitized, there was a high rate of successful emergence (78.3%). *T. euschisti* attacked 6.5% of egg masses deployed with two egg masses in each of the control, 100%, and 90% attractant treatments and none in the 80% attractant treatment. Successful emergence of *T. euschisti* only occurred in one of the control treatment egg masses and the rate of overall emergence from attacked egg masses (136 eggs) was 1.8%. Two egg masses in the control treatment were parasitized by an unknown *Trissolcus* sp(p) and demonstrated no successful emergence (Table III-2). In one instance, a *T. euschisti* female was found guarding an egg mass which later produced 26 *T. japonicus* individuals (92.9% emergence rate) and 2 inviable eggs.

Undeveloped parasitoid rates ranged from 1.6% to 5.9% across treatments, were highest in the 80% attractant treatment, and lowest in the 100% attractant treatment. The rate of unhatched *H. halys* was also variable across treatments, making up the largest percentage of egg fate for the control treatment (26.5%), and was noticeably lower in the 100% attractant treatment compared to others. There was less than a 2% difference in the predation between lure treatments. Sunken rates were relatively high (17.7–26.0%), and the combination of missing and empty on average across lure treatments made up <10% of egg fate. Rates of hatched *H. halys* nymphs were similar across lure treatments containing stink bug kairomones (36.4–41.0%) but were unexpectedly low for the control lure making up approximately half of that seen in non-control lures.

3.2. Mesocosm Trials

In the mesocosm system, *T. japonicus* females showed a significant preference for the kairomone blend over the control for two of the four treatments tested (Figure III-3). The 10 mg—80% n-tridecane showed the most significant response (p = 0.003) with 73% of individuals choosing the kairomone lure. There was also a significant difference between the control and 10 mg—100% n-tridecane treatment lure (p = 0.04) with 60% of wasps choosing the kairomone-treated side. For the 10 mg—90% n-tridecane treatment, 55% of wasps chose the kairomone lure; however, there was no significant deviation from the expected response (p = 0.55). The choice between the low load rate treatment of 5 mg—100% n-tridecane and the control also showed no significance (p = 1); an even proportion of wasps chose each side. The proportion of no-choice wasps per treatment varied from 20% to 32% of wasps tested and was not associated with treatments.

4. Discussion

This study is the first to assess and provide a proof-of-concept for kairomone-infused rubber septa lures to attract *T. japonicus* and other potential *H. halys* parasitoids in field and mesocosm settings. Though the kairomone chemicals tested herein have been previously evaluated in a small-scale lab setting (Y-tube olfactometer) [20], implementation in the field may provide different results due to the influence of external factors on the shape, concentration, longevity, and spatial extent of the kairomone odor plume. In addition, the interaction of the lure plume with nearby plant surfaces and mixing with other volatiles may give rise to plume masking or plume amplification, of which little is known in a parasitoid searching context [30].

Our field results contrast those of Malek et al. [21] where the combination of the attractant and repellent was preferred over the attractant alone. In our study, not only did the 100% n-tridecane attractant lure have a numerically (not statistically) higher parasitism rate than the control, the lures containing the previously identified repellent (E)-2-decenal had less parasitism than those without the repellent, including the hexane control. These results may suggest that under field conditions a combination of the attractant and repellent is less effective at increasing parasitism by *Trissolcus* spp., at least with the specific load rate tested and placement in near proximity to the target host egg masses.

The lures used in the field study contained a load rate of 10 mg per lure, high in comparison to standard pheromone lures (1 mg), in the hopes of ensuring the attraction of parasitoids (Trécé, Inc., Adair, OK, USA); however, this relatively high load rate may have been counterproductive to our objective. In studies of pheromone lure load rates, it has been found that attraction often plateaus and can even become repellent to the insect at high release rates [23–25]. In addition, our lures were placed directly adjacent to the *H. halys* egg masses (Figure III-1), which may deter parasitoid attraction as the host female stink bug does not typically remain near the eggs following oviposition.

The effect of lure load rate on parasitoid attraction was explored by examining both a 5 and 10 mg treatment of only the attractant n-tridecane in the mesocosm trials. The results of these trials demonstrate that the higher load rate of 10 mg was a more viable option for attracting *T. japonicus* and did not have a repellent effect. In contrast, the 5 mg treatment demonstrated no difference in attraction as compared with the hexane control lure. Based on these findings, the load rate may not have been detrimentally high in the field trials; however, we did not assess if a load rate greater than 10 mg could increase parasitoid attraction in a field setting.

Given the low number of egg masses tested in field trials and a lack of statistically significant results, the parameters of this field study may have been unsuitable to discern differences in the attractiveness of the different kairomone lure treatments. We observed low parasitism rates across all egg mass deployment periods in this study. In previous surveys, the site selected for the field study had the highest abundance of *T. japonicus* observed in northern Utah with concomitant high parasitism rates of *H. halys* [9]. However, compared to *T. japonicus* populations in its native geographic regions and other adventive populations in the U.S., the abundance of *T. japonicus* in Utah is relatively low [13,31]. In addition, Utah suffered from significant drought over the time frame of this study (summer 2021), with

99.94% of the state in “extreme” or “exceptional” drought categories [15], which may have had a negative effect on host abundance, parasitoid wasp populations, and *H. halys* egg parasitism rates [6].

Other researchers have observed that lab-reared egg masses perform inferiorly to wild egg masses in terms of their attractiveness to parasitoids [9,18,19]. The lures tested here were an initial attempt to solve this issue and increase the accuracy of parasitism rates detected in deployed egg mass surveys. Parasitism was observed in wild *H. halys* egg masses near deployed, unparasitized egg masses during the field study. Without an in-depth analysis of the kairomone plume release from lures, it is unknown if the plumes for each lure treatment may have overlapped within the tree block (lures were separated by approximately 3 m of tree canopy) and potentially interfered with one another. In addition, this may suggest the lure-dispersed kairomones had unknown interactions with the surrounding environment or may have lacked the necessary kairomone load rate and/or ratio necessary to match the high attractiveness of wild egg masses with their natural kairomones intact.

Interestingly, the results of the mesocosm environment did not fully align with the field trial results, suggesting lures containing (E)-2-decenel may be repellent, but were better aligned with those of Malek et al. [21] where the 80% n-tridecane ratio was more attractive than n-tridecane alone. The result of wasp attraction to the 100% and 80% lures and unexpected lack of attraction to the 90% treatment occurred both in the field and in the mesocosm trials. Research has suggested that the variable secretions by different sexes and life stages of *H. halys* may be linked to their specific functions at said life stages and physiological states [21,32,33]. Perhaps the 100% and 80% n-tridecane treatments in this study are more closely associated with the gravid/ovipositing adult female or egg life stages that can be exploited by *T. japonicus*, while the 90% treatment is associated with other life stages. Further investigation is necessary to understand these counterintuitive results.

The mesocosm trials presented the opportunity to test the response of a much larger sample size and demonstrate significant differences between the control and treatments, verifying the validity of these lures. While these trials supported the attractiveness of certain lures in a controlled environment, they also did not include many of the external factors at play in an authentic environment such as plant volatiles and competing parasitoids and predators. In addition, our mesocosm trials did not include the presence of host eggs which may have altered the *T. japonicus* response.

In contrast, the field trials provide essential information about the interaction between hosts and parasitoids in a novel geographic and climatic environment. The results further verify the preliminary research in Utah on the effectiveness of the exotic *T. japonicus* and the common native *T. euschisti*. In this study, as in Holthouse et al. [9], *T. euschisti* demonstrated the ability to parasitize *H. halys* in a similar proportion to the natural parasitoid of *H. halys*, *T. japonicus*. However, *T. euschisti* seems an inviable option for successful biological control due to very low adult wasp emergence and successful stink bug nymph development likely associated with the failure of *T. euschisti* eggs to hatch or early death of larvae within *H. halys* eggs [34]. Additionally, this poses an evolutionary trap for *T. euschisti* and other native *Trissolcus* species that accept *H. halys* eggs as ovipositional sites despite their poor reproductive investment [35]; although, there is evidence that the recent arrival of *T. japonicus* may have implications for the success of native *Trissolcus* on *H. halys* egg masses.

Research has demonstrated that *Trissolcus* spp. are able to parasitize host eggs that have previously been parasitized. In the case of *T. japonicus* and *T. mitsukurri* (Ashmead), each species outperformed the other when it was the first to oviposit, though *T. mitsukurri* was more aggressive in chasing off *T. japonicus* when present concurrently [36]. The similar timing of the competition and outperformance may have been the case in our observation of *T. euschisti* guarding an egg mass (presumable parasitized by *T. japonicus* prior to *T. euschisti* oviposition) that only produced *T. japonicus* offspring. Conversely, research by Konopka et al. [37] demonstrated that parasitism by the exotic *T. japonicus* can provide facultative parasitism opportunities for native *Trissolcus*, such as *T. cultratus* (Mayr), to successfully develop in *H. halys* eggs when they would otherwise fail.

Regardless of their reproductive success, native *Trissolcus* species can reduce the developmental success of *H. halys* embryos providing low levels of control for the pest [38]. The attraction of *T. euschisti* and other native *Trissolcus* species to kairomone lures containing n-tridecane and (E)-2-decenal were not explored in a mesocosm environment in this study. However, the use of these kairomone lures in the field did result in attacks from *T. euschisti* in addition to *T. japonicus*. Consequently, further research into the physiological and behavioral interactions between the exotic *T. japonicus* and North American native *Trissolcus* requires investigation to fully evaluate the potential efficacy of biological control programs against *H. halys*.

While much investigation is needed into the complex system of parasitoids using semiochemicals to locate their host, the mesocosm results presented support the validity of using rubber septa as a release device for the kairomones of stink bugs, and this research provides not only preliminary results but also a baseline for future work with experimental lures for *H. halys* parasitoids in a field environment.

5. Conclusions

As biological control continues to be a preferred approach for managing the invasive *H. halys*, it is important to explore all avenues for attracting and retaining effective parasitoids. Here, we provide support for the validity of infusing rubber septa lures with *H. halys* kairomones to attract *T. japonicus*. This novel strategy has the potential to increase parasitism and, therefore, suppression of *H. halys* in agricultural and urban settings and deserves further investigation.

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Tables

Table III-1. Statistical results from Kruskal-Wallis tests to compare each egg fate category differences across treatment lure types.

Egg Fate	X^2	*df*	*p*
Hatched *H. halys*	2.79	3	0.426
Missing	2.06	3	0.561
Empty	0.98	3	0.806
Sunken	1.21	3	0.751
Predated	0.22	3	0.974
Unhatched *H. halys*	6.62	3	0.085
Undeveloped parasitoid	5.68	3	0.128
T. euschisti emergence	3.00	3	0.392
T. japonicus emergence	4.01	3	0.260

Table III-2. Number of *Halyomorpha halys* egg masses parasitized (and percent of eggs with wasp emergence) in kairomone lure treatments for observed parasitoid species. Lure treatments are labeled based on percentage of n-tridecane attractant to (E)-2-decenal repellent; the control contained only hexane. Ninety-two *H. halys* egg masses were deployed containing 2,472 eggs on *Catalpa speciosa* leaves in Salt Lake City, UT, from 24 June through 27 August 2021.

