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Case Study

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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

Dalton Ludwick,[1,†] William R. Morrison, III,[2,†] Angelita L. Acebes-Doria,[3] Arthur M. Agnello,[4] J. Christopher Bergh,[5] Matthew L. Buffington,[6] George C. Hamilton,[7] Jayson K. Harper,[8] Kim A. Hoelmer,[9] Gregory Krawczyk,[10] Thomas P. Kuhar,[11] Douglas G. Pfeiffer,[11] Anne L. Nielsen,[12] Kevin B. Rice,[13] Cesar Rodriguez-Saona,[14] Peter W. Shearer,[15] Paula M. Shrewsbury,[16] Elijah J. Talamas,[17] James F. Walgenbach,[18] Nik G. Wiman,[19] and Tracy C. Leskey[1,20]

[1]USDA, Agricultural Research Service, Appalachian Fruit Research Station, 2217 Wiltshire Road, Kearneysville, WV 25430-2771, [2]USDA, Agricultural Research Service, Center for Grain and Animal Health Research, 1515 College Avenue, Manhattan, KS 66502, [3]Department of Entomology, University of Georgia, Tifton Campus, 2360 Rainwater Road, Tifton, GA 31793, [4]Department of Entomology, Cornell University, Cornell AgriTech, 15 Castle Creek Drive, Geneva, NY 14456, [5]Virginia Polytechnic and State University, Agricultural Research and Extension Center, Winchester, VA 22602, [6]USDA, Agricultural Research Service, Systematic Entomology Laboratory, P.O. Box, Washington, DC 20013-7012, [7]Department of Entomology, Rutgers University, 96 Lipman Drive, New Brunswick, NJ 08901-8536, [8]Department of Agricultural Economics, Sociology, and Education, The Pennsylvania State University, 290 University Drive, Biglerville, PA 17307, [9]USDA, Agricultural Research Service, Beneficial Insects Introduction Research Unit, Newark, DE 19713-3814, [10]Department of Entomology, Fruit Research and Extension Center, Pennsylvania State University, P.O. Box 330, Biglerville, PA 17307-0330, [11]Department of Entomology, Virginia Tech, Price Hall, Blacksburg, VA 24061, [12]Department of Entomology, Rutgers Agricultural Research and Extension Center, 121 Northville Road, Bridgeton, NJ 08302, [13]Division of Plant Sciences, University of Missouri, 3-22B Agriculture Building, Columbia, MO 65201, [14]Department of Entomology, Rutgers University, Philip E. Marucci Blueberry and Cranberry Research Center, 125a Lake Oswego, Chatsworth, NJ 08019, [15]Strawberry Center, Cal Poly, 1 Grand Avenue, San Luis Obispo, CA 93407, [16]Department of Entomology, University of Maryland, 4112 Plant Sciences Building, College Park, MD 20742-4454, [17]Florida Department of Agriculture and Consumer Services, 1911 SW 34th Street, Gainesville, FL 32608, [18]Department of Entomology and Plant Pathology, North Carolina State University, 455 Research Drive, Mills River, NC 28732, [19]Department of Horticulture, Oregon State University, Agricultural and Life Sciences 4109, 2750 SW Campus Way, Corvallis, OR 97331, and [20] [†]These authors contributed equally to creating this work.
Corresponding author, e-mail: tracy.leskey@ars.usda.gov

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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 efforts, and over 600 million people via mainstream media. We highlight the main lessons learned from coordinating a national response to the threat posed by *H. halys* to agriculture in the United States.

Key words: *Halyomorpha halys*, specialty crop, Extension, IPM, invasive species

The brown marmorated stink bug, *Halyomorpha halys* (Stål), has become a globally distributed invasive species (Haye et al. 2015, Kriticos et al. 2017, Leskey and Nielsen 2018). The first country to experience severe agricultural damage as a result of its introduction was the United States (Hoebeke and Carter 2003). This is a polyphagous species that feeds on over 170 host plants (Bergmann et al. 2016), many of which are economically important. *Halyomorpha halys* has one to two generations per year in the United States, with voltinism influenced by both photoperiod and temperature (Nielsen and Hamilton 2009; Nielsen et al. 2011, 2016a, 2017a,b).

