Management of Brown Marmorated Stink Bug

in US Specialty Crops

2020

ANNUAL REPORT

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2021 BMSB SCRI Stakeholder Advisory Panel Meeting (Virtual)*

Wednesday – Feb 17	
1:00 – 1:15	Welcome and introductory remarks – Jim Walgenbach (NCSU)
1:15 – 2:00	Regional update on BSMB in 2020, and update of BMSB Map Southeast (Mike Toews, UGA) Pacific Northwest (Betsy Beers, WSU) Great Lakes (Larry Gut, MSU) Mid-Atlantic (Tom Kuhar, VT) West Coast (Diane Alston, USU)
	Landscape Ecology Accomplishments
2:00 – 2:30	Landscape modeling of BMSB: What have we done and where are we going. Dave Crowder and Javier Gutierrez Illan (WSU)
2:30 – 2:45	Advances in modeling of BMSB phenology – Anne Nielsen (Rutgers)
2:45 – 3:00	The Penalty Box: The High Cost of Growing up on Eastern Washington's Native Plants – Betsy Beers (WSU)
3:00 – 3:10	BREAK
3:10 – 3:25	BMSB in California: Current status and future outlook – Kent Daane (UCB)
3:25 – 3:35	Landscape Ecology Discussion/Questions
	Biological Control Accomplishments
3:35 – 3:50	*Nosema maddoxi* – Occurrence and impact on BMSB – Ann Hajek (Cornell)
3:50 – 4:05	Native natural enemies as biocontrol agents - Paula Shrewsbury (UMD)
4:05 – 4:20	Research in Virginia on *Trissolcus japonicus* foraging ecology as related to its surveillance – Nicole Quinn and Chris Bergh (VT)
4:20 – 4:35	Redistribution of *T. japonicus* and effects of infochemicals on stink bug parasitism – Joe Kaser, Don Weber, Ashot Khrimian, and Kim Hoelmer (USDA-ARS)
4:35 – 4:50	Status of *T. japonicus* in the US – Kim Hoelmer (USDA-ARS)
4:50 – 5:00	Biocontrol Discussion /Questions
Thursday – Feb 18	
1:00 – 1:10	Welcome
	Management Tactics and Outreach – Accomplishments
1:10 – 1:25	Insecticides: Current options for BMSB control, impacts, and future outlook – Tom Kuhar (VT)
1:25 – 1:40	Pheromones: Discovery, commercial development, and uses – Tracy Leskey (USDA-ARS)
1:40 – 1:55	Attract and kill technology: Progress and future directions – Jim Hepler (WSU)
1:55 – 2:10	Area-wide management of BMSB – Tracy Leskey
2:10 – 2:25	Results of a Survey on the economic impact of BMSB – Jay Harper (PSU)
2:25 – 2:40	Outreach Activities – Deb Grantham (NEIPM Center)
2:40 – 2:50	Management/Outreach Discussion and Questions
2:50 – 3:00	BREAK
3:00 – 4:00	**Interactive Stakeholder Input Session** – Nik Wiman (OSU)
4:00 – 4:15	Final questions and wrap up – Jim Walgenbach

*To register for the webinar visit:
https://cornell.zoom.us/webinar/register/WN_9QZ8K0FCTq-ULfaj9pYNWA

Project Goal and Objectives

The overall goal of this project is to develop environmentally and economically sustainable management programs for the brown marmorated stink bug (BMSB) that focus on biological control and management strategies that are informed by landscape level risk and compatible with biological control. To achieve this goal, the following specific objectives have been set:

(1) Predict risk from BMSB damage through enhanced understanding of agroecology and landscape ecology.

1a. Predict risk from BMSB damage through enhanced understanding of agroecology and landscape ecology.

1b. Assess suitability of landscapes for BMSB based on host distribution.

1c. Integrate landscape-level habitat maps and data on abiotic factors to predict BMSB distribution and risk.

(2) Implement widespread biological control of BMSB, incorporating exotic Asian parasitoids and native natural enemies.

2a. Asian parasitoids
- i. Determine distribution/range of adventive *T. japonicus* in US.
- ii. Complete host range evaluations and petition for field release of quarantine *T. japonicus*.
- iii. Determine habitat preferences and role of kairomones in host location.
- iv. Measure impact on BMSB populations and non-targets.

2b. Native parasitoids
- i. Document regional differences in key species of native parasitoids and impacts on BMSB and native stink bugs.
- ii. Assess potential adaptation of native parasitoids to BMSB.

2c. Document regional and habitat differences in native predators impacts on BMSB populations.

2d. Identify entomopathogens of BMSB that contribute to BMSB population regulation.

(3) Develop management tools and strategies that are compatible with biological control and informed by risk from landscape factors.

3a. Develop decision support tools to assess BMSB abundance and to mitigate damage.
- i. Optimize trap design for monitoring and surveillance.
- ii. Determine the relationship between captures in traps and crop injury.

3b. Identify effective uses of insecticides that minimize impacts on natural enemies.
- i. Evaluate new insecticides and threat of resistance
- ii. Evaluate impact of insecticides on natural enemies.

3c. Improve agroecosystem sustainability through spatially focused management or habitat manipulation.
- i. Evaluate impact of behaviorally-based management on BMSB and natural enemies.

ii. Refine and expand trap crop utilization within the agroecosystem.
iii. Conserve beneficial insects to enhance biological control of BMSB.

3d. Integrate IPM tools across landscape factors.

(4) Managing the Economic Consequences of BMSB Damage.

4a. Assess economic potential of biological control of BMSB on specialty crops.

4b. Develop estimates of the costs and benefits of specific management practices for BMSB.

4c. Assist with the development of program evaluation tools, including survey instruments.

(5) Outreach Plan – Deliver new information on BMSB to stakeholders.

5a. Inspire the next generation of invasive pest experts.

5b. Build upon existing BMSB outreach resources, develop and maintain a knowledge repository that captures lessons, insights, and success stories over time.

5c. Expand relevancy of BMSB outreach resources to all U.S. regions.

5d. Evaluate social benefits of improved conditions resulting from increased awareness and knowledge of sustainable practices and their adoption.

Project Participants[1]

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[1] Names with * serve as Institutional Leaders responsible for local budgets and submission of reports.

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Journal publications (including those in press)

Acebes-Doria, AL, AM Agnello, DG Alston, H Andrews, EH Beers, JC Bergh, R Bessin, BR Blaauw, GD Buntin, EC Burkness, S Chen, TE Cottrell, KM Daane, LE Fann, SJ Fleischer, C Guédot, LJ Gut, GC Hamilton, R Hilton, KA Hoelmer, WD Hutchison, P Jentsch, G Krawczyk, TP Kuhar, JC Lee, JM Milnes, AL Nielsen, DK Patel, BD Short, AA Sial, LR Spears, K Tatman, MD Toews, JF Walgenbach, C Welty, NG Wiman, J van Zoeren, TC Leskey. 2020. Season-long monitoring of the brown marmorated stink bug (Hemiptera: Pentatomidae) throughout the United States using commercially available traps and lures. J.Econ. Entomol. 113:1 (159-171). https://doi.org/10.1093/jee/toz240

Aita, RC, AM Kees, BH Aukema, WD Hutchison and RL Koch. 2021. Effects of starvation, age, and mating status on flight capacity of laboratory-reared brown marmorated stink bug (Hemiptera: Pentatomidae). Environ. Entomol. Accepted/in press.

Akotsen-Mensah, C, B Blaauw, B Short, TC Leskey, JC Bergh, D Polk, AL Nielsen. Using IPM-CPR as a management program for apple orchards. J. Econ. Entomol. 113(4):1894–1902, https://doi.org/10.1093/jee/toaa087

Alford, A, TP Kuhar, GC Hamilton, P Jentsch, G Krawczyk, JF Walgenbach, and C Welty. 2020. Baseline toxicity of the insecticides bifenthrin and thiamethoxam on *Halyomorpha halys* (Hemiptera: Pentatomidae) collected from the eastern United States. J. Econ. Entomol. 113(2):1043-1046. https://doi.org/10.1093/jee/toz361

Blaauw, BR, G Hamilton, C Rodriguez-Saona, and AL Nielsen. 2019. Plant stimuli and their impact on brown marmorated stink bug dispersal and host selection. Front. Ecol. Evol. doi: 10.3389/fevo.2019.00414

Chambers, BD, TC Leskey, JP Cullum, AR Pearce, and TP Kuhar. 2020. Cavity tightness preferences of overwintering *Halyomorpha halys* (Hemiptera: Pentatomidae). J. Econ. Entomol. 113:1572–1575.

Chambers, BD, TP Kuhar, TC Leskey, G Reichard, and AR Pierce. 2020. Negative gravitaxis in overwintering *Halyomorpha halys* (Hemiptera: Pentatomidae). J. Agr. Urban Entomol. 36:109-114.

Cornelius, ML, MV Herlihy, BT Vinyard, DC Weber, and MH Greenstone. 2021. Parasitism and predation on sentinel egg masses of three stink bug species (Hemiptera: Pentatomidae) in native and exotic ornamental landscapes. J. Econ. Entomol. doi:10.1093/jee/toaa329.

Cullum, JP, LJ Nixon, WR Morrison, MJ Raupp, PM Shrewsbury, PD Venugopal, H Martinson, JC Bergh, and TC Leskey. 2020. Influence of landscape factors and abiotic conditions on dispersal behavior and overwintering site selection by *Halyomorpha halys* (Hemiptera: Pentatomidae). J. Econ. Entomol. 113(4): 2016-2021. doi: 10.1093/jee/toaa077

Fisher, JJ, JP Rijal, FG Zalom. 2020. Temperature and humidity interact to influence brown marmorated stink bug (Hemiptera: Pentatomidae) survival. Environ. Entomol. https://doi.org/10.1093/ee/nvaa146

Formella, AF, SJ Dorman, SV Taylor, and TP Kuhar. 2020. Effects of aggregation lure and tree species on *Halyomorpha halys* (Hemiptera: Pentatomidae) seasonal oviposition. J. Econ. Entomol. 113: 203-210.

Hepler, JR, K Athey, D Enicks, PK Abram, TD Gariepy, EJ Talamas, and EH Beers. 2020. Hidden host mortality from an introduced parasitoid: Conventional and molecular evaluation of non-target risk. Insects 11:822.

Hepler, JR, R Cooper, and EH Beers. 2020. Host plant signal persistence in the gut of the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). Environ. Entomol. https://doi.org/10.1093/ee/nvaa152

Holthouse, MC, LR Spears, and DG Alston. 2021. Urban host plant utilisation by the invasive *Halyomorpha halys* (Stål) (Hemiptera, Pentatomidae) in northern Utah. Neobiota. 64: 87–101.

Holthouse, MC, ZR Schumm, E Talamas, LR Spears, and DG Alston. 2020. Surveys in northern Utah for egg parasitoids of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) detect *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae). Biodivers. Data J. 8:e53363.

Hunt, LG, G Dively, and CRR Hooks. 2020. Flowering *Chamaecrista fasciculata* borders enhance natural enemy populations and improve grain quality in field corn. Agri. Ecosys. Environ. 306 (2021) 107193.

Kereselidze, M, D Pilarska, A Linde, ND Sanscrainte, AE Hajek. 2020. *Nosema maddoxi* infecting the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in the Republic of Georgia. Biocontr. Sci. Technol. DOI: 10.1080/09583157.2020.1787346

Khadka, A, A Hodges, N Leppla, and PG Tillman. 2020. The effects of relative humidity on *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) egg hatch, nymph survival, and adult reproduction. Fl. Entomol. 103:136-138.

Krawczyk, G, H Peterson, H Rice and EH Winzeler. 2020. Insecticide treated nets as an alternative tool to manage brown marmorated stink bug, *Halyomorpha halys* (Stal). Pennsylvania Fruit News 100(1): 20-22.

Ludwick D, WR Morrison III, AL Acebes-Doria, AM Agnello, JC Bergh, ML Buffington, GC Hamilton, JK Harper, KA Hoelmer, G Krawczyk, TP Kuhar, DG Pfeiffer, AL Nielsen, KB Rice, C Rodriguez-Saona, PW Shearer, PM Shrewsbury, EJ Talamas, JF Walgenbach, NG Wiman, and TC Leskey. 2020. Invasion of the brown marmorated stink bug (Hemiptera: Pentatomidae) into the USA: Developing a national response to an invasive species crisis through collaborative research and outreach efforts. 2020. J. Integ. Pest Manag. 11(1):1–16. doi: 10.1093/jipm/pmaa001

Ogburn, EC, and JF Walgenbach. 2020. Impact of temperature storage conditions of *Halyomorpha halys* (Hemiptera: Pentatomidae) eggs on parasitism by *Anastatus reduvii* (Hymenoptera: Eupelmidae). J. Econ. Entomol. 113:98-107. https://doi.org/10.1093/jee/toz274

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Peterson, H, and G Krawczyk. 2020. Utilizing the samurai wasp a potential control tool agent against brown marmorated stink bug. Pennsylvania Fruit News 100(1): 16-18.

Preston, CE, AM Agnello, AE Hajek. 2020. *Nosema maddoxi* (Microsporidia: Nosematidae) in brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), populations in the United States. Biol. Control. 144:104213.

Preston, CE, AM Agnello, FM Vermeylen, and AE Hajek. 2020. Impact of *Nosema maddoxi* on the survival, development, and female fecundity of *Halyomorpha halys*. J. Invertebr. Pathol. 169: 107303.

Quinn, NF, EJ Talamas, TC Leskey, and JC Bergh. 2021. Seasonal captures of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) and the effects of habitat type and tree species on detection frequency. Insects. 12(2):118. https://doi.org/10.3390/insects12020118

Schumm, ZR, DG Alston, LR Spears, and K Manlove. 2020. Impact of brown marmorated stink bug (Hemiptera: Pentatomidae) feeding on tart cherry quality and yield in Utah. J. Econ. Entomol. 113:2328-2334.

Schumm, ZR, DG Alston, MC Holthouse, and LR Spears. 2020. Non-sib male guarding behavior observed in *Trissolcus euschisti* (Hymenoptera: Scelionidae). Science Matters – Matters Select. https://sciencematters.io/articles/202004000005.

Stahl, JM, D Scaccini, A Pozzebon, and KM Daane. 2020. Comparing the feeding damage of the invasive brown marmorated stink bug to a native stink bug and leaffooted bug on California pistachios. Insects 11: 688-701.

Sutton, KL, TP Kuhar, SL Rideout, and B Zhang. 2020. Evaluation of insecticides to control stink bug in edamame, 2019. Arthropod Manag. Tests. 45(1).

Tillman, G, T Cottrell, R Balusu, H Fadamiro, D Buntin, A Sial, E Vinson, M Toews, D Patel, and E Grabarczyk. 2021. Effect of duration of deployment on parasitism and predation of

Halyomorpha halys (Stål) (Hemiptera: Pentatomidae) sentinel egg masses in various host plants. Fl. Entomol. In press.