	Parasitized Egg Masses (% Emergence)			
Treatment	***T. japonicus***	***T. euschisti***	**Unknown**	**Total**
Control	1 (100.0%)	2 (5.5%)	2 (0.0%)	5 (23.0%)
100%	3 (89.0%)*	2 (0.0%)	0 (0.0%)	5 (51.6%)
90%	0 (0.0%)	2 (0.0%)	0 (0.0%)	2 (0.0%)
80%	1 (28.6%)	0 (0.0%)	0 (0.0%)	1 (28.6%)
Total	5 (78.3%)	6 (1.8%)	2 (0.0%)	13 (30.2%)

*A *T. euschisti* female was found guarding an egg mass that resulted in 0% *T. euschisti* and 92.9% *T. japonicus* emergence. It was therefore only counted in the *T. japonicus* column.

Figures

Figure III-1. Deployed laboratory reared *Halyomorpha halys* egg mass with adjacent kairomone treatment rubber septa lure on the underside of a northern catalpa leaf in Salt Lake City, UT, 24 June to 27 August 2021.

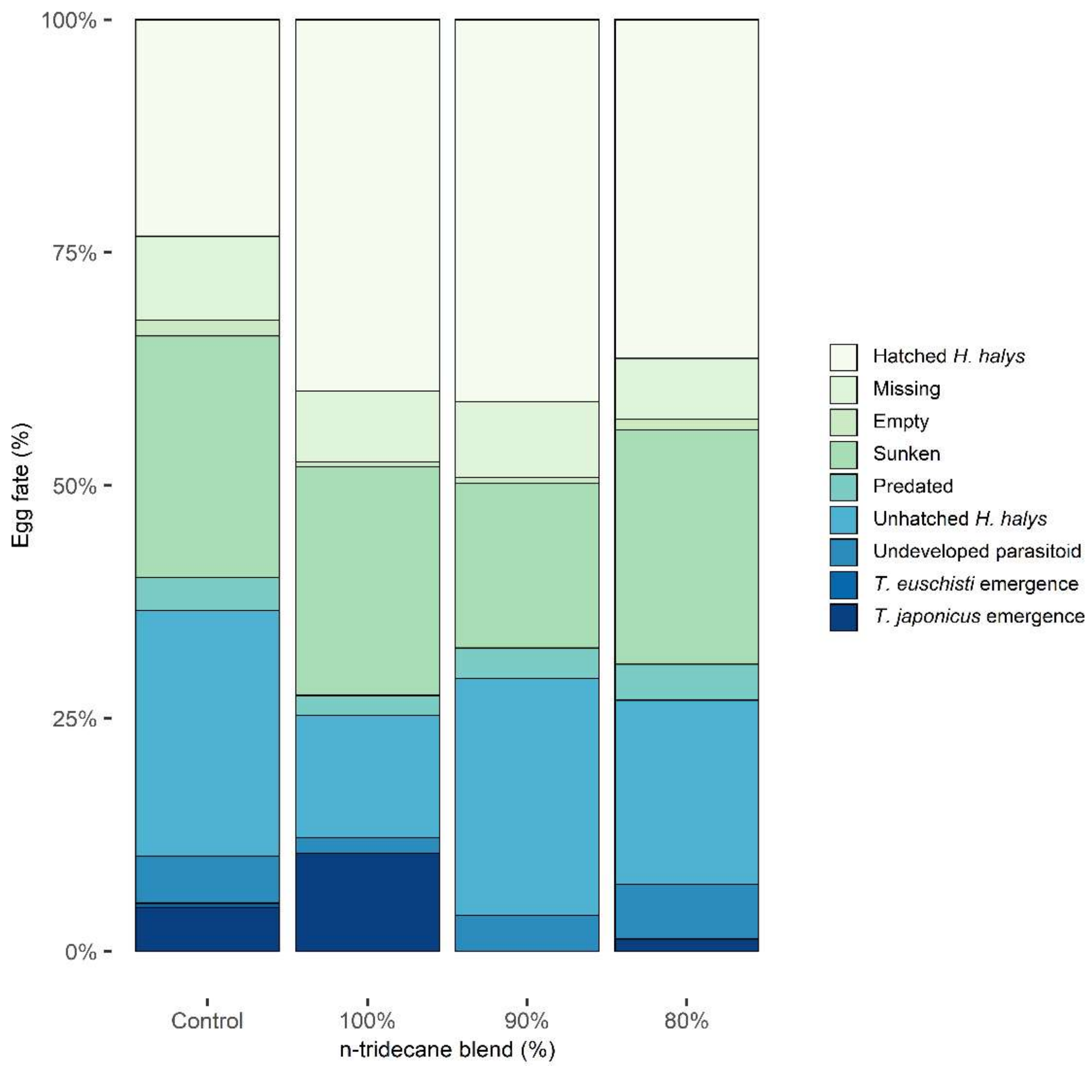

Figure III-2. Fate of field-deployed *Halyomorpha halys* eggs (n=2,472) in each kairomone lure treatment, shown as percentage of total eggs. Lure treatments are labeled based on percentage of n-tridecane attractant to (E)-2-decenal repellent: hexane (control, n=598), 100% (n=615), 90% (n=617), and 80% (n=597). A total of 6 egg mass deployments were made in Salt Lake City, UT, from 24 June through 27 August 2021.

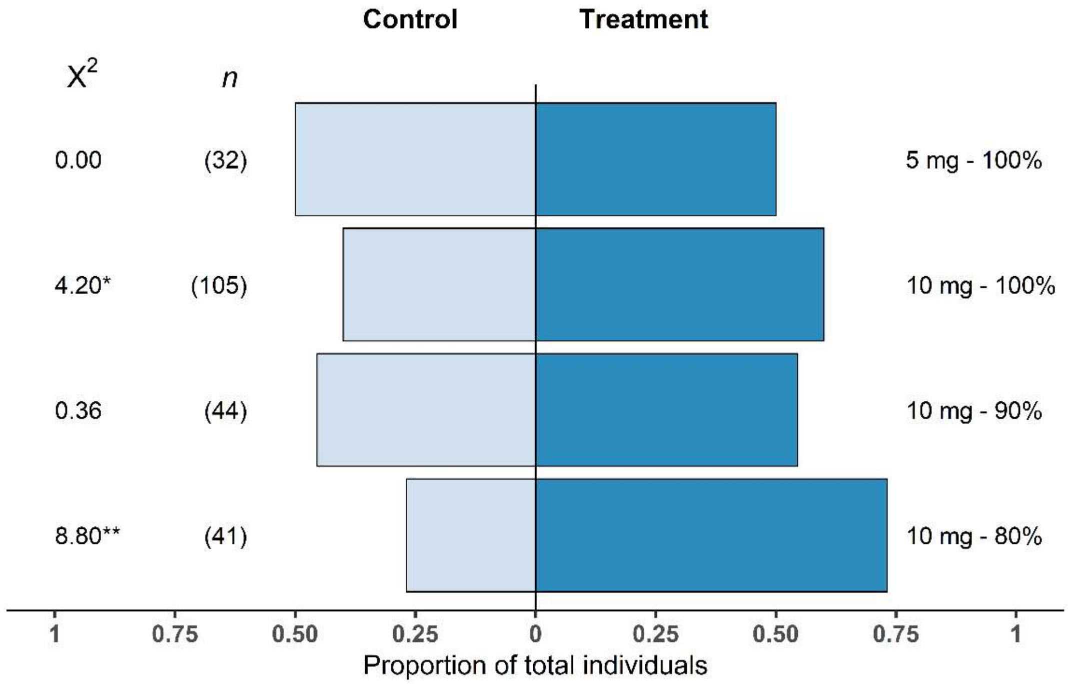

Figure III-3. Proportional response of *Trissolcus japonicus* female adults that chose a kairomone lure treatment or control (n = 32–105) within the 30 min experimental period. Chi-squared values are presented and numbers in parentheses represent sample size; * $p < 0.05$; ** $p < 0.01$.

CHAPTER IV

ADVENTIVE POPULATION OF *Trissolcus japonicus* (HYMENOPTERA: SCELIONIDAE), PARASITOID OF Halyomorpha halys (HEMIPTERA: PENTATOMIDAE), DISCOVERED IN SOUTHWESTERN IDAHO[1, 2]

Abstract

Adventive populations of *Trissolcus japonicus* (Ashmead) have been detected in the eastern and western U.S. including the western states of Washington, Oregon, California, and Utah. These populations may provide classical biological control for the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), which can cause economic loss to many specialty crops in western North America. Idaho has not previously been surveyed for the exotic *T. japonicus* or native parasitoids of *H. halys*. In July 2021, *T. japonicus* was discovered emerging from wild *H. halys* egg masses in Star, Idaho (43.69788, -116.49427), and was detected on yellow sticky cards from July to September. This is the first record of *T. japonicus* in the state of Idaho. *Trissolcus japonicus* constituted only a small portion of *Trissolcus* species detected; other species included *T. euschisti* (Ashmead), *T. hullensis* (Harrington), and *T. utahensis* (Ashmead). Genetic population level analysis of *T. japonicus* specimens from Idaho support the likelihood of its expansion inland from the west coast, inhabiting ecozones previously considered unsuitable due to high temperatures and low humidity. This report opens the prospect of an effective biological control agent for *H. halys* in Idaho and potentially other hot and dry

geographic regions and expands documentation of the presence of adventive *T. japonicus* populations in North America.

Keywords

Biological control, Invasive species, Brown marmorated stink bug, Samurai wasp, Parasitism

[1]We thank the Journal of Integrated Pest Management team and the director of publications for allowing the reprinting of this publication in this thesis.

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

Pest Status of *Halyomorpha halys*

Since the accidental introduction of the brown marmorated stink bug, *Halyomorpha halys* (Stål), in the U.S. in 1996 (Hoebeke and Carter 2003), this invasive species has demonstrated swift expansion and the propensity to utilize more than 300 host plants that include fruits, vegetables, field crops, and ornamentals (Lee et al. 2013, Holthouse et al. 2017, Schumm et al. 2020) to which it can cause severe damage and economic loss (Haye, Gariepy, et al. 2015). Though broad-spectrum insecticides are the most common management strategy, they are only moderately effective against *H. halys* due to the insect's strong flight capability allowing them to rapidly disperse (Lee and Leskey 2015, Wiman et al. 2015), and their tolerance to insecticide residues (Kuhar and Kamminga 2017). In response to the challenges of managing *H. halys*, suppression strategies have shifted to include biological control programs (Ogburn et al. 2016, Dieckhoff et al. 2017).