Halyomorpha halys was first detected in the 1990s near Allentown, PA, but its presence was not confirmed until 2001 (Hoebeke and Carter 2003). Fruit damage on commercial farms (Pittstown, NJ, and Macungie, PA) was first reported in 2006 (Nielsen and Hamilton 2009). Widespread damage reports further surfaced in the Mid-Atlantic in the latter part of the 2008 growing season when large numbers of adults moved into apple and peach orchards nearing harvest and caused fruit damage that resulted in losses of up to 10%. This observation was recorded during the first BMSB IPM Working Group meeting, funded by the Northeastern IPM Center and held in Kearneysville, WV, in June 2010. Thirty members were in attendance and included research and Extension personnel, growers, and other affected stakeholders. During this meeting, the group developed research, Extension, and regulatory priorities for *H. halys* based on needs articulated by affected stakeholders (Leskey and Hamilton 2010). In the Pacific Northwest, there were also reports of scattered *H. halys* problems in hazelnut (Hedstrom et al. 2014).

In the summer of 2010, the situation became dire for the Mid-Atlantic specialty crop growers, with *H. halys* populations feeding on and inflicting extreme damage to peach and apple crops, vegetables, small fruit, and to a lesser extent, soybeans and corn (Leskey et al. 2012b,c). In early September 2010, USDA-ARS organized an emergency meeting at two Maryland farms. Over 60 growers, research, Extension and regulatory personnel, and industry representatives were in attendance to observe the damage firsthand and discuss concerns for the future. In late September 2010, severe nuisance problems were experienced by homeowners and businesses as adult *H. halys* dispersed to potential overwintering sites, including human-made structures (Leskey et al. 2012a). By November 2010, the BMSB IPM Working Group received additional funds from the Northeastern IPM Center and more than doubled in size to 68 attendees since its inception. The Working Group continued to meet once or twice a year for the next 7 yr. Feedback generated by membership at each meeting was used to continuously refine research, Extension, and regulatory priorities with consumer priorities added in 2012.

The Working Group was awarded a USDA-NIFA Specialty Crop Research Initiative (SCRI) grant to address the extreme problems being generated by *H. halys* for specialty crops. The project, 'Biology, Ecology, and Management of Brown Marmorated Stink Bug in Orchard Crops, Small Fruit, Grapes, Vegetables and Ornamentals', had the primary goal to 'develop economically and environmentally sustainable pest management practices for the brown marmorated stink bug…in specialty crops and to implement a coordinated, rapid delivery system to disseminate critical information generated from this project to specialty crop end-users'. The four objectives of the project included: 1) establishing the biology and phenology of *H. halys* in specialty crops, 2) developing monitoring and management tools for *H. halys*, 3) establishing effective management programs for *H. halys* in specialty crops (e.g., orchards, small fruit, grapes, and vegetables), and 4) integrating stakeholder input and research findings to form and deliver practical outcomes. This project focused solely on specialty crops, and additional projects included those funded by the United Soybean Board (e.g., Aigner et al. 2017), state-level projects, regional IPM and SARE grants, Specialty Crop Block grants, commodity grants, USDA-NIFA OREI grant, USDA-ARS in-house funds, and the USDA-APHIS Farm Bill, all of which contributed to and complemented the SCRI project efforts.

While multiple reviews of *H. halys* literature exist (Lee et al. 2013b, Rice et al. 2014, Leskey and Nielsen 2018), including its chemical ecology (Weber et al. 2017), biological control (Abram et al. 2017), and chemical control (Kuhar and Kamminga 2017), the process by which this invasive species threat was addressed in the United States has not been reviewed in detail. Thus, our goal is to provide details on how a coordinated national response to an invasive species was executed, using *H. halys* as a model. In particular, we highlight the research, Extension, regulatory and consumer priorities pursued, and document key Extension and outreach topics covered based on knowledge generated by researchers. We further discuss how inputs from our grower stakeholders were addressed. Moreover, we highlight survey data regarding homeowner and grower stakeholder perceptions of the effectiveness of new tactics for management of *H. halys*. Finally, we highlight lessons learned from working within a large, multistate, multi-institutional project.