Tillman, PG, M Toews, B Blaauw, A Sial, TE Cottrell, E Talamas, D Buntin, S Joseph, R Balusu, H Fadamiro, S Lahiri, and D Patel. 2020. Parasitism and predation of sentinel eggs of the invasive brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae) in the southeastern US. Biol. Control. 145 (2020) 104247. https://doi.org/10.1016/j.biocontrol.2020.104247

Walgenbach, JF, TR Bilbo, DA Tussey, EC Ogburn. 2020. Chemigation versus foliar insecticide use: Management of lepidopteran larvae and stink bugs in North Carolina field tomatoes with environmental and farmworker benefits. Pest Manag. Sci. 76: 758-768. https://doi.org/10.1002/ps.6074

Presentations/posters at scientific meetings

Acebes-Doria, AL. Feb. 22, 2020. Investigating the impacts of pecan hedging on pest and beneficial insects. Southeastern Pecan Growers Conference, Panama City, FL.

Acebes-Doria, AL. Jan. 7, 2020. Brown marmorated stink bugs (BMSB): stinky home invaders. Annual Conference of the Georgia Pest Control Association. Athens, GA.

Akotsen-Mensah, C, C Rodriguez-Saona, and AL Nielsen. 2020. Behavioral responses of BMSB and its egg parasitoid *T. japonicus* to host based plant volatiles. Entomological Society of America Annual Meeting. (virtual, on-demand)

Alston, DG. Oct. 31, 2020 (recorded). Raspberry pest management: fruit-eating insects and cane borers. Pesticide Education Course, Utah State University Extension. (available online)

Beers, EH. Jan. 28, 2021. Integrated control of brown marmorated stink bug. Year 2 of 3 continuing report on project CP-19-105. Apple Crop Protection Research Review. (virtual)

Bergh, JC. Jan. 28-30, 2020. Release and redistribution of *T. japonicus* in the Mid-Atlantic. Mid-Atlantic Fruit and Vegetable Conference. Hershey, PA.

Bergh, JC, A Edwards, C MacRae, SN Brandt, and EJ Talamas. Dec. 2-4, 2020. Redistributing *Trissolcus japonicus* in Virginia: 2020 Update. 96th Annual Cumberland-Shenandoah Fruit Workers Conference. Winchester, VA. (virtual)

Bergh, JC, EJ Talamas, and NF Quinn. Jul. 20-24, 2020. Redistribution of adventive *Trissolcus japonicus* (Hymenoptera: Scelionidae) in Virginia, USA. International Congress of Entomology, Helsinki, Finland. (symposium; postponed due to COVID)

Daane, KM. Nov. 2020. Small and large bug damage in nut crops. Advances in Pistachio Short Course. (live webinar, CV19)

Dabek, EZ, P Shrewsbury, and CRR Hooks. Nov. 11-25, 2020. Effects of temperature on the fitness of *Anastatus reduvii* (Hymenoptera: Eupelmidae) and *Trissolcus japonicus* (Hymenoptera: Eupelmidae) and *Trissolcus japonicus* (Hymenoptera: Scelionidae) parasitoids of *Halyomorpha halys* (Heteroptera: Pentatomidae): Implications for climate change. Entomological Society of America Annual Meeting. (virtual, on-demand)

Dyer, JE, EJ Talamas, TC Leskey, and JC Bergh. Dec. 2-4, 2020. Are captures of *Trissolcus japonicus* correlated with captures of its host, *Halyomorpha halys*? 96th Annual Cumberland-Shenandoah Fruit Workers Conference. Winchester, VA. (virtual)

Dyer, JE, EJ Talamas, TC Leskey, and JC Bergh. Nov. 16-19, 2020. Sampling *Trissolcus japonicus* using yellow sticky traps: Does location in the tree canopy matter? Entomological Society of America Annual Meeting. (virtual, on-demand)

Fann, LE. 2020. Managing stink bug in your garden. University of Kentucky Graduate Community Garden. Lexington, KY.

Fann, LE, and RT Bessin. 2020. Management of the brown marmorated stink bug (*Halyomorpha halys*) using attract and kill methods in sweet corn. Entomological Society of America Annual Meeting. (virtual, on-demand)

Fann, LE, and RT Bessin. 2021. Management of the brown marmorated stink bug (*Halyomorpha halys*) using attract and kill methods in sweet corn. Kentucky Fruit and Vegetable Conference. (virtual)

Fisher, JJ, C Ingels, R Jhalendra, and F Zalom. 2020. Temperature and humidity influence brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), survival. Entomological Society of America Annual Meeting. (virtual, on-demand)

Flesicher, S, S Chen, AL Nielsen. 2020. Modeling the influence of egg mortality on *Halyomorpha halys* dynamics and phenology. Entomological Society of America Annual Meeting. (virtual, on-demand)

Gut, LJ. Dec 2020. Michigan State Horticultural Society. Managing BMSB to maintain fruit quality and production efficiency. (virtual)

Gyawaly, S, and J. Rijal. 2020. Seasonal distribution of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae) in almond and peach orchards in upper San Joaquin Valley in California. Entomological Society of America Annual Meeting. (virtual, on-demand)

Hadden, WT, TC Leskey, and JC Bergh. Dec. 2-4, 2020. Deciphering the seasonal host use patterns of *Halyomorpha halys* on select deciduous plants. 96th Annual Cumberland-Shenandoah Fruit Workers Conference. Winchester, VA. (virtual)

Hadden, WT, TC Leskey, and JC Bergh. Nov. 16-19, 2020. Retention of *Halyomorpha halys* (Hemiptera: Pentatomidae) adults and nymphs on wild and cultivated host trees as a proxy for host acceptability at different points in the growing season. Entomological Society of America Annual Meeting. (virtual, on-demand)

Holthouse MC, DG Alston, and LR Spears. Mar. 5, 2020. Natural enemies of the invasive brown marmorated stink bug. Utah Urban and Small Farms Conference. West Valley City, UT. 47 participants.

Holthouse, MC, DG Alston, and LR Spears. Feb. 26, 2020. Common stink bugs of Utah and their management. Utah State University Extension Annual Conference. Logan, UT. 13 participants.

Holthouse, MC, D Alston, and L Spears. 2020. Effectiveness of yellow and blue sticky cards for monitoring parasitoid wasps of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål). Entomological Society of America Annual Meeting. (virtual, on-demand)

Holthouse, MC, LR Spears, and DG Alston. 2021. Effectiveness of yellow and blue sticky cards for monitoring parasitoid wasps of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae). Orchard Pest & Disease Management Conference. (virtual)

Hong, Z(L). April 2020. Analysis of biology and host specificity of *Nosema maddoxi* (presentation on senior honors' thesis). Jugatae seminar series, Dept. of Entomology, Cornell University.

Kaser, J, D Weber, and K Hoelmer. Nov. 2020. Effects of kairomones on field parasitism of stink bugs by *Trissolcus japonicus*. Invited for symposium: Synergy in biological control of invasive insects: Utilizing the ecology and behavior of natural enemies. Entomological Society of America Annual Meeting. (virtual, on-demand)

Kuhar, TP. Feb. 20, 2020. Update from the mid-Atlantic U.S. BMSB SCRI Stakeholder Advisory Meeting. Davis, CA.

Marshall, AT, JR Hepler, and EH Beers. Nov. 16-19, 2020. Exploiting stink bug migration: The intersection of chemical, physical, and behavioral control methods. Entomological Society of America Annual Meeting. (virtual, on-demand)

McDougall, R, D Ludwick, T Leskey, G Krawczyk, H Peterson, CJ, Bergh, Y-L Park, and A Nielsen. Dec. 2-4, 2020. Effects of land use on the natural enemies of brown marmorated stink bug (*Halyomorpha halys*). 96th Annual Cumberland-Shenandoah Fruit Workers Conference. Winchester, VA. (virtual)

Mills, N, PK Abram, and EH Beers. Nov. 16-19, 2020. Why is life cycle vulnerability key to the development of biological control programs for invasive stink bugs? Entomological Society of America Annual Meeting. (virtual, on-demand)

Nielsen, AL. 2019. Integrating behavioral ecology into pest management. Institute for Biological Control, JKI, Darmstad, Germany.

Nielsen, AL. 2020. Integrating behavioral ecology into brown marmorated stink bug management. University of Missouri, Division of Plant Sciences Seminar.

Ogburn, E, T Ohmen and JF Walgenbach. Dec 2-4, 2020. Brown marmorated stink bug phenology in two ecoregions of North Carolina: Mountains vs coastal plains. 96th Annual Cumberland-Shenandoah Fruit Workers Conference. Winchester, VA. (virtual, 70 attendees)

Ogburn, EC and JF Walgenbach. Feb. 20, 2020. Natural enemy impacts in apple and corn agroecosystems. BMSB SCRI Stakeholder Advisory Meeting. Davis, CA. (60 attendees)

Patel, D, G Tillman, B Blaauw, M Toews and A Sial. April 1, 2020. Parasitism and predation rates of natural-laid eggs and sentinel eggs masses of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), on Georgia blueberries. Annual Meeting of the Southeastern Branch of the Entomological Society of America. (virtual)

Patel, D, G Tillman, M Toews, A Sial, and B Blaauw. Nov. 18, 2020. Parasitism and predation rates of natural-laid eggs and sentinel eggs masses of brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), on Georgia blueberries. Entomological Society of America Annual Meeting. (virtual, on-demand)

Peterson, H, G Krawczyk, JG Ali, and E Talamas. 2020. Potential brown marmorated stink bug chemical cues used by the samurai wasp. 96th Annual Cumberland-Shenandoah Fruit Workers Conference. Winchester, VA. (virtual)

Richardson, KV, MC Holthouse, D Alston, and L Spears. Nov. 16-19, 2020. Status and enhancement of *Trissolcus japonicus* (Ashmead) for biological control of *Halyomorpha halys* (Stål) in Utah. Entomological Society of America Annual Meeting. (virtual, on-demand)

Schumm, Z, D Alston, and L Spears. Nov. 16-19, 2020. Colonization behavior of brown marmorated stink bug (Hemiptera: Pentatomidae; *Halyomorpha halys* Stål) in the Utah agricultural landscape. Entomological Society of America Annual Meeting. (virtual, on-demand)

Schumm, Z, D Alston, and L Spears. 2021. Impact of brown marmorated stink bug feeding on the development, yield, and quality of tart cherry in Utah. Orchard Pest & Disease Management Conference. (virtual)

Schumm, ZR. Sep. 24, 2020. Identifying and managing stink bug pests. USU Extension, Cultivating Healthy Plants Webinar Series. (83 attendees)

Spears, LR. May 5, 2020. Early detection of invasive agricultural pests. Utah Department of Agriculture and Food. (virtual, 20 participants)

Spears, LR. Feb. 4-12, 2020. Entomology, IPM concepts, and invasive species. USU Extension, Master Gardener Series (6 total presentations). Salt Lake City (2 presentations), Kanab, Ogden, Kaysville, Logan, UT. (250 total participants)

Spears, LR. Jan. 23, 2020. Invasive insect update. Utah State Horticultural Association. Spanish Fork, UT. (80 participants)

Spears, LR. Feb. 28, 2020. Invasive pest surveys, research, and outreach. Utah State University, Applied Entomology Guest Lecture. Logan, UT. (20 students)

Spears, LR. Jan. 13, 2021. Entomology, IPM concepts, and invasive species. USU Extension, Master Gardener Series (2 presentations). (virtual, 250 participants)

Spears, LR. Jan. 20, 2021. Invasive insect update. Utah State Horticultural Association. (virtual, 100 participants)

Stahl, JM, RK Straser, H Wilson, and KM Daane. Nov. 11-25, 2020. The potential of irrigated cover crops as a management tool for stink bugs in organic pistachios. Entomological Society of America Annual Meeting. (virtual, on-demand)

Szűcs, M, O Simaz, J Wilson, L Gut, and J Pote. Dec 2020. Biological control of brown marmorated stink bug in Michigan. Great Lakes EXPO, Virtual Poster Session.

Tillman, PG, and MT Toews. Feb. 20-21, 2020. Who are the native natural enemies in the southeast? BMSB SCRI Stakeholder Advisory Meeting. Davis, CA.

Toews, MD. Aug. 18, 2020. Research on invasive insects in agriculture. Georgia Honor's Program Science Seminar Series. (virtual, 12 people)

Valentin, R, J Lockwood, AL Nielsen, and D Fonseca. 2020. The next generation of biosurveillance: How modern genetic techniques identified populations and modeled the spread of *Halyomorpha halys.* Entomological Society of America Annual Meeting. (virtual, on-demand)

Walgenbach, JF. Feb. 20, 2020. Temperature and photoperiod influences on phenology in NC. BMSB SCRI Stakeholder Advisory Meeting. Davis, CA. Feb 20, 2020. (60 attendees)

Welty, C, KF Vik, and J Jasinski. Nov. 11-25, 2020. Re-distribution of samurai wasp (*Trissolcus japonicus*) on fruit farms in Ohio. Poster, submission 892331. Entomological Society of America Annual Meeting. (virtual, on-demand)

Welty, C. Oct. 1, 2020. Biological control of stink bugs by tiny parasitoid wasp: *Trissolcus japonicus*, the samurai wasp. Annual meeting of the Midwest Fruit Workers Group. (virtual)

Wilson, JK. Dec. 2020. Brown marmorated stink bug: 2020 report. Great Lakes EXPO, Virtual Poster Session.

Non-refereed publications (proceedings, abstracts, popular magazines, etc.)

Beers, EH. 2021. Integrated control of brown marmorated stink bug. Continuing report (year 2 of 3) on WFTRC grant CP-19-105.

Beers, EH. Dec. 1, 2020. Control of brown marmorated stink bug using attract-and-kill. WSCPR# 20AN014. Washington State Commission on Pesticide Registration.

Schumm, ZR, DG Alston, and LR Spears. 2021. Behavior of brown marmorated stink bug (Hemiptera: Pentatomidae; *Halyomorpha halys* Stål) in the Utah agricultural landscape. Proceedings of the Entomological Society of Washington. In press.

Weber, DC, AE Hajek, KA Hoelmer, U Schaffner, PG Mason, R Stouthamer, EJ Talamas, M Buffington, MS Hoddle, and T Haye. 2021. Unintentional biological control. Chapter 5 in: Biological control: Global impacts, challenges and future directions of pest management (Ed. PG Mason). CSIRO Publishing, Melbourne, in press. Pp. 114-144.

Extension publications

Krawczyk, G. Sep. 10, 2020. Big stink bug home invasion season is coming. Patriot News/Penn Live article. https://www.pennlive.com/life/2020/09/big-stink-bug-home-invasion-season-is-coming.html

Krawczyk, G. Aug. 31, 2020. Brown marmorated stink bug reminder. Fruit Times Newsletter. 2020. https://extension.psu.edu/brown-marmorated-stink-bug-reminder

McDougall, R, and A Nielsen. Apr. 20, 2020. Integrating Management for Key Orchard Pests. NJAES Plant and Pest Advisory.

NEIPM Center. 2020. BMSB distribution map (update). https://www.stopbmsb.org/where-is-bmsb/state-by-state

NEIPM Center. 2020. Field recoveries of *Trissolcus japonicus* (update). https://www.stopbmsb.org/biological-control/samurai-wasp-trissolcus-japonicus/

NEIPM Center. 2020. List of BMSB scientific publications (update). https://www.stopbmsb.org/about-us/scientific-publications/

Ogburn, EC, and JF Walgenbach. 2020. Biological control of brown marmorated stink bug. NC Coop. Extension Service. https://entomology.ces.ncsu.edu/biological-control-of-brown-marmorated-stink-bug/

Potter, ME, and PM Shrewsbury. 2021. Project Stink-Be-Gone "2". Citizen Science project engaging citizens to elucidate alternate in-season and overwintering host of *Anastatus reduvii*, a native egg parastiod of the invasive brown marmorated stink bug. https://shrewsburylab.weebly.com/project-stink-be-gone-2.html

Richardson, K, MC 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.