Adventive Status of *Trissolcus japonicus*

The samurai wasp, *Trissolcus japonicus* (Ashmead), is the predominant parasitoid of *H. halys* in its native range of Asia and is responsible for population suppression by stinging and parasitizing up to 60–90% of *H. halys* eggs (Zhang et al. 1993, Yang et al. 2009). Due to only modest suppression of *H. halys* by U.S. native *Trissolcus* spp. (Cornelius et al. 2016, Ogburn et al. 2016), *T. japonicus* has been under study in U.S. quarantine facilities since 2007 to evaluate its efficacy as a biological control option for *H. halys*, and to assess its possible negative effects on native stink bugs (Talamas, Herlihy, et al. 2015).

An adventive population of *T. japonicus* was detected in Beltsville, Maryland in 2014 (Talamas, Herlihy, et al. 2015), and additional recoveries have occurred in many states (Leskey and Nielsen 2018) and other countries outside its native range: Canada (Abram et al. 2019, Gariepy and Talamas 2019), Switzerland (Stahl et al. 2019), Italy (Peverieri et al. 2018), and Germany (Dieckhoff et al. 2021). The continued detections of *T. japonicus* in association with the spread of its host suggest that previous geographic modeling of suitable habitats may have underestimated its ability to survive and thrive outside optimal climates (Avila and Charles 2018, Illán et al. 2022).

Trissolcus japonicus was discovered on the west coast in 2015 in Washington (Milnes et al. 2016), and then again in Oregon in 2017 (Hedstrom et al. 2017). Surveys for the wasp in Utah detected an adventive population in 2019 near the initial detection point for *H. halys* in 2012 (Spears et al. 2018, Holthouse et al. 2020). Genetic analysis of individuals from *T. japonicus* adventive populations in the U.S. has separated west coast field populations from those on the east coast, suggesting at least two distinct introductions of *T. japonicus* (Talamas, Herlihy, et al. 2015, Bon and Lesieur 2016).

Detections of *Trissolcus japonicus* in Idaho

Yellow sticky card surveys were conducted at nine residential and rural sites in the Treasure Valley of southwestern Idaho to survey for parasitoids of *H. halys*. These surveys were conducted from 6 June through 19 October 2021 in approximately biweekly intervals and detected *T. japonicus* at three sites in Ada

County and one site in Payette County (Fig. IV-1). In addition to *T. japonicus,* three other species of *Trissolcus* were captured on sticky cards: *T. euschisti* (Ashmead) (62% of total individuals), *T. hullensis* (Harrington) (20%), and *T. utahensis* (Ashmead) (8%). Due to specimen damage, 5% of *Trissolcus* captures were unidentifiable beyond genus. Although yellow sticky card surveys did detect *T. japonicus* earlier in the season than the initial discovery via egg mass collection (see below), cards were not processed for wasp identification until after the initial detection via wild egg masses was confirmed.

Parasitism of Wild *Halyomorpha halys* Eggs in Idaho

On 5 July 2021, while conducting a parasitoid study in Star, Idaho (43.697882, -116.494272), an *H. halys* egg mass was discovered on the underside of a leaf approximately two meters above the ground of a northern catalpa tree (*Catalpa speciosa* (Warder) Warder ex Engelm.) in a residential park adjacent to an agricultural field. This egg mass appeared to have been parasitized and the surrounding branches were subsequently searched for additional egg masses. A total of five egg masses were collected, and each egg mass later exhibited previous parasitism by *T. japonicus* as evidenced by the successful emergence of 12-23 adults *T. japonicus* from each egg mass. *Trissolcus japonicus* adults emerged from 86 (62%) of the 138 total eggs making up the five masses. Individual eggs without successful *T. japonicus* emergence were dissected and categorized as un-emerged *T. japonicus* (4%), aborted parasitoid (1%), unhatched *H. halys* nymph (18%), predated (4%), or empty (11%). No *H. halys* nymphs successfully hatched and no other parasitoid species emerged from the wild egg masses.

After initial identification by Utah State University researchers, *T. japonicus* specimens (Fig. IV-2) were sent to Idaho State Department of Agriculture contacts, and subsequently confirmed by Dr. Matt Buffington, Research Entomologist at the U.S. Department of Agriculture, ARS Systematic Entomology Laboratory and seconded by Dr. Elijah Talamas, Curator of Hymenoptera at the Florida Department of Agriculture and Consumer Services. Voucher specimens were deposited in the Utah State University Insect Collection.

Ecological and Economic Impacts

Halyomorpha halys continues to threaten agricultural crops in the U.S., and while potential distribution modeling indicates the southwestern region of Idaho has the greatest potential for *H. halys* establishment in Idaho, no significant damage or populations have been reported thus far. However, climate models predict that climate change will likely increase the proportion of highly suitably habitat for this invasive insect (Streito et al. 2021, Illán et al. 2022). The Treasure Valley, which includes counties in this study that were surveyed for *Trissolcus* spp., is specifically expected to experience increased suitability for *H. halys* and increased negative impacts on agricultural production (Illán et al. 2022). As the risk to Idaho's agriculture increases, it is critical to better understand the role that *T. japonicus* may play in biological control of *H. halys*.

The first surveys conducted in Idaho for this parasitoid positively confirmed its presence; it is uncertain how long *T. japonicus* populations have been in the area. *Trissolcus japonicus* was first confirmed in Utah in June 2019, later than initial detections in Washington and Oregon. Recent population level genetic analysis has determined that specimens from Idaho belong to a cluster of specimens including those collected from California and Oregon (Personal communication, Marie Claude Bon). This may suggest that *T. japonicus* populations are continuing to expand inland from the west coast. However, western population origination is still under investigation and future research may clarify if the Idaho population is a distinct introduction of *T. japonicus* or if it has spread from nearby populations.

Regardless of its origin, a recent introduction may explain the low numbers of *T. japonicus* detected in surveys. A total of eight *T. japonicus* individuals were recovered over 4.5 months on yellow sticky cards. These detections are incredibly low compared to that of the eastern U.S. (Quinn et al. 2021, Dyer et al. 2022). Although overall captures were low, it is clear that *T. japonicus* is present in Idaho and in at least two counties (Ada and Payette).

The surveys for parasitoids in Idaho also shed light on the lack of opportunity for *H. halys* management via native wasps. The most abundant wasp captured on yellow sticky cards was *T. euschisti* which previous research has shown can parasitize *H. halys* eggs; however, this species has exhibited low rates of successful emergence, 0–25% (Cornelius et al. 2016, Dieckhoff et al. 2017, Schumm et al. 2019, Costi et al. 2020, Holthouse et al. 2020, Konopka et al. 2020). There is little evidence of successful control by the other native wasps detected. While both *T. hullensis* and

T. utahensis, have been observed attacking *H. halys* egg masses in Utah, little is known about their rates of successful emergence other than *T. hullensis* has shown able to emerge from *H. halys* eggs while *T. utahenesi*s has not (Schumm 2019). Furthermore, egg mass collections in Idaho did not show evidence of parasitism by any native *Trissolcus* spp. or other parasitoids. While these collections were far from comprehensive as evidenced in other states, the potential for suppression of *H. halys* by native parasitoids and predators is of lower likelihood than that from *T. japonicus* (Ogburn et al. 2016).

A lack of suppression by natural enemies and an increased risk to Idaho's agriculture emphasize the importance of using sustainable integrated pest management programs. Pending further research to determine possible non-target effects, biological control programs utilizing *T. japonicus* could be a beneficial complement to or replacement of heavily used insecticide applications (Leskey, Short, et al. 2012, Roubos et al. 2014). The detection of *T. japonicus* in Idaho opens the opportunity to using a natural and effective control of *H. halys* in Idaho and provides further record of the presence of adventive *T. japonicus* populations and their effective parasitism of *H. halys* in the U.S.

Acknowledgments

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Talamas (USDA/ARS Systematic Entomology Laboratory) for their assistance with specimen identification. We thank Marie Claude Bon for sharing genetic analysis results. This study was supported by U.S. Department of Agriculture—National Institute of Food and Agriculture—Specialty Crop Research Initiative (USDA–NIFA–SCRI) grant # 2016-51181-25409. This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number G219-22-W8615 through the Western Sustainable Agriculture Research and Education program under project number GW21-221. USDA is an equal opportunity employer and service provider. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture. This study was supported by Utah Department of Agriculture and Food through the Utah Specialty Crop Block Grant 201182. This research was supported by the Utah Agricultural Experiment Station, Utah State University and approved as journal paper number 9610. Maps throughout this study were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.

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Figures

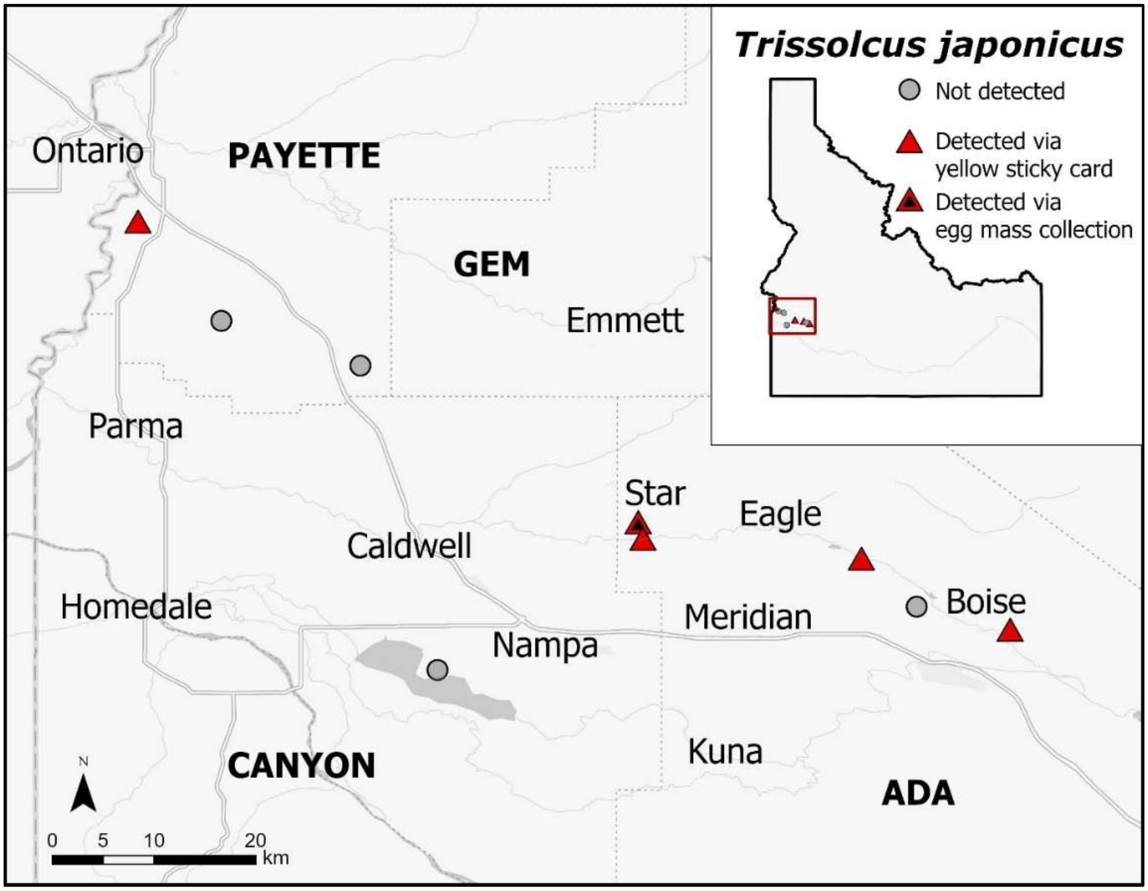

Figure IV-1. *Trissolcus japonicus* detections in southwestern Idaho from yellow sticky card surveys and egg mass collections conducted 6 June through 19 October 2021, in Ada, Canyon, and Payette counties.