Materials and Methods

BMSB IPM Working Group Membership and Priorities

Beginning in June 2010, the BMSB IPM Working Group generated priorities for research, Extension, and regulatory issues. Consumer priorities were added in 2012. All priorities were developed and subsequently ranked by participants of the Working Group to guide the future direction of effort. We evaluated the top five research, Extension, and regulatory priorities from 2010 to 2016, consumer priorities from 2012 to 2016 to establish frequency of appearance on the priority list. In addition, we designated whether a top five priority was accomplished during the designated time frame. Executive summaries of each meeting were reviewed to document changes in attendance, meeting content, and institutional involvement from different regions over time.

SAP Recommendations and Extension/Outreach Products

In accordance with the FY2011 USDA-NIFA SCRI request for applications, a Stakeholder Advisory Panel (SAP) was formed and included grower and environmental advocacy group representatives; specifically, the nursery, processing, marketing, and wholesale industries, grower organizations, specialty crop growers, the organic community, and research and Extension personnel. The SAP met annually to review project accomplishments, provide feedback on research plans, and guide the execution of objectives. At each meeting, the SAP received research, Extension, and budgetary updates, as well as developments regarding the spread and establishment of *H. halys* and regulatory changes. SAP members also served as members of the larger BMSB IPM Working Group to promote a dynamic interface with the entire Working Group and encourage robust, informed feedback from the SAP throughout the life of this project. This manuscript highlights the SAP's key annual recommendations and reports on how these suggestions were addressed.

Annual reports generated for the SAP were compiled from information provided by each of the 14 institutions as well as cross-institutional specialty crop commodity teams (orchard crops, grapes, ornamentals, vegetables, and small fruit). From these reports, we extracted information on Extension presentations by the SCRI team from 2011–2013 and 2014–2016 to examine subject matter and commodity-specific content at the start and latter parts of the project. Additionally, we assessed selected media coverage (print, broadcast, and commodity press) as a mechanism for reaching a larger number of stakeholders, including specialty crop consumers and the general public. Furthermore, we report on additional funding generated by team members that was leveraged to help achieve the goal of managing the invasive *H. halys*. Finally, we report total numbers of high school students, undergraduate students, graduate students, postdoctoral fellows, and technical personnel that received specialized training as part of this project.

National Outreach Efforts

In 2012, the SCRI-funded StopBMSB.org website was launched to communicate outreach materials to a national audience. Metrics from StopBMSB.org were compiled by period: original SCRI grant (2012 to 30 September 2016) and the start of the second SCRI project to the time of analysis (1 September 2016 to 6 March 2019). The second grant will end on 31 August 2021. The total number of visitors to the site was tracked and broken down by page views and downloads for key pages, as well as by year the site was accessed, noting the U.S. state of origin of the visitor. In addition, we compiled information on the number of views for the *H. halys* short-form documentary video series on its basic biology, ecology, and management as well as distribution of DVDs of the series. Moreover, we compiled information on the number of distributed copies of provisional management guides developed for orchard crops, grapes, small fruit, and vegetables by commodity teams, the pocket-sized 'Field Guide to Stink Bugs of Agricultural Importance in North America', and Stink Bug ID kits. The kits consisted of a postcard with information and link to the *H. halys* video series, a copy of the stink bug guide, regional pest alert for *H. halys*, a reprint of an IPM Practitioner article on IPM tactics for *H. halys*, and an infographic of *H. halys* risk to specialty crops (Fig. 1).

As biological control is considered a key long-term strategy for managing *H. halys* and a major thrust of the previous and current BMSB SCRI CAP, we compiled national outreach efforts for the biological control aspects of the project. Adventive populations of the most effective *H. halys* egg parasitoid, *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae), were found in the United States in 2014 (Talamas et al. 2015a), and the majority of outreach efforts with biological control have focused on this species. We obtained estimated numbers of participants in annual parasitoid identification workshops designed to train research and Extension personnel, estimated number of visits to the *T. japonicus* exhibit at the National Museum of Natural History (Smithsonian Institution) based on internal auditing procedures, as well as the number of downloads of *T. japonicus* outreach brochures from StopBMSB.org.

Halyomorpha halys Management Tactics: Outputs and Perceptions

Insecticide costs for impacted growers

During 2010, *H. halys* became the primary species driving management programs in tree fruit in the Mid-Atlantic United States. Pesticide application records were collected from nine apple growers and 12 stone fruit growers in West Virginia, Maryland, Pennsylvania, and New Jersey from 2009–2012 to track the impact of *H. halys* on insecticide costs. Costs were calculated based on pesticide usage rates, average material costs from local distributors, and the spray application method. We compared insecticide costs in 2009 with 2012 to establish how programs changed following the major outbreak of *H. halys* in 2010 and information subsequently generated by the team for its management.