Rijal, JP. 2020. How nut growers can get the best of brown marmorated stink bugs. https://bit.ly/2JlMWFo

Rijal, JP, and FG Zalom. 2020. Provisional guidelines for brown marmorated stink bug control in almond. (UCIPM peer-reviewed). http://ipm.ucanr.edu/PMG/r3303211.html

Spears, LR, A Mull, A Fabiszak, M Murray, R Davis, DG Alston, and R Ramirez. 2020. Invasive pests of landscape trees in Utah. Utah State University Extension (98 pp). Logan, UT.

Szucs, M, O Simaz, L Gut, J Pote, and J Wilson. Dec. 2020. Increasing the abundance of samurai wasp for biological control of brown marmorated stink bug. MSU Extension News.

Walgenbach, JF. 2020. WNC Orchard Insect Update. Weekly (Apr. thru Sep.) newsletter blog on tree fruit pest activity and pesticide recommendations.

Welty, C. Aug. 2020. Brown marmorated stink bug. Ohio Fruit news. p. 7. https://cpb-us-w2.wpmucdn.com/u.osu.edu/dist/b/28945/files/2020/08/OFN_August_2020_FINAL.pdf

Welty, C. Aug. 29, 2020. Do you recognize stink bug injury on sweet corn? Ohio VegNet newsletter. https://u.osu.edu/vegnetnews/2020/08/29/do-you-recognize-stink-bug-injury-on-sweet-corn/

Wilson, J. Sep. 2020. Managing brown marmorated stink bugs in homes & gardens. Major revision of 2015 tip sheet originally written by P. Botch and D. Brown. Fact Sheet.

Wilson, J, L Gut, M Grieshop, and W Shane. Revised Aug. 2020. Managing brown marmorated stink bug in Michigan orchards. Fact Sheet.

Wise, J, LJ Gut, R Isaacs, AMC Schilder, B Zandstra, E Hanson and B Shane. 2020. Michigan Fruit Management Guide. Michigan State University Extension Bulletin E-154.

WSU-TFREC Entomology. BMSB feeding on tomato – closeup of stylets. https://youtu.be/zyYtaPkOMY4

WSU-TFREC Entomology. Time lapse of BMSB egg mass hatching. https://youtu.be/t0PTCRjBGj4

WSU-TFREC Entomology. *Trissolcus japonicus* ovipositing in *H. halys* and *P. maculiventris* eggs. https://youtu.be/fL1tA0DFEuo

Extension presentations

Acebes-Doria, A.L. Sep. 16, 2020. Brown marmorated stink bugs (BMSB): a homeowner pest. Green Industry Webinar. UGA Center for Urban Agriculture.

Acebes-Doria, A.L. Sep. 10, 2020. Overview of the UGA entomology pecan research and extension programs. Georgia Pecan Grower Conference. Tifton, GA.

Blaauw, B. Feb. 17, 2020. Insect pest management update. 2020 North Georgia Apple Production Meeting. Ellijay, GA.

Blaauw, B. Jan. 11, 2021. Insect pest management update. Annual Georgia Commercial Peach Production Meeting. Fort Valley, GA. (virtual)

Blaauw, B. Jan. 26, 2021. Stink bugs: Monitoring and management recommendations. Chilton Area Peach Production Meeting. Chilton County, AL .(virtual)

Hooks, CRR. Posted Sep.11, 2020. Virtual Field Day. Marigolds, more than dependable bloomers. https://www.youtube.com/watch?v=qqW-t4bxXzo&list=PLVHDC0BV7YWxTEGSMpVIMncOsdRm-soBb&index=5

Nielsen, A. NJ Fruit twilight meeting III: Updates for BMSB management and what to expect in 2020. (virtual)

Nielsen, A. Mar. 2020. Integrating management for key orchard pests. N. Jersey Fruit Mtg. Hunterdon, NJ.

Nielsen, A. Mar. 2020. Integrating mgt for key orchard pests. S. Jersey Fruit Mtg. Bridgeton, NJ.

Shrewsbury, PM. 2020. Arborists' Question Time. Which tree pests and diseases should we be most worried about in the UK? United Kingdom Arboricultural Society. (virtual, international, 190 attendees)

Shrewsbury, PM. Jan. 2021. Bugs, aphids, adelgids, thrips. Advanced Landscape IPM Shortcourse. Department of Entomology, University of Maryland. College Park, MD. (virtual - 60 attendees)

Shrewsbury, PM. Jan. 2021. Insect Pests of Ornamentals (1 day Virtual Short Course). Continuing Professional Education Short Course, Rutgers University, New Brunswick, NJ. (12 attendees)

Walgenbach, JF, and SC Schoof. Jan. 8, 2020. Using pheromone traps to determine when to spray for brown marmorated stink bug. Southeastern Apple Growers Meeting. Asheville, NC. (60 attendees)

Walgenbach, JF. 2020. Peach insect update: San Jose scale and brown marmorated stink bug. NC Peach Society Annual Meeting. Carthage, NC. Jan 28, 2020.

Zalom, F. Oct. 16, 2020. Brown marmorated stink bug and other bug pests of almonds. Continuing Education Seminar, UC Cooperative Extension, Merced County. (virtual)

Zalom, F. Dec. 15, 2020. Plant and stink bugs of almonds and pistachios. Grower meeting, Madera Farm Bureau. (virtual)

News, Print, Broadcast

Krawczyk, G. Sep. 10, 2020. Newsweek: BMSB update. https://www.newsweek.com/stink-bug-invasion-fall-2020-how-treat-prevent-1531023

Nielsen, A. 2019. Fox TV interview: Overwintering BMSB management.

Leveraged funding/complimentary resources

Alston, DG, and LR Spears. Sep. 30, 2019 – Sep. 29, 2022. USDA Utah Department of Agriculture and Food Specialty Crop Block Grant Program. Searching for the samurai wasp and promoting native parasitoid wasps for biological control of the invasive brown marmorated stink bug. $45,358.

Alston, DG. Jul 1, 2018 - Jun 30, 2023. Utah Agricultural Experiment Station. Brown marmorated stink bug: an invasive pest of economic importance to Utah's specialty crops. $29,250.

Beers, EH. 2020. Integrated control of brown marmorated stink bug. CP-19-105. Washington Tree Fruit Research Commission (WTFRC). $99,851.

Beers, EH. 2020. Control of brown marmorated stink bug using attract-and-kill. WSCPR# 20AN014. Washington State Commission on Pesticide Registration. $16,505.

Cornell Univ. 2019-2020. Expanding the range for establishing the samurai wasp*, Trissolcus japonicus*, in orchards and vegetable crops of NYS. New York Farm Viability Institute Inc, Contract: FVI 19 017.

Cornell Univ. 2019-2020, 2020-2021. Expanding the range for establishing the samurai wasp, *Trissolcus japonicus*, in orchards and vegetable crops of NYS. Apple Research and Development, New York State Department of Agriculture and Markets.

Daane, K. Jan. 2019 to Apr. 2022. California Dept Food and Agriculture, Specialty Crop Research Initiative. Ground cover strips in pistachio to control stink bug and leaffooted bugs through improved biocontrols and monitoring. $215,000.

Daane, K. Mar. 2018 to May 2020. California Pistachio Research Board. Comparing the feeding damage of the invasive brown marmorated stink bug to native large bugs. $39,833.

Daane, K. Mar. 2019 to May 2021. California Pistachio Research Board. The use of trap crops to monitor and suppress large bug damage. $38,454.

Gut, L. Michigan Apple Research Committee. Managing BMSB to maintain fruit quality and production efficiency. $22,000.

Gut, L. Michigan State Project GREEEN. Management of BMSB using strategies to minimize insecticide use. $35,000.

Holthouse, MC, DG Alston, LR Spears. 2018-2020. Brown marmorated stink bug in Utah's Intermountain West. USDA Western SARE Graduate Student. $24,999.

Krawczyk, G. 2020-2021. State Horticultural Association of Pennsylvania. Integration of bio-pesticides into sustainable insect pest management in fruit. $28,796.

Spears, LR. and C Nischwitz. 2019-2020. Specialty crop commodity survey. USDA APHIS. $17,000.

Spears, LR and C Nischwitz. 2020-2021. Specialty crop commodity survey. USDA APHIS. $17,000.

Spears, LR, M Murray, Z Schumm, J Gunnell, and K Wagner. 2020-2021. Invasive pest outreach. USDA APHIS. $49,995.

Spears, LR, R Davis, M Murray, J Gunnell, and K Wagner. 2019-2020. Invasive pest outreach. USDA APHIS. $49,995.

Walgenbach, JF. 2020-2021. Attract and Kill for managing brown marmorated stink bug. NCDA&CS SCRI Block Grant. $127,595.

Zalom, F. Almond Board of California: $44,590.

Zalom, F. California Cling Peach Board: $12,195.

Zalom, F. California Pear Board: $2,500.

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Research

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Ecology and Behavior

Season-Long Monitoring of the Brown Marmorated Stink Bug (Hemiptera: Pentatomidae) Throughout the United States Using Commercially Available Traps and Lures

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Abstract

Reliable monitoring of the invasive *Halyomorpha halys* abundance, phenology and geographic distribution is critical for its management. *Halyomorpha halys* adult and nymphal captures on clear sticky traps and in black pyramid traps were compared in 18 states across the Great Lakes, Mid-Atlantic, Southeast, Pacific Northwest and Western regions of the United States. Traps were baited with commercial lures containing the *H. halys* pheromone and synergist, and deployed at field sites bordering agricultural or urban locations with *H. halys* host plants. Nymphal and adult captures in pyramid traps were greater than those on sticky traps, but captures were positively correlated between the two trap types within each region and during the early-, mid- and late season across all sites. Sites were further classified as having a low, moderate or high relative *H. halys* density and again showed positive correlations between captures for the two trap types for nymphs and adults. Among regions, the greatest adult captures were recorded in the Southeast and Mid-Atlantic on pyramid and sticky traps, respectively, with lowest captures recorded in the West. Nymphal captures, while lower than adult captures, were greatest in the Southeast and lowest in the West. Nymphal and adult captures were, generally, greatest during July–August and September–October, respectively. Trapping data were compared with available phenological models showing comparable population peaks at most locations. Results demonstrated that

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Research

Using IPM-CPR as a Management Program for Apple Orchards

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Abstract

We have demonstrated how management of key orchard pests including the insect invasive species *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) can be accomplished using a systems-level approach termed IPM-CPR (Integrated Pest Management-Crop Perimeter Restructuring) in apple. We conducted on-farm comparisons of IPM-CPR to standard management program for managing *H. halys*, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae), and *Lygus lineolaris* Palisot de Beauvois (Hemiptera: Miridae) in commercial apple orchards in 2014, 2016, and 2017 in New Jersey, Maryland, and Virginia. The presence and abundance of key pests and fruit injury at harvest were used as a measure of success of the program. We compared the amount of insecticide applied for each management program. In majority of instances, there were no differences in the IPM-CPR and the standard management program in terms of *H. halys* numbers in baited pyramid traps and stink bug injury at harvest. Damage from *C. pomonella* and *G. molesta* in the IPM-CPR treatment was significantly lower than the standard management program in 2014 and 2017. Amount of active ingredient used was on average 62.1% lower in the IPM-CPR treatment compared with standard management program. Despite a reduction in insecticide use, there were minimal impacts on beneficial insects. Overall, IPM-CPR in apples successfully managed key orchard pests, including *H. halys*, and used significantly less insecticide than a standard insecticide-based management program and could be adopted as a systems-level approach for pest population reduction.

Key words: *Halyomorpha halys*, *Malus domestica*, Mid-Atlantic, border sprays, systems-level management

Like most crops, tree fruit production is constrained by a number of problems, including insect pest damage (Agnello et al. 2009). Orchard management practices are constantly evolving to include new tactics and pest issues. Tree fruit crops constitute a major component of specialty crop production in the United States, and particularly, in the Mid-Atlantic region (USDA-NASS 2016). Insects like codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), oriental fruit moth, *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) (Brunner et al. 2005, Knight 2007), plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae) (Vincent et al. 1999, Leskey et al. 2010), and apple maggot (*Rhagoletis pomonella* Walsh [Diptera: Tephritidae]) (Prokopy et al. 1971, Rull and Prokopy 2000) are key primary pests that can cause significant yield losses and reduction in fruit quality if not managed properly. Secondary arthropod pests including *Tetranychus* spp. mites (Trombidiformes: Tetranychidae), and San Jose scale *Quadraspidiotus perniciosus* Comstock (Hemiptera: Diaspididae) (Van Den Bosch et al. 1971, Chiappini and Negri 2004) can drastically increase in population when their predators are disrupted by broad-spectrum insecticides. These secondary and indirect pests are managed with integrated pest management (IPM) programs in the Mid-Atlantic and other regions. However, orchard pest complexes and their management approaches have shifted since the establishment of the invasive *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) as a critical pest in the Mid-Atlantic region (Rice et al. 2014, Leskey and Nielsen 2018).

Halyomorpha halys is a difficult insect to manage because of its high mobility in the landscape and polyphagous feeding behavior, allowing it to colonize new areas very quickly. Even a few observed individuals in tree fruits can cause up to 25% injured fruit (Nielsen and Hamilton 2009). Additionally, because tree fruits are a high value crop,

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Short Communication

OXFORD

Baseline Toxicity of the Insecticides Bifenthrin and Thiamethoxam on *Halyomorpha halys* (Hemiptera: Pentatomidae) Collected From the Eastern United States

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Abstract

Brown marmorated stink bug, *Halyomorpha halys* (Stål), is an invasive species in the United States that attacks a wide variety of agricultural commodities including fruits, vegetables, agronomic crops, and ornamental plants. Populations of *H. halys* adults were collected from four and six states in 2017 and 2018, respectively, and tested using topical applications to establish baseline levels of susceptibility to two commonly used insecticides, bifenthrin and thiamethoxam. A Probit-estimated (95% fiducial limits) LD_{50} and LD_{99} of 2.64 g AI/L (1.2–3.84 g AI/L) and 84.96 g AI/L (35.76–716.16 g AI/L) for bifenthrin, and a LD_{50} and LD_{99} of 0.05 g AI/liter (1.14E-5–0.27 g AI/L) and 150.11 g AI/L (27.35–761,867 g AI/L) for thiamethoxam, respectively. These baseline levels can be used for future insecticide resistance monitoring in *H. halys*.