Figure IV-2. An adult female *Trissolcus japonicus* emerged from an *Halyomorpha halys* egg mass collected in Star, Idaho, July 2021.

CHAPTER V

SUMMARY AND CONCLUSIONS

The current knowledge on the effective biological control of the invasive *Halyomorpha halys* (native to Asia) in the U.S. is primarily founded on studies conducted in regions vastly more suitable for parasitoid establishment than the harsh climates and high elevation landscapes of Utah and the Intermountain West. The novel studies addressed in this thesis explore the status and enhancement of both the exotic parasitoid *Trissolcus japonicus* and native *Trissolcus* species for the sustainable management of this severe agricultural and nuisance pest in the Intermountain West. The exploration of establishment of *T. japonicus* in northern Utah and southwestern Idaho, the impact of landscape habitats, and the potential use of stink bug kairomone lures to attract parasitoids create a substantial baseline for continued research on these parasitoid-stink bug host interactions.

In Chapter II, surveys were conducted to better understand the range of *T. japonicus* and native *Trissolcus* in northern Utah's urban-agricultural landscapes. *Trissolcus japonicus* was detected in six counties and up to 85 km both north and south from its original detection site in Salt Lake City (in three years since 2019). In addition, this exotic wasp has exhibited a strong association with its natural stink bug host from Asia, following its patterns of seasonality, orchard groundcover preference, and reliance on urban landscape resources. These surveys suggest *T. japonicus* is taking advantage of urban ornamentals outside of agricultural orchard sites, but groundcover habitat resources may be significant factors as population establishment and expansion continues.

This chapter also demonstrates the importance of floral groundcovers for native *Trissolcus* spp. Though they demonstrated a seasonal misalignment and have shown low effectiveness against *H. halys*, these native parasitoids continue to be an option for biological control of *H. halys* as well as native pest stink bugs. The highest abundance of native *Trissolcus* spp. was found in orchards with floral groundcovers including weeds, wildflowers, and strip-cropped herbaceous plants. These native wasps are likely taking advantage of the nectar resources they have naturally evolved alongside. As literature continues to support floral resources for enhancement of parasitoids, this research may lead to the suggestion of specific floral plants better suited to support exotic *T. japonicus* sustainment.

Lastly, this chapter supports sustainable conservation of *Trissolcus* wasps through management decisions informed by seasonality of both the pest and biological control agents. Both *T. japonicus* and its host experienced peak abundances from 1,000-1,400 $DD_{12°C}$ in 2021, while native *Trissolcus* spp. experienced a later peak that did not resolve before the end of sampling. Knowledge of peak activity for both exotic and native *Trissolcus* wasps will aid in timely releases of *T. japonicus* for successful establishment, avoidance of pesticides when they are most harmful to these important natural enemies, and the provisioning of floral resources to best sustain parasitoids.

Chapter III explores the potential use of stink bug kairomone lures to attract and retain *T. japonicus*. The field study results provide valuable information on rates of parasitism of an adventive population of *T. japonicus* in Utah and on the attack of *H. halys* egg masses by native parasitoids. *Trissolcus euschisti* is not only the most abundant parasitoid in Utah, as seen in the results of Chapter II, but is also the only native *Trissolcus* found to be parasitizing *H. halys* egg masses in this study. While this native wasp attacked egg masses at almost an equal proportion to the exotic *T. japonicus*, egg mass incubation and evaluation showed very low adult emergence success, demonstrating that IPM efforts should focus on the release and conservation of *T. japonicus* rather than the Utah native *Trissolcus* species.

In addition, research is presented on the attractiveness of kairomone lures in a controlled mesocosm environment. Field research throughout this thesis led to the conclusions that *T. japonicus* populations were low overall and may not provide the sample size needed for specific conclusions on the use of these lures. The successful attraction of *T. japonicus* to the blends of 10 mg at 100% and 80% attractant in a small scale mesocosm environment supports the validity of this approach and supports future research to fine-tune the optimal chemical makeup of said lures. This novel strategy could provide benefits of increased accuracy in estimating impacts of adventive *T. japonicus* populations on *H. halys*, and current parasitism rates as they continue to arrive in new locations throughout the U.S.

Chapter IV investigates the occurrence of *Trissolcus* in a state previously un-surveyed for the exotic *T. japonicus* and potential native *H. halys* parasitoids. This research provides the first record of *T. japonicus* in southwestern Idaho and explores its locality and abundance. Overall, parasitoid abundance detected on yellow sticky cards in surveys was low; however, collection of *H. halys* egg masses proved *T. japonicus* is taking an active role in *H. halys* population suppression. Furthermore, the genetic analysis of Idaho *T. japonicus* specimens have significant implications for the potential geographic range expansion through repeated introductions or population spread of this parasitoid alongside its invasive host. This discovery opens the door to utilizing releases of *T. japonicus* as a beneficial complement or replacement of heavily relied-upon insecticide applications.

An important component of this thesis research has been the extension outreach efforts to provide knowledge to diverse communities and stakeholders. Included is a report sent to *H. halys* researchers throughout the U.S. announcing the discovery of *T. japonicus* in Idaho (Appendix D) to quickly inform relevant parties and establish the discovery. Revisions of current resources are essential for the general public; therefore, an updated version of a fact sheet detailing parasitoids of *H. halys* in Utah was produced (Appendix E). Utah Pest newsletters (USU Extension) have been utilized as well to update home gardeners and agricultural professionals on research findings in this thesis (Appendix F). In addition to written products presented in this thesis, numerous presentations at various events including conferences, conventions, field days, workshops, and webinars have supported the distribution of vital findings and general IPM information to a broad audience. Public awareness and support are pivotal in the prevention and suppression of harmful invasive species, including the biological control of *H. halys* through parasitoid wasps in the Intermountain West.

APPENDICIES

APPENDIX A

AUTHORSHIP AND CITATION OF CHAPTERS

Chapter II:

This is an author-produced version of an article intended for publication by Environmental Entomology.

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Chapter IV:

This is a pre-copyedited, author-produced version of an article published by the Journal of Integrated Pest Management following peer review. The version of record **Richardson, K. V., D. G. Alston, and L. R. Spears**. **2023**. Adventive Population of *Trissolcus japonicus* (Hymenoptera: Scelionidae), Parasitoid of *Halyomorpha halys* (Hemiptera: Pentatomidae), Discovered in Southwestern Idaho. *Journal of Integrated Pest Management*. 14: 6. is available online at: https://doi.org/10.3390/insects14020125

APPENDIX B

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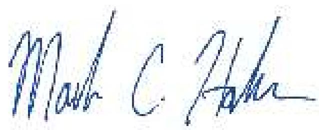

November 22, 2022

I, Zachary D. Ross, hereby grant permission for the use of "Status of the Samurai Wasp (*Trissolcus japonicus*) in Utah", of which I am a coauthor, in the thesis of Kate V. Richardson.

Sincerely,

Zachary D. Ross

APPENDIX C

ADVENTIVE POPULATION OF *Trissolcus japonicus*, PARASITOID OF *Halyomorpha halys*, DISCOVERED IN SOUTHWESTERN IDAHO

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Abstract

Adventive populations of *Trissolcus japonicus* (Ashmead) have been detected in eastern and western U.S. including the western states of Washington, Oregon, California, and Utah. These populations may provide classical biological control for the invasive stink bug *Halyomorpha halys* (Stål) which can cause severe damage and economic loss, especially to specialty crops in western North America. Idaho has previously been un-surveyed for the exotic *T. japonicus* and native parasitoids of *H. halys*. To assess the presence of stink bug parasitoids in Idaho, we deployed yellow sticky cards at nine sites in southwestern Idaho between June and October 2021. We discovered *T. japonicus* on sticky cards and emerging from wild *H. halys* egg masses. This is the first record of *T. japonicus* in the state of Idaho. *Trissolcus japonicus* constituted only 5% of *Trissolcus* species detected; other species included *T. euschisti*, *T. hullensis*, and *T. utahensis*. In other studies, native *Trissolcus* have been found to provide low parasitism rates of *H. halys* in invaded regions. Through genetic population level analysis, specimens from this study may suggest that *T. japonicus* is expanding inland from the West Coast, inhabiting ecozones

previously considered unsuitable due to high temperatures and low humidity. These findings open the prospect of an effective biological control agent for *H. halys* in Idaho and potentially other hot and dry geographic regions and expands documentation of the presence of adventive *T. japonicus* populations in North America.

Keywords

Biological control, Invasive species, Brown marmorated stink bug, Samurai wasp, Natural enemy, Parasitism

Key Message

- Idaho survey for *Halyomorpha halys* parasitoids detected adventive *Trissolcus japonicus*.
- *T. japonicus* made up a small portion of *Trissolcus* spp. detected on yellow sticky cards.
- *T. japonicus* demonstrated a successful emergence rate of 62% from wild *H. halys* egg masses.
- Idaho specimens of *T. japonicus* cluster with California and Oregon specimens in genetic analysis.
- Biological control programs utilizing *T. japonicus* to control *H. halys* can be initiated in Idaho.

Introduction

Invasive species continue to invade new locations worldwide (Hulme 2009; Seebens et al. 2017) and increasingly threaten agriculture (Paini et al. 2016) and forestry (Holmes et al. 2009) industries as well as cause urban nuisance problems. As research shifts towards sustainable management approaches, biological control has become a central component in the long-term suppression of harmful species. Non-native natural enemies both through unintended entry and intentional release can provide relief from their associated invasive hosts through classical biological control; however, the potential for non-target effects are a documented concern (Louda et al. 2003).

Since the accidental introduction of *Halyomorpha halys* in the U.S. in 1996 (StopBMSB.org 2022), it has demonstrated swift expansion and the propensity to utilize more than 300 host plants that include fruits, vegetables, field crops, and ornamentals (Lee et al. 2013; Holthouse et al. 2017; Schumm et al. 2020) to which it can cause severe damage and economic loss (Haye et al. 2015). Though broad-spectrum insecticides are the most common management strategy, they are only moderately effective against *H. halys* due to the insect's strong flight capability allowing them to rapidly disperse, and their tolerance to insecticide residues. In response to the challenges of managing *H. halys*, suppression strategies have shifted to include biological control programs (Ogburn et al. 2016; Dieckhoff et al. 2017).