Grower perceptions of pheromone-based tools

Fruit growers in the Mid-Atlantic region of the United States were surveyed about whether they experienced damage from *H. halys* and their perceptions of pheromone-based monitoring tools and attract-and-kill (AK) technology as part of a Northeastern SARE-funded project. Surveys were administered at Extension meetings, winter fruit schools, IPM training courses, and other grower outreach events in Maryland, New Jersey, Pennsylvania, Virginia, and West Virginia from January to April in 2015 (before the start of the SARE AK project, full survey in Supp Appendix 1 [online only]), 2016 (Supp Appendix 2 [online only]), and 2017 (end of SARE AK project; pertinent questions in Supp Appendix 3 [online only]). Here, we present data on which pheromone-based tools growers were most interested in using and how grower perceptions changed over the course of the project while providing a barometer of stakeholder feedback for research efforts in the SCRI project. For calculation of acreage affected by *H. halys*, we used self-reported acreages by growers and included only growers who indicated that *H. halys* was a problem for their production.

***Halyomorpha halys* nuisance survey**

A survey was conducted via StopBMSB.org in 2015 to characterize homeowner perceptions of the severity of issues, sources of information, and control options for the annual *H. halys* invasion (Supp Appendix 4 [online only]). In total, 527 individuals responded to the survey distributed by listservs from the Northeastern IPM Center, with some opting not to answer all questions. Using the information collected, a multivariate modified Poisson regression model was used to predict participants' perception of the severity of the issues with the number of *H. halys* reported and the length of time the problem has existed as predictors. The number of years a participant had experienced *H. halys* infestations was used to adjust the model.

Results and Discussion

Working Group Membership

In total, there were 120 unique institutions (Supp Table 1 [online only]) that participated in the BMSB IPM Working Group over 6 yr, including representatives from 33 U.S. states and 10 countries. On average, 35 institutions participated per Working Group meeting, which consisted of representatives from research and Extension

Fig. 1. Stink bug identification kit for outreach, which included a preserved *H. halys* specimen in hand sanitizer, post card with information on *H. halys* video series and link, stink bug identification guide, regional pest alert for *H. halys*, reprint of an IPM Practitioner article on IPM for *H. halys*, six specialty crops at-risk documents, all in a bag.

organizations, growers, industry representatives, and governmental and regulatory agencies (Supp Table 1 [online only]). Attendance peaked in December 2013 at 89, then gradually declined (Fig. 2). In 2010 and 2011, there was strong representation by growers. In the last several years, participants were mostly research and Extension personnel and to a lesser extent, industry, an indication that grower needs were being met following the launch of the SCRI and other affiliated projects.

Working Group Priorities

Three topics were most often ranked in the top five research priorities by members of the Working Group from 2010 to 2016: development of IPM-friendly management tactics, studies on *H. halys* behavior (host preferences, movement, and responses to cues), and studies of biocontrol agents (Table 1). The Working Group also ranked the study of basic *H. halys* biology, the identification