Key words: Chemical control, insecticide resistance, stink bug, pyrethroids, neonicotinoids

Brown marmorated stink bug, *Halyomorpha halys* (Stål), is an invasive species from Asia that was first detected in the United States in the 1990s in Pennsylvania (Hoebeke and Carter 2003), and has since become established in much of the continental United States as well as Europe, where it has become a significant pest of tree fruit, vegetables, tree nuts, and other crops (Rice et al. 2014, Haye et al. 2015, Leskey and Nielsen 2018). Despite encouraging progress with regards to biological control and integrated pest management (Leskey and Nielsen 2018), insecticides are the most commonly used tools to control this pest on high value horticultural crops, particularly pyrethroids and neonicotinoids (Kuhar and Kamminga 2017). Their use has increased substantially in the eastern United States during the past 8–10 yr that this pest has increased in importance. For instance, Leskey et al. (2012b) reported that some tree fruit growers in the mid-Atlantic United States increased the number of insecticide applications nearly fourfold from 2010 to 2011 to combat *H. halys*. Although pyrethroids and neonicotinoids, such as bifenthrin and thiamethoxam, respectively, have been quite efficacious at controlling *H. halys* (Kuhar and Kamminga 2017), good stewardship dictates that resistance monitoring programs be implemented to detect changes in the susceptibility of populations to these groups of insecticides. Detection of changes in susceptibility of field populations can denote the need for alternative control measures. Bioassays for field-resistance monitoring requires the establishment of reliable susceptible toxicity baselines and/or discernable doses, as a standard of control. This information is currently lacking for *H. halys*. The goal of this project was to obtain baseline data on the susceptibility of *H. halys* adults from multiple populations in the mid-Atlantic United States to bifenthrin and thiamethoxam, two commonly used insecticides to control them. While so doing, we also tested the hypothesis that no sex-related differences in insecticide susceptibility exist.

Materials and Methods

Bioassays

Collections of *H. halys* adults were made in September 2017 from four states (NC, OH, PA, VA) and six states (NJ, NY, NC, OH, PA, VA) in 2018 for bioassays. Adults were separated by sex and exposed individually to bifenthrin (Brigade 2EC, 25.1% bifenthrin, FMC Corporation, Philadelphia, PA) and thiamethoxam

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Plant Stimuli and Their Impact on Brown Marmorated Stink Bug Dispersal and Host Selection

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A diverse diet in polyphagous insects satisfies changing nutritional needs but the choice of host plant may vary throughout the insect and plant life cycle. The behaviors associated with host choice in the immature stages may differ from the egg laying site chosen by the mother. To evaluate this for an important agricultural pest, we looked at host choice over two growing seasons for the invasive *Halyomorpha halys*. *H. halys* has a host breadth of over 170 known species in its invaded range and adults can satisfy nutritional needs through a strong dispersal capacity. Nymphs are more limited in their ability to choose host plants and we investigated if they make a choice that differs from the source plant (to simulate maternal choice) and characterized volatile organic compounds that are present during attraction. In a mark-release-recapture experiment we quantified dispersal and host choice by nymphs to four common vegetable hosts throughout the growing season. Applying an attraction index to quantify host choice we identified that nymphs switch host plants depending on host phenology. Plants with maturing fruits were most attractive. Volatile organic compounds were collected from host plants during the same time period. Multivariate and correlation analyses categorized phenol, undecane, decanal, and caryophyllene as compounds associated with host plants during peak attractive periods. Thus, the availability of suitable food and associated olfactory cues appears to be influencing the spatiotemporal distribution of *H. halys* within the agroecosystem. Exploiting dispersal behavior and olfactory cues may be used to help increase the effectiveness and efficiency of current management practices for this severe and widespread pest.

Keywords: phenology, volatile, attraction, mark-release-recapture, nymph

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INTRODUCTION

Organisms make many "decisions" during their life to maximize reproductive success, which often are at the cost of compromises. Such decisions may encompass how much to invest in growth relative to defense, mate attraction, spatiotemporal reproduction choices, and whether to disperse in search of resources or to hide from endangerment. Most herbivorous arthropods are considered "specialists" because they specialize in obtaining resources from a narrow range of plant species (Strong et al., 1984). For these specialists, appropriate host selection is essential and chemical cues from host plants may provide the information in order to make such host selection decisions (Dicke, 2000). Herbivore host-choice decisions are largely determined by the mothers, which

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Short Communication

Short Communication

Cavity Tightness Preferences of Overwintering *Halyomorpha halys* (Hemiptera: Pentatomidae)

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Abstract

Brown marmorated stink bug (*Halyomorpha halys*) (Stål) is a household nuisance pest that seeks shelter in buildings during the winter months. It has been found in a variety of cavities and spaces between building elements, as well as in the objects stored within buildings. This experiment examined the cavity tightness preferences for these insects as they settled in winter refugia. Adult overwintering *H. halys* were placed in two types of simulated refugia made from rigid material. Each type had a cavity of constant width, while one had a flat lid and constant tightness, and the other had a sloped lid that became tighter as insects moved inside. Adults were allowed to enter and settle, then their locations were recorded. In sloped lid cavities, *H. halys* tended to settle where the cavity tightness was between 4.5 and 5.5 mm. In the flat lid cavity boxes, *H. halys* tended to move all the way back. In both configurations, *H. halys* had a significant tendency to orient their heads towards the cavity entrance. A field comparison of cavity tightness in refugia with less rigid cardboard substrates was also performed, with spacers consisting of one or two layers of 3-mm cardboard. This comparison found differences in cavity selection by sex, with males more likely to pick single-spaced layers, and females more likely to select double-spaced layers. Understanding these preferences could be useful for collection, pest management, trap design, and study of impacts on structures.

Key words: diapause, home invasion, brown marmorated stink bug, urban pest, building envelope

Brown marmorated stink bug, *Halyomorpha halys* (Stål), is a major agricultural pest (Leskey and Nielsen 2018). It is also a major nuisance pest in homes due to its tendency to aggregate on exteriors each fall before entering in search of winter shelter, in numbers as high as tens of thousands (Inkley 2012). Observations of overwintering aggregations suggest that *H. halys* prefer tight spaces (Lee et al. 2014). However, rigid openings exclude most females at 4 mm and most males at 3 mm (Chambers et al. 2019a). The cloth, tarps, and wood piles from which they can be collected have varying and/or flexible opening and cavity sizes. The cavities in old buildings in which they shelter may also vary as buildings settle and warp with moisture and age.

Several kinds of overwintering shelters have been deployed to capture or store *H. halys* for research and management. Taylor et al. (2017) built shelters with a substrate of plastic foundation sheets spaced 1 cm apart, and shelters with substrates of paper towels and corn–starch based packing peanuts. Cira et al. (2016) used 18.9-liter buckets filled with 12.7-mm thick foam pipe insulation for insect storage. A slit trap shelter, used by Watanabe et al. (1994a, b), was a 90- × 180-cm rectangular panel leaning at a 30° angle, with 10-mm thick veneer panels, and three layers of 3-mm slits, though some details are unclear in the available translation. Bergh et al. (2017) described two overwintering shelters for *H. halys*. In one, opaque plastic containers contained concentric tubes of rolled 4.8-mm thick cardboard sheets, with a 5-mm space between layers, and extra space between tubes and outer walls. Insects were placed directly inside. The second design was used for fall collection. It consisted of a plywood box similar to a birdhouse, containing a stack of 3-mm thick cardboard sheets, spaced with strips of 3-mm cardboard, creating 3-mm high cavities, though those varied due to deformations in the cardboard. Spaces between sheets and the outer walls were 13 or 25 mm. This inexpensive and easily built wooden box design has been used by researchers in the mid-Atlantic United States for several years, including the relatively flexible cardboard substrate. However, if this 3-mm spacing were rigid, it would exclude most males and all females (Chambers et al. 2019a), which suggests questions about the tightness preferences of these insects, and optimal substrate spacing.

NOTE

Negative Gravitaxis in Overwintering *Halyomorpha halys* (Hemiptera: Pentatomidae)[1]

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KEY WORDS Structural nuisance pest, brown marmorated stink bug, diapause, home invasion, geotaxis

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is a significant household and agricultural pest (Leskey & Nielsen 2018). Each fall, adult *H. halys* seek overwintering sites in houses and other buildings. Tens of thousands may infest a single home (Inkley 2012). Pest control options against shelter-seeking *H. halys* may include traps and pesticide applications on building exteriors (Watanabe et al. 1994b), and insecticide-treated window screens that can both exclude and kill (Mooneyham et al. 2016). These control methods may require exterior access to upper story features because overwintering *H. halys* are found at various heights above ground level. Watanabe et al. (1994b) found higher capture rates in traps leaning against the wall at ground level than in those under eaves and on roofs. Cambridge et al. (2015) surveyed two four-story college dormitories over a single winter and found significantly more *H. halys* inside the building on the fourth floor than on the first floor. Lee et al. (2014) found more *H. halys* in tree cavities than in fallen logs or leaf litter. It is unclear why some structures had more bugs high above ground and others close to the ground, but site characteristics such as vegetation and structural features may be relevant. For example, Bergh & Quinn (2018) found higher densities on dark panels and door frames, and Watanabe et al. (1994a) suggested that bugs preferred settling in brown or white traps to black ones. Movement patterns can indicate information such as common angles of approach, and what environmental or visual cues *H. halys* could be exposed to as they search for entry points. By better understanding movement patterns of shelter-seeking *H. halys*, control methods can be applied or oriented in more targeted ways.

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Research

Biological and Microbial Control

Parasitism and Predation on Sentinel Egg Masses of Three Stink Bug Species (Hemiptera: Pentatomidae) in Native and Exotic Ornamental Landscapes

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Abstract

This study evaluated parasitism and predation on sentinel egg masses of three stink bug species, the spined soldier bug, *Podisus maculiventris* (Say), the brown stink bug, *Euschistus servus* (Say), and the invasive brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål), in ornamental landscapes composed of either native or exotic plants. This study also compared the species composition of parasitoids attacking two native stink bug species (*P. maculiventris* and *E. servus*) with those attacking the invasive BMSB on the same tree species in the same habitat. Overall, egg parasitism and predation were much higher on the two native stink bug species compared with BMSB, with an average parasitism rate of 20.6% for *E. servus*, 12.7% for *P. maculiventris*, and only 4.2% for *H. halys* and an average predation rate of 8.2% for *E. servus,*17.7% for *P. maculiventris,* and 2.3% for *H. halys*. Egg predation was also significantly higher on *P. maculiventris* than on *E. servus* eggs. Eight parasitoid species attacked sentinel stink bug eggs in the ornamental landscaped plots. *Trissolcus euschisti* (Ashmead) (Hymenoptera: Scelionidae) was the predominant parasitoid for all three stink bug species. There were no significant differences in parasitism and predation rates on any of the stink bug species between native and exotic plots. Therefore, there is no evidence that ornamental landscapes composed of native plants increased parasitism or predation rates of sentinel egg masses of two native stink bug species or the invasive BMSB, compared with those composed entirely of exotic plants.

Key words: parasitoid, biological control, natural enemies, urban landscape

Currently, 55% of the world's population is living in urban areas, and this proportion is projected to increase to 68% by 2050 (United Nations 2018). The loss of habitat and conversion of land to urbanization are major factors in the loss of insect biodiversity (Sánchez-Bayo and Wyckhuys 2019). Therefore, the management of urban areas to enhance biodiversity is of critical importance. The increasing popularity of urban agriculture and horticulture in major cities will be an important component in maintaining biodiversity as urbanization continues to expand (Benis and Ferrão 2018). Urban landscapes often comprise a mosaic of native and exotic plant and arthropod species. Native plants can increase the abundance and biodiversity of herbivorous insects (Narango et al. 2017, Richard et al. 2019). The increased abundance of caterpillars in native habitats provided better foraging for chickadees which were more likely to build nests and breed in yards with native plants than in those with nonnative plants (Narango et al. 2017).

Studies of the impact of exotic plants on arthropod natural enemies have found mixed results. Simao et al. (2010) showed that there was a 61% reduction of natural enemies in plots with invasive grass compared with plots with native grass. Fiedler and Landis (2007) found selected native perennials to be more attractive to natural enemies than were selected annual exotic plants, due to their nectar and pollen resources. Gibson et al. (2019) found that 32 species of native perennial flowering plants attracted more natural enemies than two nonnative species. However, in another study, the abundance of ants was higher on exotic thistles compared with native plants due to higher population densities of aphids on the invasive plants (Lescano and Farii-Brener 2011). Frank et al. (2019) found the abundance and diversity of predators and parasitoids were

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Short Communication

Short Communication

Influence of Landscape Factors and Abiotic Conditions on Dispersal Behavior and Overwintering Site Selection by *Halyomorpha halys* (Hemiptera: Pentatomidae)

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Abstract

Since the initial detection of the invasive *Halyomorpha halys* (Stål) in the United States in the late 1990s, this insect has emerged as a severe agricultural and nuisance pest. Nuisance problems are due to adult dispersal to overwintering sites in the fall at which time they alight onto and eventually settle within human-made structures in addition to natural harborage. This study examined how three factors, elevation, light, and moisture affected overwintering site selection by *H. halys* in the mid-Atlantic. Observational counts performed along elevational transects revealed elevation was significant predictor of *H. halys* abundance during both years of the study in 2014 and 2015 with more adults observed at higher elevations. Choice tests examining effects of moisture and light on settling behavior demonstrated *H. halys* settled within overwintering shelter boxes in significantly greater numbers when shelters were dry compared with those having moist conditions, and in darkened shelters compared with those augmented with LED lights. Our findings indicate that *H. halys* use cues at both landscape and very localized levels when seeking and selecting overwintering sites.

Key words: brown marmorated stink bug, overwintering, behavior

Halyomorpha halys (Stål), the brown marmorated stink bug, is an invasive species native to Asia that was initially detected in the United States in Pennsylvania in the late 1990s (Hoebeke and Carter 2003). This species has emerged as a severe agricultural pest resulting in significant economic losses in crop quality, insecticide management costs, and overall yield in the United States and Europe (Leskey and Nielsen 2018). Research has focused primarily on managing these significant agricultural issues generated by *H. halys*, although issues associated with *H. halys* as a nuisance pest remain problematic (Ludwick et al. 2020). Problems posed by *H. halys* to homeowners and businesses can be extreme; Inkley (2012) reported that during a 6-mo period (January–June), over 26,000 *H. halys* were removed from a single dwelling. Based on a survey of homeowners, although <2% of respondents reported numbers at a similar scale to Inkley (2012), over 34% reported problems as being 'bad' or 'horrible' despite most having fewer than 100 individuals in their homes (Ludwick et al. 2020). Therefore, having even limited numbers of invading adult *H. halys* is considered problematic by homeowners.

In the mid-Atlantic, *H. halys* disperse to overwintering sites throughout September and into mid-October, with peak dispersal occurring close to the fall equinox (Bergh and Quinn 2018). Observations in Japan indicate ridge tops have higher numbers of dispersing adults in the fall (Watanabe 1994, Lee et al. 2013), and though similar anecdotal observations have been made in the United States, they have never been quantified. These findings and observations suggest landscape factors may play a role in initial overwintering location selection by dispersing *H. halys*. Moreover, what happens after reaching potential overwintering locations is not well understood. In natural landscapes, *H. halys* have been found overwintering in dry, protected areas, such as under bark of dead standing trees (Lee et al. 2014). However, in human-made dwellings,

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Research

OXFORD

Physiological Ecology

Temperature and Humidity Interact to Influence Brown Marmorated Stink Bug (Hemiptera: Pentatomidae), Survival

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Abstract

High-temperature events can influence insect population dynamics and could be especially important for predicting the potential spread and establishment of invasive insects. The interaction between temperature and environmental humidity on insect populations is not well understood but can be a key factor that determines habitat range and population size. The brown marmorated stink bug, *Halyomorpha halys* (Stål), is an invasive agricultural pest in the United States and Europe, which causes serious economic damage to a wide range of crops. This insect's range continues to expand. It has recently invaded the Central Valley of California, which has a hotter and drier climate compared with the Eastern United States where this insect is established. We investigated how high-temperature events and relative humidity would impact the survival and reproduction of *H. halys.* Using incubators and humidity chambers, we evaluated the impact of humidity and short-term (2 d) high-temperature exposure on the survival and development of *H. halys* eggs, nymphs, and adults. We found that high temperatures significantly reduced *H. halys* survival. The impact of humidity on *H. halys* survival was dependent on temperature and life stage. Low humidity decreased first-instar survival but not third- to fourth-instar survival. High humidity increased first instar survival but decreased third- to fourth-instar survival. Humidity did not influence adult or egg survival. We also found that high temperatures decreased *H. halys* reproduction. Our findings have important implications for understanding the invasive ecology of *H. halys* and may be used to improve models predicting *H. halys* range expansion.