The samurai wasp, *Trissolcus japonicus*, is the predominant parasitoid of *H. halys* in its native range of Asia and is responsible for population suppression with parasitism rates up to 60-90% (Zhang et al. 1993; Yang et al. 2009).

Trissolcus japonicus has been under study in U.S. quarantine facilities since 2007 to evaluate its efficacy as a biological control option for *H. halys*, and to assess its possible negative effects on native stink bugs (Talamas et al. 2015a). However, an adventive population of *T. japonicus* was detected in Beltsville, Maryland in 2014 (Talamas et al. 2015a), and additional recoveries have been made in 15 states (StopBMSB.org 2020) and other countries outside its native range: Canada (Abram et al. 2019; Gariepy and Talamas 2019), Switzerland (Stahl et al. 2019), Italy (Peverieri et al. 2018), and Germany (Dieckhoff et al. 2021). The continued detections of *T. japonicus* in association with the spread of its host suggest that previous geographic modeling of suitable habitats may have underestimated its ability to survive and thrive outside optimal climates (Illán et al. 2022).

Trissolcus japonicus was discovered on the West Coast in 2015 in Washington (Milnes et al. 2016), and then again in Oregon in 2017 (Hedstrom et al. 2017). Surveys for the wasp in Utah detected an adventive population of *T. japonicus* in 2019 near the initial detection point for *H. halys* in 2012 (Spears et al. 2018; Holthouse et al. 2020). Genetic analysis of individuals from *T. japonicus* adventive populations in the U.S. has separated these West Coast field populations from those on the East Coast suggesting there have been at least two distinct introductions of *T. japonicus* (Talamas et al. 2015a; Bon and Lesieur 2016).

Many states have put forth extensive research efforts on possible control options for *H. halys* including the use of *T. japonicus* releases and/or utilizing natural enemies native to the area. However, Idaho has had little to no research on the invasive *H. halys* and its parasitoids. The surveys conducted in this study represent the first *T. japonicus* detection efforts conducted in Idaho and provide an exploration of potential native parasitoid species for suppression of *H. halys*. We report the first record of adventive *T. japonicus* populations in Idaho and provide a discussion of its origins and significance to the current and future suppression of *H. halys*.

Methods

Deployment and Processing of Yellow Sticky Cards

In 2021, yellow sticky cards (YSC) (Alpha Scents, Inc; 8 x 5.5 in), a common and effective way to monitor for parasitoid wasps (Quinn et al. 2021; Peterson et al. 2021; Holthouse et al. 2021a; Dyer et al. 2022), were placed at nine sites (Table 1) in southwestern Idaho with previously reported *H. halys* populations. YSC were deployed and collected from 6 June through 19 October at approx. 15-day deployment intervals. At each site, YSC were secured with two twist ties to a branch at approximately 2 m height on selected ornamental and fruit trees based on past studies that support *H. halys* oviposition on these hosts (Holthouse et al. 2021b). All sites had eight to nine deployments throughout the season with the exception of site A1 (due to the removal of a large portion of the deployment tree) and A2 (due to irregular sampling).

Table 1 Description of sites where yellow sticky cards were deployed 6 June through 19 October 2021 in approx. 15-day deployment intervals. Location coordinates, characteristics, and total number of deployments are provided.

Site ID	County	Latitude	Longitude	Tree	Landscape	# of Deployments
A1	Ada	43.69789	-116.49428	*Catalpa speciosa*	Residential Park	3
A2	Ada	43.68276	-116.49001	*Catalpa speciosa*	Residential Park	6
A3	Ada	43.66529	-116.29698	*Populus* sp.	Riparian Trial	9
A4	Ada	43.62149	-116.24813	*Prunus* sp.	Urban Residence	9
A5	Ada	43.60248	-116.16556	*Malus* sp.	Urban Commercial	9
C1	Canyon	43.56541	-116.67166	*Ulmus* sp.	Forest Edge	9
P1	Payette	43.96311	-116.93636	*Malus* sp.	Rural Orchard	8
P2	Payette	43.87395	-116.86274	*Prunus* sp.	Rural Orchard	8
P3	Payette	43.83426	-116.73962	*Catalpa speciosa*	Rural Residence	9

Upon retrieval, YSC were examined under a stereomicroscope (Leica Stereozoom S9E, Leica Microsystems Inc.) with 97.6x–880x magnification for the presence of *Trissolcus* spp. Wasps were initially removed on a small piece of YSC and directly identified. All *Trissolcus* specimens were identified to species-level following the key to Nearctic *Trissolcus* (Talamas et al. 2015b). Some *Trissolcus* specimens were unidentifiable beyond genus level due to physical damage. Intact parasitoid wasps were pinned through YSC pieces, labeled, and stored in the Alston Lab, Department of Biology, Utah State University, Logan, UT. Voucher specimens were deposited in the Utah State University Insect Collection.

Wild Egg Masses and Identification

While exchanging YSC at site A1 on 5 July 2021, an *H. halys* egg mass was discovered on the underside of a leaf approximately two meters above the ground. This egg mass appeared to have been parasitized and the surrounding branches were subsequently searched for other egg masses. A total of five egg masses were collected and incubated for 14 days for possible parasitoid emergence. Emerged wasps were identified to species using the key to Nearctic *Trissolcus* (Talamas et al. 2015b). Egg masses were observed again eight weeks after collection to identify late-emerging wasps or those with partially developed wasps or stink bugs within eggs. Individual egg fate was recorded as emerged *T. japonicus*, unemerged *T. japonicus*, aborted parasitoid, unhatched *H. halys* nymph, predated, or empty.

After identification, *Trissolcus japonicus* specimens were sent to Idaho State Department of Agriculture contacts, and subsequently confirmed by Dr. Matt Buffington, Research Entomologist at the U.S. Department of Agriculture, ARS Systematic Entomology Laboratory and seconded by Dr. Elijah Talamas, Curator of Hymenoptera at the Florida Department of Agriculture and Consumer Services.

Results

Trissolcus japonicus was detected at four of nine sites for a total of eight individuals, comprising 5% of the 158 total *Trissolcus* detections (Table 2). All positive *T. japonicus* detections on YSC were between 30 July and 14 September 2021. Three positive detection sites were in Ada County and one site was in Payette County (Fig. 1). In addition to *T. japonicus,* three other species of *Trissolcus* were detected on YSC: *T. euschisti* (Ashmead) (62% of total individuals), *T. hullensis* (Harrington) (20%), and *T. utahensis* (Ashmead) (8%). Due to specimen damage, 5% of *Trissolcus* captures were unidentifiable beyond genus (Table 2).

Table 2 The number of *Trissolcus spp*. identified on yellow sticky cards at each survey site. Total proportional abundance of each species by site is provided in parentheses in the bottom row. Data was collected 6 June through 19 October, 2021 in western Idaho.

Site	# Deployment Days	*T. japonicus*	*T. euschisti*	*T. utahensis*	*T. hullensis*	*Trissolcus* spp.*	Total
A1	50	0	2	0	0	0	2
A2	125	2	0	0	0	1	3
A3	137	4	1	0	0	0	5
A4	136	0	12	8	12	5	37
A5	136	1	57	1	19	1	79
C1	136	0	1	0	0	0	1
P1	110	1	0	2	1	1	5
P2	110	0	0	0	1	0	1
P3	124	0	25	0	0	0	25
Total		8 (0.05)	98 (0.62)	11 (0.07)	33 (0.21)	8 (0.05)	158

**Trissolcus* wasps that were unidentifiable below the genus level due to damage are presented as *Trissolcus* spp.

At site A1 (Star, Idaho) on 5 July 2021 (43.697882, -116.494272), five *H. halys* egg masses were found on the leaves of a single northern catalpa tree (*Catalpa speciosa* Warder) Warder ex Engelm.), approximately 2 m above the ground. The tree was in a residential park adjacent to an agricultural field. *Trissolcus japonicus* adults emerged from all five egg masses collected, and out of 138 total eggs, *T. japonicus* successfully emerged from 86 (62%). Eggs that did not have successful emergence of *T. japonicus* were unemerged *T. japonicus* (4%), aborted parasitoid (1%), unhatched *H. halys* nymphs (18%), predated (4%), or empty (11%). No *H. halys* nymphs successfully hatched and no other parasitoid species emerged from these egg masses.

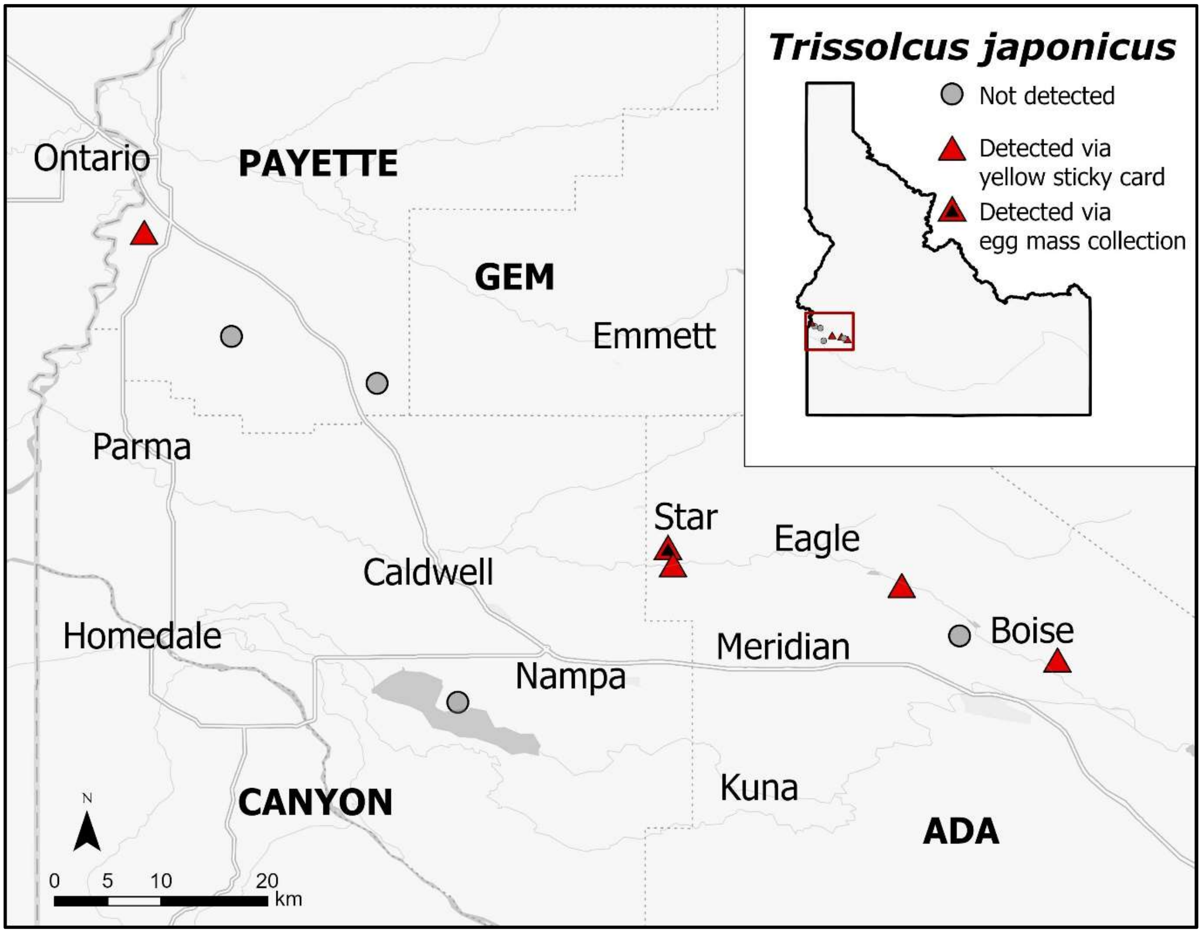

Fig 1 *Trissolcus japonicus* detections in southwestern Idaho from yellow sticky card surveys and egg mass collections conducted 6 June through 19 October 2021, in Ada, Canyon, and Payette counties