Key words: brown marmorated stink bug, heatwave, environmental humidity, climate change, invasive

Increasing environmental temperatures are predicted to significantly influence insect pest population dynamics and the ability of insects to invade new habitats (Cammell and Knight 1992, Bale et al. 2002, Deutsch et al. 2018). Heatwaves, which are short, extreme high temperature events that occur over multiple days, are projected to increase in frequency across the globe (Perkins and Alexander 2012, Perkins et al. 2012). Environmental humidity can influence insect pest population dynamics, but it is not well understood how humidity can influence the effect of temperature on invasive pest populations (Chown et al. 2011).

The brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål), is an invasive pest, native to China, Japan, Korea, and Taiwan (Hoebeke and Carter 2003, Lee et al. 2013) that has become a serious agricultural and nuisance pest in the United States, Canada, and Europe (Rice et al. 2014, Leskey and Nielsen 2018). The insect was introduced into the Eastern United States in the mid-1990s, where it has caused over $37 million U.S. dollars in loss in 1 yr-2010, in the Eastern U.S. specialty tree fruit industries (Leskey et al. 2012). *Halyomorpha halys* has a wide host range of over 179 species in over a dozen families (Leskey and Nielsen 2018) and was first reported in California in 2002 (Lara et al. 2016). In California, *H. halys* has been predominately an urban nuisance pest until 2016 when a breeding population was first found in a peach, *Prunus persica* ((L.) Batsch) (Rosales: Rosaceae) orchard in Stanislaus County (Rijal and Duncan 2017) and in 2018 and 2019, *H. halys* caused severe damage in several almond, *Prunus dulcis* (Mill.) (Rosales: Rosaceae) orchards (Rijal and Duncan 2017). Climate based habitat suitability models predict that *H. halys* will continue to expand into Western states including California (Zhu et al. 2012, 2017; Kriticose et al. 2017) though the climate is predicted to be less suitable for *H. halys* in California compared to the Eastern United States. *Halyomorpha halys* has the potential to cause substantial damage to California agriculture due to its wide host range and ability to cause severe damage to almonds (Rijal and Gyawaly 2018), which is a 5.5-billion-dollar

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Ecology and Behavior

Effects of Aggregation Lure and Tree Species on *Halyomorpha halys* (Hemiptera: Pentatomidae) Seasonal Oviposition

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Abstract

The brown marmorated stink bug, *Halyomorpha halys* (Stål), is a polyphagous pest that feeds on a wide variety of agricultural commodities including tree fruits, berries, vegetables, field crops, and ornamental trees and shrubs. Accurate knowledge of where *H. halys* lays eggs is critical to optimize the potential release of *Trissolcus japonicus* (Ashmead), a scelionid egg parasitoid native to the same host region as *H. halys*. Ideally, parasitoids should be released in and around areas with high host density. In southwestern Virginia in 2017 and 2018, we searched trees for egg masses in an urban environment and nonmanaged wooded border environment. We also evaluated the effects of a commercial aggregation lure on the number of eggs being deposited. This aggregation lure, when combined with methyl (*E*,*E*,*Z*)-2,4,6-decatrienoate (MDT), has been shown to attract both adult and nymph *H. halys* and its effects on egg laying were not known. Results of this study showed no difference between the number of eggs laid on trees with and without lures. Catalpa trees, *Catalpa bignonioides* Walter, had the most egg masses throughout the course of the study; however, the redbud, *Cercis canadensis* L., had similar numbers in the late July and August. There was an overall trend with more eggs masses found on trees with fruiting structures present. This information can provide insight on where and when to make augmentative releases of egg parasitoids for *H. halys*.

Keywords: Brown marmorated stink bug, ornamental host, aggregation lure, oviposition

Native to East Asia, *Halyomorpha halys* (Stål) is an invasive stink bug pest that is rapidly spreading throughout North America and Europe (Haye et al. 2015, Leskey and Nielsen 2018). Since its arrival in the United States in the 1990s (Hoebeke and Carter 2003), from a population likely originating from Beijing, China (Xu et al. 2014), *H. halys* has caused millions of dollars of economic loss to a variety of commodities including tree fruit, vegetables and row crops (Leskey et al. 2012, Rice et al. 2014).

The accelerated rate of its spread and the extent of the economic damage it causes is due, in part, to a host range of over 170 plants (Leskey and Nielsen 2018). The ability to feed on a variety of hosts enables *H. halys* to move from one plant to the next as fruiting structures and more suitable food become available (Zobel et al. 2016). High numbers of *H. halys* adults seek shelter in human dwellings and buildings, then move to suitable host plants in the spring to begin feeding and reproduction (Bergmann et al. 2016). Knowing what plants *H. halys* is primarily feeding and ovipositing on in the landscape is useful for monitoring and developing crop-specific scouting plans in new regions (Bakken et al. 2015).

In this study, we surveyed host trees in Montgomery County, Virginia that *H. halys* may deposit eggs on over its reproductive period (May through late Aug/early Sep). Tree species were chosen based on a prior study exploring the range of tree hosts in this geographic area (Bakken et al. 2015) and the predominance of each species in the landscape. To determine if these ovipositional trends could be manipulated by semiochemicals, commercial *H. halys* aggregation pheromone lures were added to half of the trees. It is not known whether lures influence *H. halys* oviposition preference. The results of this study may augment biological control efforts for *H. halys*, in particular, adventive populations of the egg parasitoid *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae). This species is capable of parasitizing *H. halys* egg masses in its native range at rates of almost 80% (Yang et al. 2015). This parasitoid has been detected in several states in the United States (Talamas et al. 2015, Herlihy et al. 2016, Hedstrom et al. 2017, Hoelmer and Tatman 2017), and efforts to distribute field-collected and lab-reared *T. japonicus* are in progress at the time of this manuscript. Thus, knowledge of where

insects

MDPI

Article

Hidden Host Mortality from an Introduced Parasitoid: Conventional and Molecular Evaluation of Non-Target Risk

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Simple Summary: Classical biological control (CBC), i.e., the release of a natural enemy from the pest's native range, has long been recognized as a viable approach to controlling invasive pests. CBC is considered specific to a given pest and does not come with the environmental risks often associated with broad-spectrum chemical pesticides. However, an exotic natural enemy may pose environmental risks, specifically to native species that are not the target of the biological control program. Some effects of an exotic natural enemy, such as consumption or reproduction, can be measured more readily than others. Our research points out that some of these 'hidden effects' can be quite important and merit our attention. We use molecular tools and modeling to help understand the hidden effects both for the target and non-target species. Our model system was an invasive fruit and vegetable pest from Asia, the brown marmorated stink bug (BMSB), *Halyomorpha halys*, and an exotic parasitoid, *Trissolcus japonicus*. *T. japonicus* has become established in North America and could help limit outbreaks of this pest. Unfortunately, it also kills non-target stink bugs with varying degrees of reproductive success, which may have both direct and indirect ecological effects on *H. halys* and non-target stink bug species.

Abstract: Hidden trophic interactions are important in understanding food web ecology and evaluating the ecological risks and benefits associated with the introduction of exotic natural enemies in classical biological control programs. Although non-target risk is typically evaluated based on evidence of successful parasitism, parasitoid-induced host mortality not resulting in visible evidence of parasitism (i.e., nonreproductive effects) is often overlooked. The adventive establishment of *Trissolcus japonicus*, an exotic parasitoid of the introduced stink bug *Halyomorpha halys*, provides an opportunity to investigate the total impact of this parasitoid on target and non-target hosts in the field. We developed a new methodology to measure nonreproductive effects in this system, involving a species-specific diagnostic PCR assay for *T. japonicus*. We applied this methodology to field-deployed eggs of four pentatomid species, coupled with traditional rearing techniques. Nonreproductive effects were responsible for the mortality of an additional 5.6% of *H. halys* eggs due to *T. japonicus*, and were even more substantial in some of the non-target species (5.4–43.2%). The observed hidden mortality of native non-target species from an introduced parasitoid could change predictions about direct and indirect ecological interactions and the efficacy of biological control of the target pest.

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Research

Plant-Insect Interactions

Host Plant Signal Persistence in the Gut of the Brown Marmorated Stink Bug (Hemiptera: Pentatomidae)

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Abstract

Determining the host range of an invasive insect in a new environment is a key step in the development of management strategies. As the brown marmorated stink bug, *Halyomorpha halys* Stål, expands into agricultural regions of North America, efforts to elucidate its dietary habits on a landscape scale rely on intensive sampling of potential host plants. Although this approach yields useful information, results can be biased toward common and easily sampled plant species; important hosts can be missed if sampling them is impractical or limited in scope. Here we lay the groundwork for the application of gut content analysis to the feeding ecology of *H. halys* by investigating the persistence of host plant DNA in the digestive tracts of insects with known feeding histories. Adult *H. halys* were fed bean seedlings (*Phaseolus lunatus* L.) for 7 d, followed by a forced host switch to carrot (*Daucus carota* L.). Insect guts were dissected out at 0, 1, 3, 7, and 14 d following the switch, and host plant chloroplast genes (*trnF* and *trnL*) were amplified via polymerase chain reaction. Amplicons were identified using high-throughput sequencing and analyzed for *Phaseolus* DNA. The original host remained detectable at 3 d (*trnF*) and 14 d (*trnL*) in substantial quantities. The proportion of total reads identified as *Phaseolus* rapidly decreased with time; a concomitant increase in *Daucus* reads was observed. Our results indicate that high-throughput sequencing of gut contents has great potential for exploring the dietary histories of field-caught *H. halys* and other phytophagous insects.

Key words: gut content analysis, polyphagy, trnF, trnL, high-throughput sequencing

When an invasive insect pest is first detected in a new region, one of the first priorities of researchers seeking to develop management strategies is to determine how or whether its ecology differs from that in its previously known range. For phytophagous insects, this research focuses on determining the host plants, known or novel, that the pest can utilize in its new environment (e.g., Asplen et al. 2015, Bakken et al. 2015, Liu 2019). Host range studies typically rely on observing feeding behavior directly (Barone 1998), collecting and rearing insects on suspected hosts (Dyer et al. 2007), or surveying likely vegetation for the presence of the pest and inferring host status from the presence of the insect (Erwin 1982, Bergmann et al. 2016, Liu 2019). Plants associated with multiple life stages of the insect are inferred to be 'key' or 'developmental' hosts (Bergmann et al. 2016). While certainly valuable, these association-based studies are at risk of missing potentially important hosts that are undersampled due to their rarity or inaccessibility (e.g., uncommon species or tall trees), misinterpreting the presence of insects on nonfood hosts, or failing to detect the insect because of its cryptic coloration or evasive behaviors (De la Cadena et al. 2017). This risk is heightened when the insect in question is highly polyphagous and frequently moves between hosts. Furthermore, surveys are incapable of tracking all but the most general patterns of host use over time; determining the feeding histories of individual insects is generally not feasible.

Gut content analysis (GCA) has emerged as an alternative tool for determining the host range of both phytophagous and predatory insects with greater accuracy than classical methods (Zhu et al. 2019). In addition to being less labor intensive, GCA has the benefit of showing only those species that were ingested, providing a clearer picture of food plant utilization. Specifically, the adaptation of gene sequencing technology to insect GCA has permitted the generation of detailed feeding histories without the need for the host plant- or prey-species-specific primers required by conventional methods (e.g., Symondson 2002, Pumarino et al. 2011, Wallinger et al. 2012, Wang et al. 2017, Lantero et al. 2018), the selection of which presupposes knowledge of potential hosts. The study of phytophagous insect feeding habits has therefore benefited immensely from the development of 'universal' plant primers. These primers allow the amplification of highly conserved regions of the plastid genome (e.g., *trnF* and *trnL*) that can be sequenced and consistently identified to the genus or species level (Taberlet et al. 1991, Tsai et al. 2006, Taberlet et al. 2007, Navarro et al. 2010, Cooper et al. 2019, Avanesyan and Lamp 2020).

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RESEARCH ARTICLE

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Urban host plant utilisation by the invasive *Halyomorpha halys* (Stål) (Hemiptera, Pentatomidae) in northern Utah

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Abstract

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

Keywords

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

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Research Article

Surveys in northern Utah for egg parasitoids of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) detect *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae)

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Abstract

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

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Flowering *Chamaecrista fasciculata* borders enhance natural enemy populations and improve grain quality in field corn

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A R T I C L E I N F O

Keywords:
Conservation biological control
Parasitism
Partridge pea
Insectary
Natural enemies
Floral border

A B S T R A C T

Plants with floral resources are advocated to enhance natural enemy density and efficacy in conservation biological control systems. Field experiments were conducted to examine the ability of partridge pea (*Chamaecrista fasciculata*) planted along two borders of organic field corn (*Zea mays*) plots to attract natural enemies and enhance biological control, yield and profit. Partridge pea significantly increased natural enemy abundances, including parasitoid and predators; however, some key natural enemy and target pest abundances within field corn were unaffected. Crop damage was reduced, and grain quality improved significantly in corn adjacent to partridge pea compared with corn plots without partridge pea. Despite these benefits, there was no economic gain with respect to improved corn yields or increased profits.

1. Introduction

Increasing crop complexity by cover cropping, intercropping, planting flowering borders, or establishing beetle banks can be used to manage arthropod pests and limit environmental disruption (González-Chang et al., 2019; Hooks et al., 2013; Koji et al., 2007; Landis et al., 2000; Morandin et al., 2016; Pease and Zalom, 2010; Tschumi et al., 2016b). Growing floral resources that enhance natural enemies of crop pests may reduce the need for synthetic inputs, while improving crop productivity (Begg et al., 2017; Gurr et al., 2003). Increasing vegetation biodiversity within arable lands can also provide additional ecosystem services such as pollination, conserving plant and animal species, enhancing recreational opportunities, improving aesthetics, and preventing erosion and nutrient runoff across landscapes (Fiedler et al., 2008; Garratt et al., 2017; Gurr et al., 2003; Holland et al., 2017). However, studies investigating effects of floral resources and other habitat complexity methods on agroecosystems thus far have focused mainly on herbivore and natural enemy abundances. Few have included a complete assessment of their impact on crop quality, yield and profits, or provided an economic assessment of cost for farmer adoption (Cullen et al., 2008; Jonsson et al., 2015; but see Morandin et al., 2016; Tschumi et al., 2016a).

It is well documented that plant-derived provisioning can enhance biological control of pests (Balmer et al., 2014; Géneau et al., 2012; Holland et al., 2016; Tschumi et al., 2015). Insectary plantings, which are plants grown to attracts insects, can increase the abundance of parasitoids and predators when planted near grain (Jonsson et al., 2010; Zehnder et al., 2007), fruit and vegetable (Manandhar and Wright, 2016; Morandin et al., 2014; Ribeiro and Gontijo, 2017; Tschumi et al., 2016b), and orchard crops (Campbell et al., 2017; Irvin et al., 2006; Stephens et al., 1998). Floral resources can increase natural enemy longevity and/or fecundity by providing them food, favorable habitat, refuge and a source of alternative prey (Begum et al., 2006; Irvin et al., 2006; Lavandero et al., 2006; Russell, 2015; Winkler et al., 2006). In addition, the availability of nectar has been posited to increase pest suppression by parasitoids by improving their searching efficacy (Lavandero et al., 2006).

However, not all flowering plants are equally attractive to natural enemies and the presence of additional floral resources does not guarantee enhanced biological control and subsequent pest suppression within crops. For example, beneficial arthropods attracted to resource provisioning plants may fail to forage in neighboring crops. These plants may act as a natural enemy sink rather than a source by attracting natural enemies that would otherwise forage within the crop (Denys and Tscharntke, 2002; Koji et al., 2007; Moore et al., 2019). Plants with floral resources can alternatively behave as trap crops by attracting and retaining pests, subsequently reducing their populations in nearby crops (Balzan et al., 2014; Mizell et al., 2008; Swezey et al., 2007). Floral resources may also unintentionally enhance the fitness of herbivorous pests, thereby enhancing their populations (Baggen and Gurr, 1998;

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Nosema maddoxi infecting the brown marmorated Stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in the Republic of Georgia

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ABSTRACT

Halyomorpha halys is an invasive, polyphagous stink bug from Asia, first reported attacking hazelnut orchards in the Republic of Georgia in 2015. A microsporidian pathogen discovered in Georgian *H. halys* has been identified as *Nosema maddoxi* by sequencing the ribosomal small subunit gene. *Nosema maddoxi* is native to North America and has also been found in China and South Korea; in North America it infects native stink bugs and *H. halys*. Investigations were carried out during different seasons in three regions of West Georgia in 2018–2019. The highest prevalence of *N. maddoxi* was detected among overwintered adults collected in May in the Guria region.

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Microsporidia; entomopathogen; invasive species; natural enemy

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) (BMSB), is a polyphagous insect species impacting agriculture and forestry. It is native to China, Taiwan, Japan, and the Korean Peninsula. It was first collected invading North America in 1998 and since then has spread within the US (Hoebeke & Carter, 2003; Leskey et al., 2012) and has also been found in Europe (Callot & Brua, 2013; Haye et al., 2015; Wermelinger et al., 2008), and South America (Faúndez & Rider, 2017). *Halyomorpha halys* was first observed in the Samegrelo region, in West Georgia, in 2015 and later spread to the Guria and Imereti regions (Kereselidze et al., 2019). In Georgia, *H. halys* feeds on many agricultural plants, but significant damage has been caused in hazelnuts (*Corylus avellanae* L.), the most important, and most profitable crop. The estimated economic impact of *H. halys* to Georgian hazelnut production in 2016 was approximately US$52.7–68.6 million (see Murvanidze et al., 2018). *Halyomorpha halys* is also a nuisance problem in Georgia, as in other invaded areas (Leskey & Nielsen, 2018).

To develop biological control strategies, natural enemies associated with *H. halys* are being investigated. In 2017, a new microsporidian pathogen, *Nosema maddoxi* Becnel, Solter, Hajek,

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The effects of relative humidity on *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) egg hatch, nymph survival, and adult reproduction

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The brown marmorated stink bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae), originally from South Korea, Japan, and eastern China, was discovered recently in the USA (Hoebeke & Carter 2003; Hamilton 2009) and has since spread throughout most of eastern and western North America (Rice et al. 2014). As of Jun 2019, only 1 limited population has been detected in Lake County, Florida, USA (Penca & Hodges 2018). However, 36 interceptions were recorded at Florida Agricultural Inspection Stations prior to Feb 2016 (S. Halbert, Florida Division of Agriculture and Consumer Services, Division of Plant Industry, personal communication). The potential for *H. halys* to establish in other areas of Florida depends on various environmental factors, including atmospheric moisture. We tested 15 to 90% RH at 25 °C on egg hatch, nymph survival, and adult reproduction to determine if *H. halys* could establish in Florida.

The current project was conducted in the quarantine laboratory at the University of Florida, Entomology and Nematology Department, Gainesville, Florida, USA, using an *H. halys* colony established with about 95 egg clutches obtained from a colony maintained for several yr at the USDA, ARS Crop Protection and Management Research Laboratory, Tifton, Georgia, USA. Rearing procedures were adapted from Medal et al. (2012), and maintained in the laboratory at 25 **±** 3 °C, 55 ± 3% RH, and a 16:8 h (L:D) photoperiod. The insects were reared for 1 generation in Gainesville before either eggs, nymphs, or adults were placed into an 18 cm diam by 7.5 cm high plastic container for the tests. Containers were placed inside a reach-in environmental chamber maintained at 25 ± 3 °C with a 16:8 h (L:D) photoperiod provided by 32 W and 3,500 K lights mounted on a stand in front of the chambers (Ecolux XL Starcoat®, GE Lighting, Cleveland, Ohio, USA) (Niva & Takeda 2003). Lights were turned on at 4:00 A.M. and off at 8:00 P.M. The RH was maintained at 15%, 35%, 55%, 75%, or 90% provided by glycerol-water solutions of 390:8, 350:58, 302:119, 230:211, and 135:330, respectively. Salt solutions could have been used to maintain RH levels at constant temperatures (Winston & Bates 1960) but glycerol solutions are relatively independent of temperature (Soderstrom et al. 1990; Forney & Brandl 1992). A constant flow of humidified air was pushed from a flask containing a glycerol solution into the test container by an aquarium pump (Graystone Creations, Cleveland, Georgia, USA) (0.014 MPa air pressure and 0.00015 m^3 per s air vol). Hobo software (Onset®, Cape Cod, Massachusetts, USA) was used to record temperature and RH inside the containers.

The stink bug stages to be tested were removed randomly from the colony and exposed to each RH in the test container. A single clutch containing 25 to 28 eggs was used for each egg hatch test. To further randomize the eggs, single clutches were divided into 5 approximately equal samples, and single samples were placed into the test container. The number of eggs that hatched and survived to third, fourth, fifth instar or adults were recorded after 7 d. A more precise nymph survival test was conducted by removing 6 second instar nymphs from the colony and placing them in a test container where they were fed peanuts and beans, then observed daily until they died or eclosed as adults. To test the effect of RH on reproduction, 2 males and 2 females were taken from the colony, marked with different dye colors (Testors®, Vernon Hills, Illinois, USA), placed in a test container, then exposed to 1 of the 5 RH treatments for 10 d. Adult survival and number of eggs oviposited were recorded. All tests were repeated 6 times and data analyzed by 1-way ANOVA with means compared by Tukey- Kramer HSD (RStudio 2012). Differences were considered significant at $P \leq 0.05$.

There was no significant difference in the percentage of egg hatch for whole and divided clutches for each RH (Fig. 1). However, significantly more eggs hatched at 55%, 75%, and 90% RH than at 15% and 35%. At 55%, 75%, and 90% RH, mean hatch was 85%, 81%, and 88% for whole clutches, and 83%, 87%, and 92% for divided clutches, respectively. Survival of nymphs from divided clutches was greater than from whole clutches at 55% and 75% RH, but not at 15%, 35%, or 90%. At 55% and 75% RH, respective mean nymph survival was 72% and 68% for whole clutches, and 75% and 77% for divided clutches, respectively.

Survival of the 6 second instar nymphs to the third instar was highest at 55%, 75%, and 90% RH, averaging 6.0, 5.5, and 5.1, respectively (Fig. 2). At these same relative humidities, mean survival to the fourth instar was 5.8, 4.8, and 4.6, and to the fifth instar was 4.5, 2.8, and 3.0, respectively. Second instar nymphs survived to the adult stage only under 55%, 75%, and 90% RH, and averaged 2.5, 1.3, and 0.8, respectively.

On the average, significantly more egg clutches (12.0 ± 0.3) were laid at 55% RH compared with 35%, 75% at 4.0 ± 0.2 each, whereas 90% RH produced only a mean of 1.0 ± 0.2. No eggs were laid at 15% RH. The respective mean numbers of egg clutches oviposited at 35%, 55%, 75%, and 90% RH were 4.0 ± 0.2, 12.0 ± 0.3, 4.0 ± 0.2, and 1.0 ± 0.2.

Clearly, *H. halys* could establish and proliferate within the range of RH that occurs in Florida, exhibiting a wide host range that would

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Insecticide Treated Nets as an Alternative Tool to Manage Brown Marmorated Stink Bug, *Halyomorpha halys* (Stal).

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Introduction: The brown marmorated stink bug (BMSB) *Halyomorpha halys* (Stäl) (Hemiptera -- Pentatomidae) continues to pose challenge for combining effective pest management with principles of Integrated Pest Management (IPM). With the broad-spectrum insecticides still representing the most effective tools to reduce the risk of fruit injuries, the use of such compounds frequently jeopardizes the role of beneficial organisms, normally controlling a plethora of other insect pests. The utilization of long-lasting insecticide incorporated nets "ghost trap" as a version of the Attract and Kill (A&K) strategy proved very promising in reducing the reliance on pesticides to reduce fruit injury caused by BMSB. Starting from the 2016 season we evaluated various nets baited with commercial BMSB attractants as a potential tool for use in the BMSB A&K programs. The utilization of alternative methods to manage BMSB resulted in comparably efficient management of target pest and reduction of toxic effect of pesticide applications on biological control agents present in orchards. Our field observations identified species of native parasitic wasps such as *Anastatus* spp., *Telenomus* spp., and *Trissolcus* spp. attempting to attack BMSB eggs, but also the presence of samurai wasp, *Trissolcus japonicus* (Ashmead), a BMSB specific parasitoid. The presence of this species in Pennsylvania orchards provides a much better chance for successful biological control of this pest. During the 2019 season, the main objectives of our field research included: a) evaluation of the practical field effectiveness of insecticide treated net "ghost traps", and b) evaluation of the most practical and cost-effective options for practical utilization of nets against BMSB.

Materials and methods: During the 2019 season we conducted field trials with two long-lasting insecticide treated nets: black color D-Terence® nets (Vestergaard, Lausanne, CH) net treated with deltamethrin and a white color MiraNet® (AtoZ Textile Mills, Arusha, TZ) treated with alpha-cypermethrin. The practical effectiveness of the nets in field settings and the impact of net age and size on capture of BMSB were evaluated in the field settings, while the impact of BMSB exposure to the nets on bug's mortality was evaluated under a laboratory conditions.

Evaluate the practical field effectiveness of "ghost traps' ...- the "ghost trap" strategy with the D-Terence nets was evaluated in two commercial orchards settings. The "ghost traps" were placed outside of the orchard at a distance about 150 ft, close to the potential sources of BMSB influx with the goal to not only to arrest the movement of BMSB toward orchard but also to attract BMSB from an orchard. Standard BMSB monitoring traps (Rescue ® traps, Sterling International, Inc. Spokane, WA) baited with Pherocon BMSB Dual lure (Trece, Inc, Adair, OK) were

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Case Study

OXFORD

Invasion of the Brown Marmorated Stink Bug (Hemiptera: Pentatomidae) into the United States: Developing a National Response to an Invasive Species Crisis Through Collaborative Research and Outreach Efforts

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Abstract

Halyomorpha halys (Stål), the brown marmorated stink bug, is a globally invasive stink bug species. Its first major outbreak was in the United States, where it has caused millions of dollars in damage, threatened livelihoods of specialty crop growers and impacted row crop growers, and become an extreme nuisance pest in and around dwellings. The BMSB IPM Working Group, funded by the Northeastern IPM Center, was central to providing a mechanism to form a multidisciplinary team and develop initial and subsequent research, Extension, regulatory and consumer priorities. Ultimately, a project team consisting of over 50 scientists from 11 institutions in 10 states obtained the largest ever USDA-NIFA Specialty Crop Research Initiative CAP grant, totaling over $10.7 million, to tackle this crisis over a 5-yr period (2011–2016). Researchers and Extension educators integrated stakeholder feedback throughout the course of the project, and priorities evolved according to needs of affected growers and public stakeholders. Initially, the team focused on identification of *H. halys*, its damage symptoms and crop-specific risks, and short-term mitigation strategies for crop protection. Subsequently, work focused on its biology, ecology, and behavior leading to the development of potential longer-term IPM tactics and landscape level management solutions, including biological control. This work continues under a second SCRI CAP grant (2016–2021). The information from the initial team reached an estimated 22,000 specialty crop stakeholder contacts via Extension

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Research

Biological and Microbial Control

Impact of Temperature Storage Conditions of *Halyomorpha halys* (Hemiptera: Pentatomidae) Eggs on Parasitism by *Anastatus reduvii* (Hymenoptera: Eupelmidae)

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Abstract

Brown marmorated stink bug, *Halyomorpha halys* Stål, is an invasive species of Asian origin that is an important agricultural pest in the eastern United States. Sentinel egg masses are tools used to assess the impact of natural enemies on *H. halys* populations. To determine the effect of host egg age and storage conditions on their susceptibility to parasitism, *H. halys* eggs were stored at different temperatures for different lengths of time and then exposed to *Anastatus reduvii* (Howard), a native natural enemy of *H. halys* occurring in eastern North America. For eggs stored at 15, 20, and 25°C and then exposed to *A. reduvii*, the number of host eggs from which parasitoid offspring emerged declined with age of eggs. Control eggs (exposed to parasitoids without being stored) and those eggs stored for only 5.5 degree-days (DD) (=0.5 days) at 25°C yielded the highest percentage of parasitoids at 88.2 and 88.3%, respectively. For eggs stored at 20 and 25°C for 7.3 DD to about 36 DD, offspring emerged from about 58 to 73% of eggs, and total parasitism (emerged + unemerged parasitoids) ranged from about 70 to 80%. Parasitoid emergence was significantly lower for host eggs stored at 15°C for comparable times at 20 and 25°C. Stink bugs nymphs hatched from <0.6% of all eggs. Parasitoid-induced host egg abortion was an important component of egg mortality caused by *A. reduvii*, with underdeveloped stink bug nymphs, undifferentiated cell contents, and parasitoid host feeding occurring across all storage treatments.

Key words: brown marmorated stink bug, egg parasitoid, native natural enemy, parasitoid-induced host egg abortion

The brown marmorated stink bug (*Halyomorpha halys* Stål) was accidentally introduced into the mid-Atlantic region of the United States from Asia in the 1990s, and has spread throughout the region causing crop damage and increased control costs for many specialty crop producers (Hoebeke and Carter 2003, Leskey et al. 2012). Understanding the ecology of this exotic pest has been a priority in efforts to develop management strategies, including research into the role of predators and parasitoids on *H. halys* populations in its introduced range. The deployment of *H. halys* sentinel egg masses has been widely used to identify and estimate the impact of native natural enemies on *H. halys* populations in a diversity of managed and non-managed habitats (e.g., Haye et al. 2015, Cornelius et al. 2016, Herlihy et al. 2016, Morrison et al. 2016, Ogburn et al. 2016, Abram et al. 2017, Dieckhoff et al. 2017, Jones et al. 2017, Zhang et al. 2017, Pezzini et al. 2018). They have also been used to detect non-native parasitoids in the stink bug's invaded range, such as *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) (Talamas et al. 2015, Milnes et al. 2016, Abram et al. 2019, Kaser et al. 2019).