Discussion

The discovery of *Trissolcus japonicus* in southwestern Idaho opens the possibility for population suppression of *Halyomorpha halys* from an adventive, naturalized parasitoid, and provides support for *T. japonicus* release and redistribution. *Halyomorpha halys* continues to threaten agricultural in the U.S. and while potential distribution modeling indicates the southwestern region of Idaho has the greatest potential for *H. halys* establishment in Idaho, no significant damage or presence problems have been reported thus far (Personal communication, Jennifer Reibe and Paul Castrovillo). However, continued research predicts that climate change will likely increase areas of high suitability (Streito et al. 2021; Illán et al. 2022). The Treasure Valley, which includes counties surveyed in this study, is specifically expected to experience further spread of *H. halys* and increased negative impacts on agriculture (Illán et al. 2022). As the risk to Idaho's agriculture increases, it is important to understand the role of *T. japonicus* in this system.

As these are the first surveys conducted in Idaho and they positively detect the exotic wasp, it is unclear how long *T. japonicus* populations have been present. Recent population level genetic analysis has determined that specimens from Idaho share the same barcode haplotype which is commonly harbored by all adventive populations in the U.S. However, the analysis of microsatellite markers evidenced that they belong to a cluster of specimens including those collected from both California and Oregon populations. The CA-OR-ID cluster is closely related and may be delineated from a cluster of Utah specimens (Personal communication, Marie Claude Bon). This may suggest that *T. japonicus* populations are continuing to expand inland from the West Coast. However, western population origination is still under investigation and future research should clarify if the Idaho population is a distinct introduction of *T. japonicus* from Asia or if it has spread from nearby populations.

Regardless of its origin, a recent introduction may explain the low numbers of *T. japonicus* detected in these surveys. A total of eight *T. japonicus* individuals were recovered over 4.5 months on YSC. These detections are incredibly low compared to that of the East Coast (Quinn et al. 2021; Dyer et al. 2022) and compared to neighboring Utah, which has only experienced the presence of

T. japonicus for three years (Holthouse et al. 2020, 2021a; K. Richardson, Unpublished data). Though overall detections on YSC were low, it is clear that *T. japonicus* is present in Idaho and in at least two counties (Ada and Payette).

Though the collection of egg masses confirms *T. japonicus* presence, no individuals were recovered on YSC deployed at site A1. Unfortunately, YSC data from mid-season at this site was lost due to severe cut back of the deployment tree. Continual tree maintenance and park construction for the remainder of the season may have disrupted the *T. japonicus* and/or *H. halys* populations and significantly affected our detection efforts via YSC.

This research also sheds light on the lack of opportunity for *H. halys* control via native parasitoid wasps. The most abundant wasp in YSC surveys was *T. euschisti* which does parasitize *H. halys;* however, at low rates of successful emergence, 0-25% (Cornelius et al. 2016; Dieckhoff et al. 2017; Schumm et al. 2019; Konopka et al. 2020; Holthouse et al. 2020; Costi et al. 2020). Furthermore, our egg mass collections did not show evidence of parasitism by any native *Trissolcus* spp. or other parasitoids. While these collections were far from comprehensive, as evidenced in other states, the potential for control by native parasitoids and predators is not likely (Ogburn et al. 2016).

A lack of control by natural enemies and an increased risk to Idaho's agriculture emphasize the importance of using sustainable integrated pest management programs.

Pending further research to determine possible non-target effects, biological control programs utilizing *T. japonicus* could be a beneficial complement to or replacement of heavily relied on pesticide applications (Leskey et al. 2012; Roubos et al. 2014). The results of this study open the door to using a natural and effective control of *H. halys* in Idaho and provides further record of the presence of adventive *T. japonicus* populations and their effective parasitism of *H. halys* in the U.S.

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APPENDIX D

SAMURAI WASP (*Trissolcus japonicus* Ashmead) DISCOVERED IN IDAHO BY UTAH STATE UNIVERSITY

Description

On July 5, 2021, five BMSB egg masses were found on a northern catalpa tree (*Catalpa speciosa*) in a residential park in Star, Idaho (43.697882, -116.494272). The egg masses were found on the underside of leaves approximately two meters above the ground. Descriptions of individual egg masses are provided below. Two female wasps from egg mass #1 were initially identified by researchers at Utah State University and confirmed by Dr. Matt Buffington at the Systematic Entomology Laboratory and Dr. Elijah Talamas, Curator of Hymenoptera at the Florida Department of Agriculture and Consumer Services. All wasps from egg masses #2-5 were identified by Utah State University. A lab colony has been initiated from the emerged wasps.

		Appearance at Collection			***T. japonicus***
Egg Mass #	**# of Eggs**	**Black**	**White/Green**	**Predated/Chewed**	**Adults Emerged**
1	28	28	0	0	23
2	28	21	6	1	20
3	28	0	23	5	14
4	26	0	26	0	17
5	28	0	28	0	12

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APPENDIX E

PARASITOID WASPS OF THE INVASIVE BROWN MARMORATED STINK BUG IN UTAH (FACT SHEET)

UTAH PESTS fact sheet
Extension UtahStateUniversity

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Parasitoid Wasps of the Invasive Brown Marmorated Stink Bug in Utah

Zachary R. Schumm • Kate V. Richardson • Mark Cody Holthouse • Yota Mizuno • Diane G. Alston • Lori R. Spears

Do You Know?

- In 2012, brown marmorated stink bug (BMSB), an invasive insect pest from eastern Asia, was first detected in Utah in Salt Lake City. Beginning in 2017, it has caused agricultural damage in northern Utah.
- There are few natural enemies of BMSB, allowing populations to increase when unchecked.
- Parasitoid wasps that sting and kill stink bug eggs show promise as a biological control method. Native parasitoid wasps in Utah have been ineffective against BMSB to date.
- Samurai wasp, the primary parasitoid of BMSB in eastern Asia, was detected in Utah in 2019; this wasp shows promise for BMSB suppression.

The brown marmorated stink bug (BMSB, *Halyomorpha halys* Stål) is an invasive agricultural and nuisance pest native to eastern Asia. It was first confirmed in the U.S. in Allentown, PA, in 1996 and has since spread to 47 U.S. states and 4 Canadian provinces, many of which have now experienced economic crop damage from this pest (Fig. 1). In Utah, BMSB is now established in six counties (Box Elder, Cache, Davis, Salt Lake, Utah, and Weber), with detection in Carbon and Kane counties.

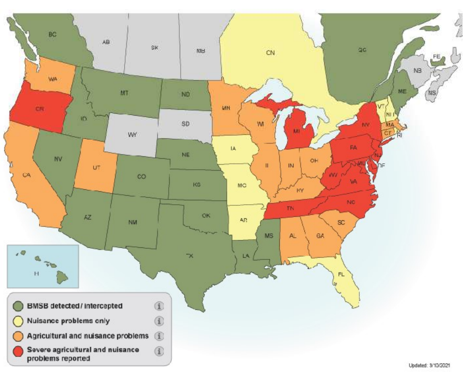

Fig. 1. The current distribution and status of BMSB in North America as of March 2021. For updates, see http://www.stopbmsb.org/where-is-bmsb/.

While crop damage to peach, apple, squash, and popcorn has been observed, it is currently causing mostly nuisance problems due to overwintering adult bugs on and within human structures.

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

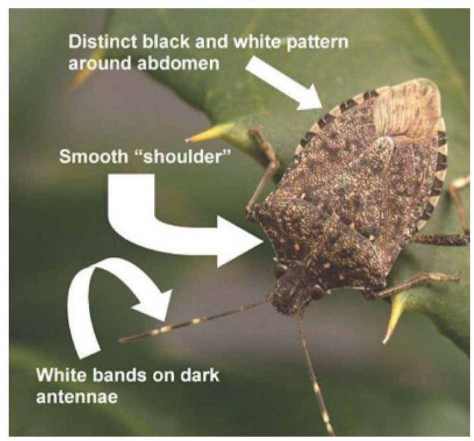

Fig. 2. A BMSB adult with quick identification characteristics. The white bands on dark antennae is the most helpful feature.

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

GENERAL PARASITOID INFORMATION

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

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

The second family, Scelionidae, includes some stink bug specialists, meaning they only sting stink bug eggs. Specialists are more promising as a control agent for BMSB. Although many of the native Scelionid species will sting BMSB eggs, some are unable to complete development to the adult stage. Those that can complete development within BMSB eggs have the potential to be more effective control agents due to self-propogation.

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

Fig. 3. Left: An adult BMSB with a freshly laid egg mass; Right top: A parasitoid wasp stings a BMSB egg mass; Right bottom: Male wasp emerges from a darkened parasitized egg mass (males emerge first).

There is usually a skewed sex ratio in emerging wasps. In a typical stink bug egg mass that consists of 14-28 eggs, one to three wasps will be male, and the rest will be female.

Fig. 4. A BMSB egg mass with triangular-shaped egg bursters. The nymphal stink bugs inside are close to hatching.

Male wasps will emerge first and wait for the females to emerge. Once mated, the females fly off in search of new egg masses to sting.

PARASITOID WASP FAMILIES IN UTAH

Eupelmidae – Generalist Egg Parasitoids

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

Fig 5. An *Anastatus* adult on BMSB eggs. Notice that the wasp is larger than an individual stink bug egg.

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

Fig. 6. An adult *Anastatus* female. Adults typically measure 3-5 mm in length and resemble ants in appearance.

Scelionidae – Specialist Egg Parasitoids

Scelionids are very small (1-2 mm), but often robust wasps that are specialists on different insect groups (Fig. 7). One genus within this family, *Trissolcus*, only stings stink bug eggs. The wasps attacking BMSB can only be identified to species by using microscopes, as they are entirely black,

Fig. 7. An adult *Trissolcus* female. Adults measure 1-2 mm with a robust body form.

Table 1. Parasitoid wasp species found in Utah as of August 2021 from stink bug egg mass and yellow sticky card deployments. *Based on results to-date from surveys in Utah.