Halyomorpha halys sentinel egg masses will continue to be an important tool used in assessing parasitism and predation of stink bug eggs, to provide baseline data and indications of parasitoid population changes, and to monitor for exotic parasitoids and *T. japonicus* population expansion. Using eggs of uniform age that exhibit a consistent response to parasitism and/or predation is important in interpreting results from sentinel egg deployment. The suitability of host eggs for successful parasitism often declines with age of the egg (Spínola-Filho et al. 2014, Yang et al. 2018, Stahl et al. 2019), and for this reason *H. halys* eggs no more than 48 h old have been commonly used in sentinel egg studies. However, it is often a challenge to maintain stink bug colonies of sufficient size to produce enough fresh *H. halys* egg masses of uniform age to deploy

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Biological control of *Halymorpha halys* (Stål) (Hemiptera: Pentatomidae) in apple orchards versus corn fields and their adjacent woody habitats: High versus low pesticide-input agroecosystems

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A B S T R A C T

Halymorpha halys is an invasive pest in the USA that inflicts damage to specialty crops, and conventional growers have increased use of broad-spectrum insecticides to manage this pest. The impacts of pest management programs on natural enemies of *H. halys* were examined in high vs. low intensity insecticide input agroecosystems in western North Carolina (USA). Apple orchards and corn fields, with their adjacent wooded habitats, served as the high and low-input environments, respectively. Sentinel egg masses and yellow sticky cards were deployed in these agroecosystems to compare predation and parasitism on *H. halys* eggs, and presence, abundance, and richness of natural enemies. A total of approximately 85% of all sentinel eggs deployed in apple orchards in both 2018 and 2019 produced a healthy stink bug nymph, higher than all other habitats. A total of 26.6% and 32.9% of eggs deployed in wooded habitats bordering corn exhibited mortality due to natural enemy attack in 2018 and 2019, respectively. Comparatively, eggs deployed in apple borders had 10.0% and 17.8% of total eggs killed by natural enemies, in 2018 and 2019, respectively. Corn agroecosystems generally had greater predation and parasitism of sentinel eggs, and greater richness and abundance of predators detected on yellow sticky cards compared to apple agroecosystems. Wooded habitats bordering crops serve as population reservoirs for *H. halys,* allowing for egg laying and dispersal into crops. If these areas are protected as refuge areas free from insecticide drift, such as from apple orchards, they can also harbor thriving natural enemy populations that could reduce populations of *H. halys.* Wooded areas free from harsh broad-spectrum insecticides are an important component for successful conservation and augmentative biological control in neighboring crops.

1. Introduction

Halymorpha halys (Stål) (Hemiptera: Pentatomidae), the brown marmorated stink bug, is a polyphagous, invasive stink bug native to Asia (Hoebeke and Carter, 2003; Lee et al., 2013). The first known US populations were detected in the 1990′s, near Allentown, Pennsylvania (Hoebeke and Carter, 2003). Since then, *H. halys* has spread throughout much of the USA and has been detected in 46 states and the District of Columbia (stopBMSB.org). *Halymorpha halys* is a household nuisance and primary pest causing millions of dollars in damage to crops annually (Leskey et al., 2012a).

The host range of *H. halys* includes at least 170 plants, both non-crop and crop plants, and requires plants with fruiting bodies to complete development (Acebes-Doria et al., 2016; Leskey and Nielsen, 2018; Zobel et al., 2016). Many of its cultivated hosts are economically important crops, including pears, peaches, apples, grapes, and corn; and *H. halys* is a season-long pest to tree fruit (Leskey et al., 2012a; Nielsen and Hamilton, 2009; Rice et al., 2014). In North Carolina (NC), overwintering *H. halys* adults emerge during April and May and disperse to host plants in non-managed arboreal habitats where they lay eggs (Bakken et al., 2015). Non-managed wooded edges, especially those surrounding crops, serve as areas for population build-up and points of dispersal (Acebes-Doria et al., 2017; Aigner et al., 2017; Bakken et al., 2015; Nielsen and Hamilton, 2009; Venugopal et al., 2015). In these habitats *H. halys* utilize numerous trees as hosts for feeding and reproduction. In NC woodland plants on which *H. halys* commonly occurs include tree of heaven (Ailanthus altissima (Miller) Swingle), paulownia (Paulownia sp.), blackberry (Rubus sp.), black walnut (Juglans nigra L.), catalpa (Catalpa sp.), cherry (Prunus sp.), dogwood (Cornus sp.), and grape (Vitis sp.) (Bakken et al., 2015). Adults and nymphs

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Utilizing the Samurai Wasp as a Potential Control Tool Against Brown Marmorated Stink Bug

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Introduction: The brown marmorated stink bug (BMSB) *Halyomorpha halys* (Stål) (Heteroptera – Pentatomidae) has been a severe agricultural pest for fruit growers in the Mid-Atlantic region since its outbreak in 2010. Unfortunately, due to a high resilience of this invasive pest to some insecticides, growers have been required to increase their inputs of broad-spectrum insecticide sprays, which have been both challenging economically and damaging ecologically. In tree fruit, inputs of insecticides have been shown to increase secondary pests such as wooly apple aphid and San Jose scale, which further disrupts the ability of growers to utilize IPM practices. In addition, BMSB adults also have the ability to fly across several habitats and can feed on vegetation in wooded areas where insecticides cannot be used. In order to utilize less insecticides for BMSB, it is important to understand the level of ecosystem services natural enemies may provide for the pest both in the orchard and in the surrounding habitats.

Egg parasitoids may be a promising group of natural enemies to provide landscape-level control for the pest, as previous studies have described populations of these insects in the orchard as well as in the surrounding woods. Parasitoids kill stink bugs before they develop by laying their own eggs inside the stink bug eggs. In its native range of Asia, BMSB is controlled by several parasitoids. One of the most effective parasitoids, *Trissolcus japonicus*, or the samurai wasp, has been investigated as a potential candidate for release in the United States. In 2014, adventive populations of the samurai wasp were discovered in Maryland. Since then, populations have been discovered in NY, PA, NJ, VA, OH, and other locations across the United States and the world.

Several species of native egg parasitoids attack native stink bug species in Pennsylvania, including closely related "cousins" to the samurai wasp in the genus *Trissolcus*. While some native parasitoids of stink bugs are specialist to stink bugs, other species are generalist parasitoids, attacking a broad range of insects including stink bugs, katydids, assassin bugs, and ants. Previous research has indicated that some species may also specialize in specific habitats. It will be useful, therefore, in planning IPM programs to understand *where* and *when* both native parasitoids and the samurai wasp can be found in commercially operated fruit orchards. The objectives of this study were to detect new populations of the samurai wasp, to evaluate the habitats and seasonality of populations of native parasitoid species, and to establish colonies of egg parasitoids to utilize for future studies.

Materials and Methods: The study was conducted at two commercial orchards, located in Lancaster and Adams County, PA, which both utilize IPM practices such as pest monitoring and mating disruption. The location in Lancaster county was conventionally managed orchard, growing apples, peaches, blackberries, and cherries. The location in Adams County was organically managed site growing apples and peaches during the 2018 season while during the 2019 season it was re-planted as a organic

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Nosema maddoxi (Microsporidia: Nosematidae) in brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), populations in the United States

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ABSTRACT

In 2017, *Nosema maddoxi* Becnel, Solter, Hajek, Huang, Sanscrainte, & Estep (Microsporidia: Nosematidae) was described as a pathogen of the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae). This study focused on the phenology, distribution, and prevalence of *N. maddoxi* infections in *H. halys* populations in the United States. Collections of *H. halys* from three sites in 2018 were evaluated for the seasonality of *N. maddoxi* infections. Prevalence of infection in spring, after *H. halys* adults overwintered, averaged 37.5 ± 18.9% (peaking at 60.0% in one site) followed by lower infection prevalence during two summer collections (9.7 ± 4.1% and 7.3 ± 2.4%). Collections of *H. halys* from 31 sites in 11 states in 2017 and 2018 were evaluated and *N. maddoxi* was found in every state sampled, averaging 18.9 ± 4.3% infection (range: 0.0–52.0%). Prevalence of low-intensity infections was higher than high-intensity infections in both the phenology study (low-intensity infections = 69.3%, high-intensity infection = 30.7%) and the distribution study (low-intensity infections = 62.4%, high-intensity infections = 37.6%). Internal melanized tissues within infected *H. halys* adults are visible as brown spots through the abdominal cuticle and this physical sign can help indicate *N. maddoxi* infection: 74.2% of *H. halys* with these spots were infected; however, 30.0% of *H. halys* adults that did not have spots were infected. Based on this study, this pathogen is widely distributed throughout *H. halys* populations in the US, and infection prevalence is variable among sites and is seasonal, with the highest infection levels occurring when *H. halys* adults are aggregated.

1. Introduction

After alien species have been introduced in new locations, they interact in ecological communities within which they have no evolutionary history. In particular, native natural enemies (i.e., parasites and predators) have potential opportunities to utilize new hosts when new invasive species are introduced that are susceptible. However, native natural enemies, especially generalists, have previously been hypothesized as having limited impacts on invasive species (Cornell and Hawkins, 1993). More recent studies have shown that when invasions are studied for longer durations, initial outbreak dynamics can change after ecological and evolutionary processes have come into play (Strayer et al., 2006). Recent data indicate that decreases in the densities and impacts of invasive species, which can occur after establishment of a new invasive, can be driven in part by impacts of non-coevolved native natural enemies (Berthon, 2015). As examples with insects, native egg parasitoids and generalist predators can negatively impact populations of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) (Abram et al., 2017). Recently, two native species of entomopathogenic fungi caused the collapse of a population of invasive spotted lanternfly, *Lycorma delicatula* (White) (Hemiptera: Fulgoridae) (Clifton et al., 2019). Here we report on a native pathogen that is presently infecting *H. halys* throughout its distribution in North America, with varying levels of infection prevalence.

In 2017, the new species *Nosema maddoxi* Becnel, Solter, Hajek, Huang, Sanscrainte, & Estep (Microsporidia: Nosematidae) was described as a pathogen of *H. halys* (Hajek et al., 2017). Field collections of *H. halys* in 2015–2016 in the United States from five eastern states showed variability in the prevalence of *N. maddoxi* infection, with a range of 0.0–28.3% in collections from four of the five states. This species was originally found in the native green stink bug, *Chinavia*

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Impact of *Nosema maddoxi* on the survival, development, and female fecundity of *Halyomorpha halys*

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ABSTRACT

Nosema maddoxi Becnel, Solter, Hajek, Huang, Sanscrainte, & Estep, a microsporidian species native to the United States, has been found infecting the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål). Microsporidian infections in insects often shorten lifespans, decrease fecundity, prolong development, and stunt growth. This study was conducted to determine the impact of *N. maddoxi* on *H. halys* fitness. Adult females (2 doses) and nymphs (1 dose) drank suspensions of *N. maddoxi* spores to promote infection. Adult females receiving a high dose died faster than the controls. *Nosema maddoxi* infections impacted female egg production and egg viability at both doses compared with the controls. Infections were transmitted to 34.9% of adult males caged with infected females. As the number of days after inoculation increased, infection intensity (# spores found within an infected individual) for both adult treatments transitioned from low-intensity to high-intensity. Infected nymphs died significantly sooner than the controls. Of the treated nymphs, 55.9% died before molting into the fourth instar and only 26.5% eclosed to adults. Nymphal development rate and size were not impacted by *N. maddoxi* infection. These results indicate that *N. maddoxi* infection can negatively impact the lifespan of adult females, female fecundity, egg viability, and nymphal survival, which we hypothesize would negatively impact *H. halys* population densities.

1. Introduction

Microsporidia are intracellular, obligate fungal parasites that usually cause chronic infections in insect hosts that can shorten lifespans, decrease fecundity, prolong development, and stunt growth (Becnel and Andreadis, 2014; Hoch and Solter, 2018). These fitness costs can become obvious when microsporidia infect laboratory colonies where transmission is often enhanced by containment, resulting in epizootics that can lead to colony decimation (Bjørnson and Oi, 2014; Hoch and Solter, 2018). Microsporidian infections can also reach high prevalence in colonies of social insects that often exhibit localized aggregation, which can enhance transmission (Solter, 2014). However, microsporidian species can also reach high prevalence in field populations of diverse insects, especially when host populations are abundant; infection is often density-dependent and can negatively impact such field populations (Andreadis, 1984; Lewis et al., 2009; van Frankenhuyzen et al., 2011; Bjørnson and Oi, 2014).

Microsporidia are well known from the major insect orders Diptera, Lepidoptera and Coleoptera, but relatively few (approximately 20) microsporidian species have been described from hosts in the order Hemiptera (Hajek et al., 2017). However, the microsporidian *Nosema maddoxi* Becnel, Solter, Hajek, Huang, Sanscrainte, & Estep, was recently described as a systemic pathogen of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in North America (Hajek et al., 2017). In 1968, Joseph Maddox first discovered this microsporidian parasitizing native green stink bugs, *Chinavia hilaris* (Say), in Illinois (Maddoxm, 1979), before *H. halys* was discovered in Pennsylvania in 1996 (Hoebeke and Carter, 2003; Hajek et al., 2017). Therefore, this pathogen is assumed to be native to North America.

Halyomorpha halys was introduced from Asia and is a major pest of fruit and vegetables in the United States (Leskey and Nielsen, 2018). Its management has mostly been dependent on insecticides, with some integrated pest management (IPM) strategies and releases of egg parasitoids (Abram et al., 2017). Bioassays have been conducted demonstrating susceptibility of *H. halys* to isolates of the acute fungal pathogens *Beauveria bassiana* (Bals.-Criv.) Vuill. and *Metarhizium anisopliae* (Metchnikoff) Sorokin, including commercially available formulations of *B. bassiana* (Gouli et al., 2012; Parker et al., 2015). To

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insects

MDPI

Article

Seasonal Captures of *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae) and the Effects of Habitat Type and Tree Species on Detection Frequency

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Simple Summary: *Trissolcus japonicus*, an important natural enemy of brown marmorated stink bug in Asia, was first detected in the USA in 2014. To investigate when and where *T. japonicus* is found in the field, yellow sticky traps were deployed in the canopy of tree of heaven growing at the edge of small isolated patches, windbreaks, and woodlots in 2018 and 2019. In both years, captures occurred from May to September, with peaks in July and August. Captures of *T. japonicus* were recorded from all three habitats but were not consistently associated with a particular habit. In 2017 and 2018, *T. japonicus* captures were compared between tree of heaven paired with several other *H. halys* host trees growing at the woods edge, and in 2019, captures in tree of heaven, black walnut, and black locust growing in the same windbreaks were compared. *Trissolcus japonicus* and several native *H. halys* parasitoids were captured in all hosts, but there was not a consistent effect of host tree species on *T. japonicus* captures. These results can be used to inform and optimize future surveillance efforts for detecting *T. japonicus* as it continues to expand its range in the USA.

Abstract: *Trissolcus japonicus*, an important egg parasitoid of *Halyomorpha halys* in Asia, was first detected in the USA in 2014. To evaluate the effect of habitat and the seasonality of *T. japonicus* detections in the USA, yellow sticky traps were placed in the canopy of *Ailanthus altissima* growing at the edge of isolated patches of trees, windbreaks, and woodlots in northern Virginia in 2018 and 2019. In both years, captures occurred from May to September, and peaked in July and August. While *T. japonicus* was detected in all habitats, there was not a consistent effect of habitat type on capture frequency. To evaluate tree species effects on *T. japonicus* captures, in 2017 and 2018, yellow sticky traps deployed in the canopy of *A. altissima* bordering apple orchards were paired with a nearby trap in one of several wild tree species along a common woods edge. In 2019, these traps were deployed in *A. altissima*, black walnut, and black locust growing in the same windbreaks. No consistent association between captures of *T. japonicus* or native parasitoids of *H. halys* and the tree species sampled was observed among years. Results are discussed in relation to the ecology and sampling optimization of *T. japonicus*.

Keywords: biological control; parasitoid; *Halyomorpha halys*; *Ailanthus altissima*

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1. Introduction

Halyomorpha halys (Stål) (Hemiptera: Pentatomidae), is a polyphagous invasive stink bug from Asia that has been a severe agricultural and nuisance pest in many parts of the USA since the late 2000s [1]. A widespread outbreak in 2010 resulted in major losses to the apple and peach crops in the Mid-Atlantic USA [2]. To manage *H. halys*, many American

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Research

OXFORD

Horticultural Entomology

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

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Abstract

Brown marmorated stink bug (*Halyomorpha halys* Stål) is an invasive and economically important agricultural and ornamental insect pest now established in 46 U.S. states. It was first detected in Utah in 2012 and began causing agricultural damage in 2017. Tart cherry (*Prunus cerasus* Linnaeus) is a major processed agricultural commodity in Utah; yet, its susceptibility to brown marmorated stink bug is unstudied. Limb cages with six brown marmorated stink bug adults, nymphs, or no brown marmorated stink bug were established in a randomized complete block design in a tart cherry orchard to determine feeding impact on different fruit developmental stages. After 1 wk of feeding, half of the fruits in each cage were removed to assess feeding intensity, and the remainder left through maturity to assess marketability and quality. Feeding by adults and nymphs between petal fall and fruit pit hardening, even at feeding pressures as low as 1.7–4.0 feeding sites per fruit, caused 100% abscission of fruits, significantly reducing marketability when compared with the control treatment. For fruits that escaped abscission and matured, few quality differences were detected among treatments, indicating that brown marmorated stink bug feeding caused minimal detectable quality loss to this processed tree fruit crop. We conclude that tart cherries are at risk of abscission with short-term brown marmorated stink bug feeding between petal fall and pit hardening when overwintered adults or F_1 nymphs are present in orchards, and suggest that longer-term feeding may be necessary to cause quality and yield reductions after pit hardening.

Key words: brown marmorated stink bug, feeding damage, *Prunus cerasus*, yield, quality

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

Studies to characterize brown marmorated stink bug damage to some vegetable and fruit crops have found high vulnerability among pepper, sweet corn, and okra, with losses exceeding 50% due to scarring, sunken lesions, and fruit deformation (Kuhar et al. 2012, Rice et al. 2014). Orchard fruits are often attacked season-long by brown marmorated stink bug, placing them at greater risk to crop loss (Nielsen and Hamilton 2009, Leskey et al. 2012b). Injury to apple can be severe, with losses exceeding 90% during periods of high brown marmorated stink bug infestations (Leskey and Hamilton 2010). Stone fruits, such as peach and nectarine, are susceptible to cat-facing and premature fruit abortion (Nielsen and Hamilton

Non-sib Male Guarding Behavior Observed in *Trissolcus euschisti* (Hymenoptera: Scelionidae)

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Abstract

Wasps in the genus *Trissolcus* (Hymenoptera: Scelionidae) are parasitoids of stink bugs and other insects in the Pentatomoidea superfamily (Order Heteroptera) and typically undergo sib-mating behavior where males emerge first from parasitized host insect eggs and remain near the natal site to mate with sib-females as they emerge. Although common in certain groups of parasitoid wasps, sib-mating often leads to inbreeding and subsequent reduced genetic diversity and fitness. During field surveys for native and exotic natural enemies of the invasive brown marmorated stink bug (BMSB, *Halyomorpha halys* Stål) in northern Utah, we discovered a male *Trissolcus euschisti* guarding a green stink bug (*Chinavia hilaris* Say) egg mass that was determined post-observation be a non-sib male based on the timing of its presence to subsequently emerging *T. euschisti* males and females. This finding suggests alternative mechanisms for avoiding inbreeding depression in a sib-mating species, and that outbreeding may be more prevalent than once thought in this sib-mating system.

Introduction

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

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

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

Evidence for mating after leaving the natal site is provided by Loch and Walter [8], where the outbreeding potential of *Trissolcus basilis* (Wollaston), an egg parasitoid of southern green stink bug (*Nezara viridula* Linnaeus) was explored. They found that a single, newly emerged male-dominated the natal site by guarding the eggs and chasing

insects

Article

Comparing the Feeding Damage of the Invasive Brown Marmorated Stink Bug to a Native Stink Bug and Leaffooted Bug on California Pistachios

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Simple Summary: The brown marmorated stink bug is native to Asia and has invaded parts of Europe and North America where it causes considerable damage to a wide range of vegetable, fruit, and nut crops. Pistachios have become an important nut crop in California, and as this invasive stink bug moved into California, farmers needed to know about the potential damage from brown marmorated stink bugs. Here, we assessed pistachio yield loss and nut damage over a two-year period. The invasive stink bug was also compared with the native green stink bug and a native leaffooted bug. We found that brown marmorated stink bug adults cause more epicarp lesions (external damage) when recorded at harvest time than the native species; however, they did not cause more kernel necrosis (internal damage) than the two native species tested, which is a more relevant damage criterion for commercial production. We conclude that the brown marmorated stink bug could cause similar damage as the native species but note that the invasive stink bug's numbers in California are still low and future damage levels will be dependent on this pest's population density.

Abstract: California currently produces about a quarter of the world's pistachios. Pistachio nuts are susceptible to feeding by stink bugs and leaffooted bugs; therefore, the invasive presence of the highly polyphagous brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is a concern to California pistachio growers. We aimed to assess the potential of *H. halys* to cause yield loss and nut damage to pistachios, which had not yet been assessed in the field. Over two years, terminal branch ends with pistachio clusters were enclosed in organdy cages from spring to fall and exposed to either *H. halys*, the native stink bug *Chinavia hilaris* Say (Hemiptera: Pentatomidae), or leaffooted bug *Leptoglossus zonatus* (Dallas) (Hemiptera: Coreidae), for 4–7-day feeding periods at different times of the season. We found that *H. halys* adults cause more epicarp lesions (external damage) when recorded at harvest time than the native species. They did not, however, cause more kernel necrosis (internal damage) than the two native species tested, which is a more relevant damage criterion for commercial production. There were no differences among insect species for any other recorded damage criteria. We conclude that *H. halys* could cause similar damage as the native species but note that *H. halys* population densities in California are still low and future damage levels will be dependent on this pest's population density.

Keywords: *Chinavia hilaris*; epicarp lesion; flat green stink bug; *Halyomorpha halys*; insect pest damage; leaffooted bug; kernel necrosis; *Leptoglossus zonatus*; stigmatomycosis

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Section E: Vegetable Crops

OXFORD

EDAMAME: *Glycine max* (L.) Merr. 'V13-1644'

Evaluation of Insecticides to Control Stink Bug in Edamame, 2019

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Brown Marmorated Stink Bug (BMSB) | *Halyomorpha halys* (Stål)

Soybean | *Glycine max*

The objective of this experiment was to evaluate the efficacy of insecticides on brown marmorated stink bug (BMSB) on edible soybean (edamame). Edamame was planted on 6 Jun at Virginia Tech Kentland Farm near Blacksburg, VA. Plots were arranged in an RCB design consisting of two row plots that were 20 ft in length spaced 3-ft apart. The experiment had seven treatments, one of which was an untreated check, with four replicates. BMSB was the predominant stink bug species observed, and bugs were assessed on 9, 19, and 23 Sep by carefully inspecting plants in each plot for 30 s and recording the numbers seen including those that flew away or dropped to the ground. Insecticide applications were made on 5 and 15 Sep using a three-nozzle boom backpack sprayer equipped with D3 tips at 40 psi. Applications were made at 10 GPA when the edamame pods were at the R4 to R5 growth stages. Immediately following the 15 Sep spray application, 5-gal paint strainer mesh bags were placed over fruiting limbs containing at least 10 pods and the bags sealed with twist ties after inserting five adult BMSB collected from nearby untreated edamame. After 4 d in the field, bags were excised from the plants and taken to the lab where insect mortality was assessed. Stink bug counts and proportion mortality data were analyzed using ANOVA. Means were separated using Fisher's protected least significant difference test ($P \le 0.05$).

BMSB densities were relatively low on 9 Sep, but increased on 19 and 23 Sep. There was a significant treatment effect on BMSB counts on 19 Sep only, when the untreated check plots had significantly more BMSB than Bifenthrin 2E, Harvanta 50SL + Assail 30SG, Sivanto Prime, Harvanta 50SL, and Beleaf 50SG + 1/10th rate Bifenthrin 2E (Table 1). Survival of the caged BMSB averaged 95% in the untreated check, which was significantly higher than all insecticide treatments except Harvanta 50SL and Sivanto 50 SL. Bifenthrin 2E had the lowest survival 0.0%. No phytotoxicity was observed.[1]

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Table 1.

Treatment	Rate/acre	No. BMSB per 30 s			Proportion survival of BMSB[a,b]
		Sep 9	Sep 19	Sep 23	Sep 19
Untreated check		1.25	2.50 a	0.75	0.95 a
Bifenthrin 2E	2.1[c]	0.00	0.25 c	1.00	0.00 d
Harvanta 50SL	22.0[c]	0.00	0.75 bc	2.00	0.75 ab
Assail 30SG	3.8[d]	0.50	2.00 ab	0.75	0.35 c
Harvanta 50SL + Assail 30SG	27.2[c] + 3.8[d]	0.50	0.25 c	0.25	0.60 bc
Beleaf 50SG + Bifenthrin (1/10th)	2.8[d] + 0.21[c]	0.50	0.75 bc	0.75	0.35 c
Sivanto Prime	14.0[c]	0.25	0.50 bc	1.75	0.75 ab
$P > F$		NS	0.08	NS	0.001

Means within columns followed by the same letter are not significantly different; $P > 0.05$.
[a]Proportion data were arcsine-sqrt transformed to normalize variance before analysis, although untransformed proportions are shown.
[b]After 4 d caged in the field on treated foliage and pods
[c]fl. oz product per acre.
[d]oz product (wt.) per acre.

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Parasitism and predation of sentinel eggs of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in the southeastern US

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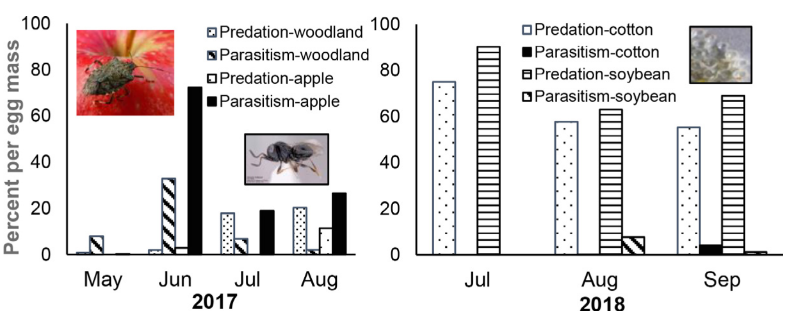
GRAPHICAL ABSTRACT



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ABSTRACT

The invasive brown marmorated stink bug, *Halyomorpha halys*, is present in the Piedmont and expanding into the Coastal Plains Regions of the southeastern US. Consequently, this study was conducted to evaluate parasitism and predation of *H. halys* sentinel egg masses by native parasitoids and predators in woodland habitats and orchard, vineyard, row, and vegetable crops alongside these habitats in Alabama and Georgia in 2017 and 2018. Ten primary parasitoid species, including two new records, and one hyperparasitoid emerged from eggs. *Trissolcus japonicus* was not detected. *Ooencyrtus* sp. was the prevalent parasitoid species in vegetables while *Telenomus podisi* was the predominant species in row crops. *Anastatus reduvii*, *An. mirabilis*, *Tr. brochymenae*, and *Tr. euschisti* were the prevalent species in woodland and orchard habitats. *Trissolcus edessae* Fouts occurred primarily in orchards. *Trissolcus basalis* and *Gyron obesum* were observed in vegetable habitats. Percentage successful development to adults, sex ratio, and percentage of parasitism per egg mass was highest for *Tr. edessae*. Predation damage included complete and incomplete chewing, stylet sucking, puncture sucking, and removal of whole eggs from egg masses. Hole and non-stylet sucking damage were discovered. Chewing and

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Comparison of chemigation *versus* foliar insecticide use: management of lepidopteran larvae and stink bugs in North Carolina field tomatoes with environmental and farmworker benefits

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Abstract

BACKGROUND: Commercial vegetable production in the United States of America (USA) often relies on foliar insecticide sprays for managing key insect pests. However, foliar applications of insecticides have a number of drawbacks to the health of consumers, farmworkers and the environment. Drip chemigation is the application of pesticides to the soil through trickle (drip) irrigation systems, and can overcome a number of the drawbacks typical of foliar insecticide applications.

RESULTS: We conducted a two-year study in five commercial fields of staked tomatoes in western North Carolina to compare the efficacy, economics and environmental impact of drip chemigation *versus* foliar sprays. Drip chemigation significantly reduced insecticide inputs, utilized more selective and environmentally compatible insecticides, and reduced the time lost to reentry intervals, while maintaining comparable efficacy and economic returns.

CONCLUSIONS: Drip chemigation was an effective tool for managing key insect pests, provided a broad range of human and environmental health benefits, and will likely become increasingly cost-effective in the future as insecticide patents expire and more insecticide options become available.

Keywords: drip chemigation; reduced risk pesticides; environmental impact quotient; economics

1 INTRODUCTION

Pesticides are key components of commercial vegetable production in the USA, especially fresh market production that has very low tolerances for damage. The vast majority of insecticide inputs are typically foliar applications, often made with high-pressure boom sprayers. Despite their overall success in managing pest populations, there are several drawbacks associated with foliar insecticide sprays related to drift, residue accumulation on plants and runoff into water resources. Drift associated with spraying pesticides varies depending on the equipment, user operations and weather conditions, but up to 50% of the amount sprayed can be lost to the atmosphere;[1] this can pollute the air, result in exposure of nontarget organisms to toxic insecticides[2] and contribute to contamination of water resources.[3,4] Spray drift also has the risk of threatening the health of farmworkers and adjacent residents[5,6] and is a common source of conflict in regions where urban and agricultural areas interface. Additionally, accumulation of pesticides on plant foliage and the soil surface within fields is a source of pesticide runoff into water resources.[7]

Chemigation is the application of pesticides to crops through irrigation systems[8] and can serve as an alternative to foliar spray applications for managing many insect pests. Application of pesticides through drip irrigation systems is referred to as drip chemigation and is particularly well-suited for managing insects in vegetable production systems that use plasticulture with subsurface drip irrigation.[9] The availability of several neonicotinoid and anthranilic diamide insecticides that have different spectrums of pest activity, and which move systemically in the plant following root uptake, offers the potential for achieving broad spectrum insect control using drip chemigation in certain cropping systems. Neonicotinoid insecticides applied through drip systems have been used for >20 years to manage aphids and

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