Species Name	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 japonicus	Scelionidae	BMSB Eggs / Sticky Cards		Yes*
Trissolcus parma	Scelionidae	Sticky Cards		Unknown
Trissolcus ruidus	Scelionidae	Sticky Cards		Unknown
Trissolcus strabus	Scelionidae	Sticky Cards		Unknown
Trissolcus thyante	Scelionidae	Sticky Cards		Unknown
Trissolcus utahensis	Scelionidae	BMSB Eggs / Sticky Cards		No*

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

In its native range of Asia, BMSB causes minimal economic damage, presumably due to effective biological control by *Trissolcus japonicus* (samurai wasp) (Fig. 9). Samurai wasp was collected in China and has undergo host range-testing in U.S. quarantine facilities to assess non-target effects for release in the U.S.

However, samurai wasp has arrived on its own to the U.S. and was first detected in Delaware in 2014. It has now been found in 13 states, Canada, and many European countries as of 2021. In 2019, samurai wasp was discovered in Salt Lake City, Utah through surveys for parasitoid wasps. The samurai wasp has now been detected in six counties in Utah (Box Elder, Cache, Davis, Salt Lake, Utah, and Weber) with higher densities of wasps detected in urban landscapes.

Fig 8. A *Trissolcus* female stinging a BMSB egg mass. Notice that the wasp is about the size of an egg.

Fig. 9. The samurai wasp (*Trissolcus japonicus*), a highly effective parasitoid against BMSB. It has been found in 15 U.S. states.

SURVEYING FOR PARASITOIDS

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

Physical Egg Mass Placements:

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

Fig. 10. A BMSB egg mass clipped to a catalpa leaf with an experimental lure to attract parasitoid wasps.

Finding Naturally-laid Egg Masses:

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

Fig. 11. An *Anastatus* wasp on naturally-laid BMSB eggs.

Yellow Sticky Cards:

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

Fig. 12. Yellow sticky card hung on a peach tree to attract parasitoid wasps.

ENHANCING BIOLOGICAL CONTROL

If You See a Parasitoid Wasp:

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

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

Fig. 13. Select native parasitoid wasps stinging BMSB in Utah. From the top left: *Trissolcus erugatus, Trissolcus utahensis, Anastatus reduvii, Telenomus podisi, and Trissolcus euschisti.*

Reduce Pesticide Use:

Parasitoid wasps are very sensitive to insecticides, so avoid or limit the use of chemical sprays. Avoid broad-spectrum, persistant insecticides that kill many different invertebrates. Carbamtes, organophosphates and pyrethroids leave harmful residues, and neonicotinoids and other systemic insecticides can poison parasitoids that feed on pollen and nectar. When needed, limit the number of chemical applications and target applications to specific problem areas.

Provide Floral Resources:

Floral resources provide a number of benefits to parasitoid wasps including attracting, feeding and sheltering them.

Flowering plants may attract parasitoids to gardens and crops. Most adult parasitoids feed on plant fluids and sugars found in the nectar and pollen of flowering plants. Access to these resources allow parasitoid wasps to survive longer and produce more progeny. The best nectar sources are often flowers with a wide or shallow corolla where wasps can easily reach the nectar. Buckwheat, sweet allyssum, basil, cilantro, and dill have specifically shown benefits to *Trissolcus* species.

These plants are also essential to the overall habitat of parasitoid wasps. They can provide shade, protection from predators, and overwintering sites. Consistently providing floral resources via companion planting in outdoor spaces supports parasitoid wasps and their ability to provide effective biological control.

Fig. 14. *Trissolcus japonicus* on buckwheat flowers.

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PHOTO CREDITS

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2 Image courtesy of Jeff Wildonger, USDA-ARS-BIIR;
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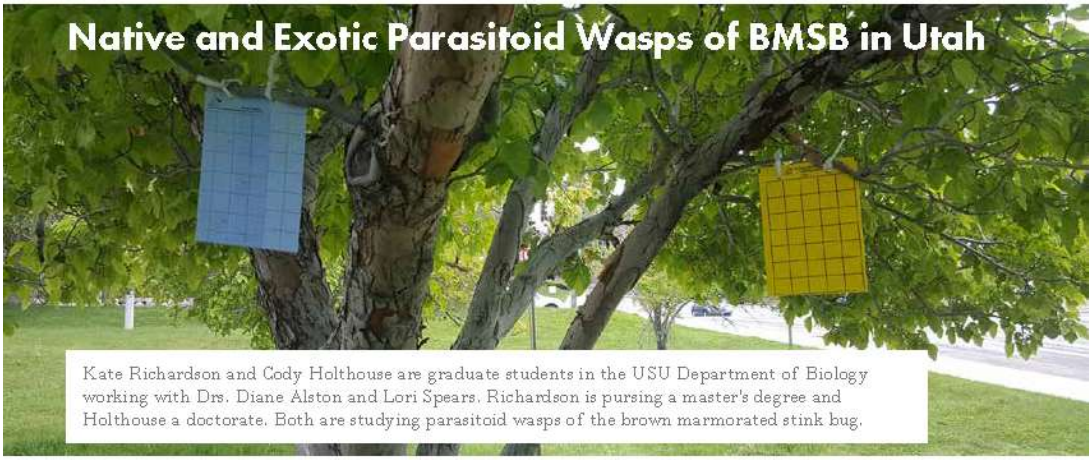
APPENDIX F

UTAH PEST NEW SLETTERS

GUEST AUTHOR SPOTLIGHT

Native and Exotic Parasitoid Wasps of BMSB in Utah



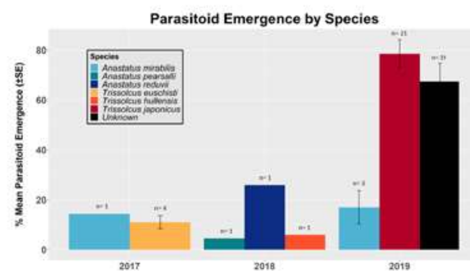
Kate Richardson and Cody Holthouse are graduate students in the USU Department of Biology working with Drs. Diane Alston and Lori Spears. Richardson is pursing a master's degree and Holthouse a doctorate. Both are studying parasitoid wasps of the brown marmorated stink bug.

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.

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.



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*.

continued on next page

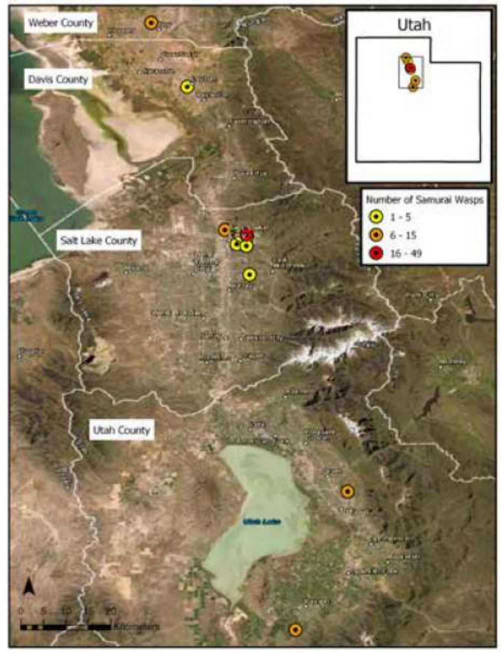
Parasitoid Wasps of BMSB in Utah, continued

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

UTAH PESTS QUARTERLY
NEWSLETTER

Winter 2023
Vol. XVI

Utah Plant Pest Diagnostic Laboratory

USU Extension

Status of the Samurai Wasp (*Trissolcus japonicus*) in Utah

Brown marmorated stink bug (BMSB, *Halyomorpha halys*) has been a highly successful invasive pest in North America not only due to its wide host range of over 300 plants, but also the lack of naturally-evolved enemies. In its native range of Asia, BMSB is primarily controlled by parasitoid wasps that lay their own eggs within stink bug eggs, killing the pest. To manage this pest, efforts have focused on biological control through Utah native parasitoids as well as a recently introduced exotic parasitoid. Management of BMSB with insecticides has had limited success.

Female *Trissolcus* wasp investigating a lab-reared BMSB egg mass with adjacent stink bug kairomone lure.

The samurai wasp (*Trissolcus japonicus*) is the primary parasitoid of BMSB in Asia and has already shown the potential to control Utah BMSB populations since its initial detection in Salt Lake City in 2019. Yellow sticky card surveys in 2020-2022 have demonstrated that the samurai wasp has spread beyond Salt Lake county to Box Elder, Cache, Davis, Utah, and Weber counties.

Urbanization and Groundcovers

Our research team investigated the effects of the surrounding landscape type, orchard groundcover, and BMSB presence on abundance of the exotic samurai wasp and native parasitoid wasps (see graph, next page). We found that the samurai wasp exhibited a strong association with BMSB, following its seasonal activity patterns and reliance on urban landscape resources. Floral groundcover in orchards, including herbaceous weeds, wildflowers, and strip-cropped flowering plants, provided resources that were significantly beneficial for enhanced abundance of native *Trissolcus* parasitoid wasps.

Experimental Attractants

Additionally, we explored the potential of lures (rubber septa) containing stink bug chemicals (kairomones) to attract and retain the samurai wasp in sites with BMSB (see image above). A field study documented BMSB egg parasitism by native and exotic parasitoids. *Trissolcus euschisti* is abundant in Utah and the only native wasp that parasitized BMSB egg masses in our study. This native attacked 7.6% of egg masses deployed, similar to the exotic samurai

continued on next page

IN THIS ISSUE

NEW MEDIA

Dahlia Mosaic Virus (fact sheet)

Integrated Pest and Pollinator Management (fact sheet)

Making and Managing Wild Bee Hotels (fact sheet)

The Backyard Garden - Pea Pests and Bean Pests (fact sheets)

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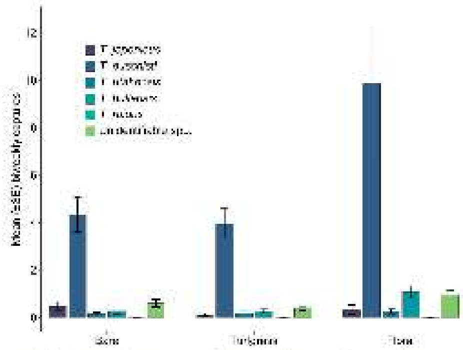
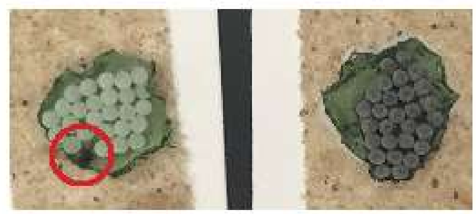
wasp which attacked 5.4%. However, only 2% of the BMSB eggs produced live *T. euschisti* adults compared to 78% for samurai wasp adult emergence. These results demonstrate that management efforts should focus on the release and conservation of samurai wasp rather than Utah native parasitoids.

In a lab study, we found that a blend of two chemicals used in the lures was most effective in attracting samurai wasps. Our results support the use of stink bug lures to attract this Asian wasp to reduce BMSB populations. Additional research is needed to fine-tune the optimal chemical ratios and release rates of lures. This approach could provide benefits of increased accuracy of estimating samurai wasp populations in agricultural areas, and estimate parasitism rates as the samurai wasp spreads to new locations in Utah and throughout the U.S.

Commercial Orchard Ground Covers Influence Abundance of Stink Bug Parasitoid Wasps



Influence of commercial orchard groundcover type (bare ground, turfgrass, and floral) on mean captures of parasitoid wasps on yellow sticky cards from May-September, 2021, in eight orchard sites. "Unidentifiable spp." represents *Trissolcus* wasps that were unidentifiable to species. The native wasp, *T. euschisti* was the most abundant, and was enhanced by floral groundcovers. The Asian parasitoid, *T. japonicus* (samurai wasp), had low abundance and was not enhanced by floral groundcovers.



Left: *T. euschisti* female (circled) guarding an unsuccessfully parasitized BMSB egg mass. **Right:** BMSB egg mass successfully parasitized by the samurai wasp (note the dark color of the eggs indicating a wasp is developing inside).

Parasitoid Interactions

To further investigate the role of the samurai wasp in biological control of BMSB in Utah, we studied interactions, competitive or facilitative, between parasitoids attacking BMSB eggs. BMSB egg masses were first exposed to female samurai wasps and then to female native *T. euschisti* to assess if initial parasitism by the exotic wasp would enhance parasitism by the native wasp. Preliminary results suggest that the samurai wasp, unfortunately, does not facilitate successful parasitism by the native wasp, and further, successful samurai wasp development in BMSB eggs could be reduced by the interaction of the two wasp species. Future research on the behavioral and physiological interactions of these parasitoids may shed light on the possible benefits or detriments samurai wasp brings to native parasitoids in the effective biological control of BMSB in Utah.

—— Kate Richardson, MS Graduate Student; Zachary Ross, Undergraduate Student; Diane Alston, Entomologist; and Lori Spears, Invasive Species Coordinator

APPENDIX G

CURRICUMLUM VITAE

Kate V. Richardson

Department of Biology | Utah State University | Logan, UT 84322
kate.richardson@usu.edu | (208) 440-0400

Education

MS, Biology/Ecology December 2022
Utah State University

"Status and Enhancement of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) for Biological Control of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) in Northern Utah"

Advisors: Dr. Diane Alston and Dr. Lori Spears
Committee members: Dr. Robert Schaeffer and Dr. Karen Beard

B.S. Biology April 2020
Utah State University

Cum laude
Minors: Chemistry | Equine Assisted Activities and Therapies
Presidential Scholarship

Professional Experience

Arthropod Diagnostician & Pest Management Specialist January 2023–Present
USU Extension, Department of Biology, Utah State University | Logan, UT

- Visual/microscope inspection and identification of arthropods
- DNA identification of arthropods to highest classification possible
- Integrated pest management consulting
- Soil insect extraction and insect trap processing
- Creation of fact sheets and other extension publications
- Instruction of Master Gardener courses
- Extension outreach workshops and presentations

Laboratory Course Teaching Assistant Fall 2020, 2021
Department of Biology, Utah State University | Logan, UT

- Instructor for two sections of Biology I Laboratory- BIOL 1615 (1 cr)
- Planned lessons, led discussions, graded exams and lab reports with a focus on discovery-based biology and research ethics
- Led students in a biodiversity themed course-based research experience

Stink Bug Shepherd (Entomology Undergraduate Research Assistant) 2018–2020
Department of Biology, Utah State University | Logan, UT

- Projects were focused on brown marmorated stink bug (*Halyomorpha halys* (Stål)) and its native and exotic parasitoid wasps in Utah
- Assisted in fruit damage, phenology, biological control, trapping, and host plant studies
- Rearing of stink bugs and parasitoid wasps
- Data collection and management (ArcGIS and Excel)
- Assisted in outreach programs and public education
- Identification and processing of parasitoid wasps

Anegada Iguana Conservation Intern August 2019
Fort Worth Zoo | Anegada, British Virgin Islands

- Conducted surveys for endangered iguanas using trapping cameras
- Baited and analyzed camera results daily
- Conducted field assays for iguanas, burrows, nests, and cow beds
- Assessed juvenile iguanas in captivity to determine release date
- Assisted in a conservation awareness event "Iguana Fest"

Assistant Reptile Manager 2015–2017
Aquarium of Boise | Boise, ID

- Educated public and school groups through guided tours
- Presented keeper talks with live reptiles
- Assisted in various outreach programs
- Housekeeping of various reptiles, aquatic animals, birds, and their exhibits

Skills

- R programming language & RStudio interface
- Esri's ArcGIS products
- Microsoft Suite products
- Adobe Software Suite: Photoshop, Lightroom, InDesign
- Website editing
- Data management and analytics
- Grant proposal writing
- Arthropod identification
- Plant pest problem diagnosis
- DNA identification
- Research team management
- Bird species identification by sight & sound
- Trained identification reptile & mammal species
- Freelance photographer

Professional Affiliations

Member | Entomological Society of America 2020–present

Fundraiser Chair | USU Biology Graduate Student Association 2021–2022

Treasurer | USU Entomology Club 2019–2020

Publications

Richardson, K. V., D. Alston, and L. Spears. 2023. Adventive population of *Trissolcus japonicus* (Hymenoptera: Scelionidae), parasitoid of *Halyomorpha halys* (Hemiptera: Pentatomidae), discovered in southwestern Idaho. *Journal of Integrated Pest Management*. Volume 14, Issue 1, 6. https://doi.org/10.1093/jipm/pmad005

Richardson, K. V., D. Alston, and L. Spears. 2023. Efficacy of Kairomone Lures to Attract Parasitoids of *Halyomorpha halys*. *Insects*, 14:125. https://doi.org/10.3390/insects14020125

Richardson, K. V., M. C. Holthouse, D. Alston, and L. Spears. Landscape Effects on Native and Exotic *Trissolcus* spp. (Hymenoptera: Scelionidae) in Northern Utah. (manuscript in prep).

Richardson, K. V., Z. Ross, D. Alston, and L. Spears. 2023. Status of the Samurai Wasp (*Trissolcus japonicus*) in Utah. *Utah Pests News, Utah State University Extension*. Vol 16: Winter edition. https://extension.usu.edu/pests/files/up-newsletter/2023/UtahPestsNews-winter23.pdf

Schumm, Z. R., **K. V. Richardson**, M. C. Holthouse, Y. Mizuno, D. Alston and L. Spears. 2022. Parasitoid Wasps of the Invasive Brown Marmorated Stink Bug in Utah. *Utah State University Extension* – Fact Sheet ENT-198-19.

Richardson, K. V. 2021. Bee Assassin Bug Predating on BMSB. *Utah Pests News, Utah State University Extension*. Vol 15: Summer edition. https://extension.usu.edu/pests/files/up-newsletter/2021/UtahPestsNews-summer21.pdf

Richardson, K. V., M. C. Holthouse, D. Alston, and L. Spears. 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/pests/files/up-newsletter/2020/UtahPestsNews-fall20.pdf

Presentations

Richardson, K. V. 2023. Spotted Lanternfly and Spongy Moth. Utah Pests Extension, March 14 Invasive Pest Workshop.

Richardson, K. V. 2023. Beneficial Insects. Utah Pests Extension, February 14 Master Gardener Program Course.

Richardson, K. V. 2023. Biocontrol of Brown Marmorated Stink Bug. Utah Pests Extension, February 9 Invasive Pest Webinar.

Richardson, K. V. 2023. Basics in Entomology. Utah Pests Extension, February Master Gardener Program Course.

Richardson, K. V., M. C. Holthouse, D. Alston, and L. Spears. 2022. Urban Landscape and Floral Resource Effects on *Trissolcus japonicus*, Parasitoid of *Halyomorpha halys*, in Utah. Entomological Society of America, November 13-16 ESA, ESC, ESBC Joint Annual Meeting- Student 10 min paper competition.

Richardson, K. V. 2022. Research on Samurai Wasp (*Trissolcus japonicus*) in Utah. Utah Pests Extension, July 5 Utah Tree Fruit Field Day.

Richardson, K. V. 2022. Biological control of Brown Marmorated Stink Bug. Utah Pests Extension, February 24 10th Annual Urban and Small Farms Conference.

Richardson, K. V. 2022. Brown Marmorated Stink Bug Biological Control. Utah Pests Extension, January 20 Utah State Horticultural Association Annual Convention.

Richardson, K. V., D. Alston, and L. Spears. 2021. Kairomone Lures to attract parasitoids of the invasive *Halyomorpha halys* (Stål). Entomological Society of America, October 31- November 3 National Annual Meeting– Student 10 min paper competition.

Richardson, K. V. 2021. Biological control of BMSB by samurai wasp (*Trissolcus japonicus*). Utah Pests Extension, September 30 First Detector Workshop.

Richardson, K. V. 2021. Beneficial Insects: Wasps and Flies. Utah Pests Extension, June 29 Vegetable IPM Twilight Meetings.

Richardson, K. V. 2021. Insect Basics Class. Freckle Farm, June 17 Little Farmers Camp.

Richardson, K. V., D. Alston, and L. Spears. 2021. Floral Resources for the Conservation and Enhancement of *Trissolcus japonicus* (Ashmead), a Parasitoid of the Invasive *Halyomorpha halys* (Stål). Entomological Society of America, April 5-7 Virtual Pacific Branch Meeting- 2nd place in Master's Student 10 min Paper Competition.

Richardson, K. V., M. C. Holthouse, D. Alston, and L. Spears. 2020. Status and enhancement of *Trissolcus japonicus* (Ashmead), for biological control of *Halyomorpha halys* (Stål) in Utah. Entomological Society of America, November 11-25 Virtual Annual Meeting– Poster and recorded oral summary.

Grants and Awards

Kate Richardson. College of Science Master's Student Researcher of the Year Award. Utah State University. 2023.

Kate Richardson. (Diane Alston). Western SARE Graduate Student Grant. "Enhancement of Samurai Wasp [*Trissolcus japonicus* (Ashmead)] for Biocontrol of Invasive Brown Marmorated Stink Bug [*Halyomorpha halys* (Stål)] in Utah" August 2021-December 2022; $30,000.

Kate Richardson. Utah State University Ecology Center Graduate Research Support Award. "Status and Enhancement of Samurai Wasp [*Trissolcus japonicus* (Ashmead)] for Biological Control of the Invasive Brown Marmorated Stink Bug [Halyomorpha halys (Stål) in Northern Utah" July 2021-July 2023; $4,000.

Kate Richardson. James A. and Patricia A. MacMahon Endowed Ecology Graduate Student Scholarship. Utah State University. April 2021-December 2021; $2,000.

Kate Richardson. Matt Del Grosso Endowed Graduate Research Award. Utah State University. April 2021-December 2021; $2,000.