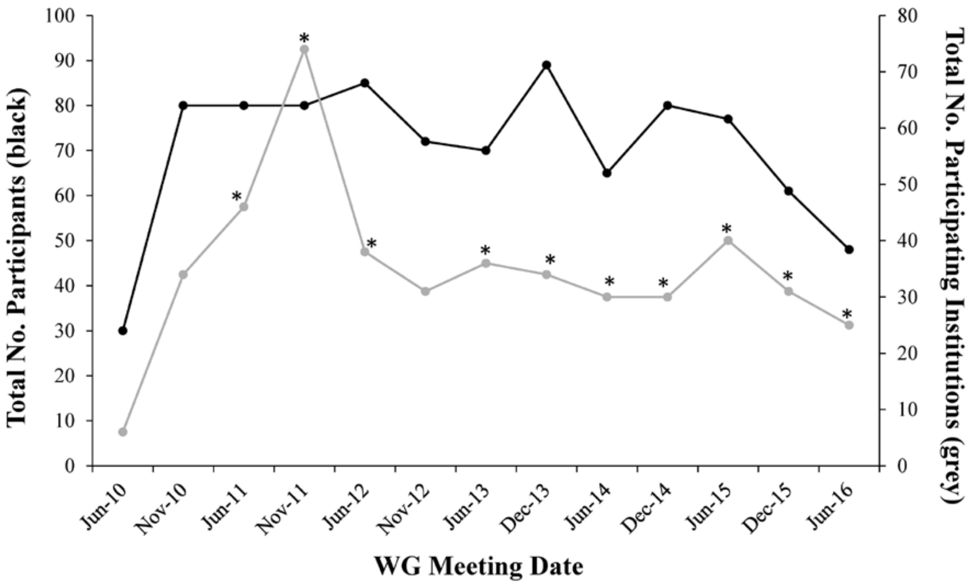


Fig. 2. The number of participants (black line) and participating institutions (gray line) at each BMSB IPM Working Group Meeting from 2010 to 2016. Asterisks indicate participation by international organizations based outside the United States.

Table 1. Research priorities generated by the BMSB IPM Working Group and the corresponding frequencies that each priority was ranked on a 1–5 scale by participants

Research priority	Frequency of research priority rankings					Total years in the top five[a]	Accomplished
	1	2	3	4	5		
Biocontrol agents—identification and study of parasitoids, fungal pathogens, and predators	1	3	1	1	0	6	Partially
Development of IPM-friendly management tactics	3	1	1	0	0	5	Partially
Studies of basic *H. halys* behavior (host preferences, movement, responses to cues)	3	1	0	1	0	5	Fully
Studies of basic *H. halys* biology (physiology, generations)	0	1	1	1	0	3	Fully
Evaluate efficacy and host range of candidate classical biological control agents	0	0	2	0	1	3	Fully
Identification of true pheromone	0	1	0	1	0	2	Fully
Evaluation of parasitoid host specificity	0	0	0	1	1	2	Fully

Shown above are research priorities that ranked in the top five two or more times from 2010 to 2016.

[a]Priorities that were tied in rank for a year may result in summations that exceed the total number of years that the BMSB IPM Working Group met. This is not a calculation error.

of candidate classical biocontrol agents, parasitoid host specificity, and the identification of a *H. halys* pheromone to be in the top five priorities in two or more years (Table 1). Research data addressing the near-term priorities were quickly generated and published by the BMSB SCRI team. Those near-term research goals included understanding 1) pest host range and preferences (Owens et al. 2013; Bakken et al. 2015; Martinson et al. 2015, 2016; Acebes-Doria et al. 2016a; Bergmann et al. 2016), 2) damage to a range of specialty crops (Kuhar et al. 2012; Leskey et al. 2012b; Pfeiffer et al. 2012; Basnet et al. 2014; Hedstrom et al. 2014; Cissel et al. 2015; Joseph et al. 2015; Martinson et al. 2015; Wiman et al. 2015a; Acebes-Doria et al. 2016a,b; Bergmann et al. 2016; Mohekar et al. 2016, 2017; Zobel et al. 2016; Philips et al. 2017), 3) *H. halys* movement, dispersal, and spread (Wallner et al. 2014; Lee et al. 2014a; Lee and Leskey 2015; Venugopal et al. 2015; Wiman et al. 2015b; Blaauw et al. 2016, 2017; Hahn et al. 2016, 2017; Acebes-Doria et al. 2016a, 2017), 4) overwintering behavior and spring emergence (Lee et al. 2014b, Cira et al. 2016, Bergh et al. 2017, Morrison et al. 2017c, Chambers et al. 2019a), 5) pheromone, pheromone synergist, and volatile identifications (Khrimian et al. 2014; Weber et al. 2014, 2019; Harris et al. 2015; Leskey et al. 2015a; Rice et al. 2018), 6) trapping (Leskey et al. 2012c, 2015b; Joseph et al. 2013; Nielsen et al. 2013; Morrison et al. 2015, 2017b, e; Rice et al. 2017, 2018; Chambers et al. 2018), 7) physiology, nutrition, and development (Nielsen et al. 2016a, 2017a,b; Skillman et al. 2018a,b), 8) summarizing knowledge from the native range of *H. halys* (Lee et al. 2013b), and 9) effective insecticides as a short-term mitigation strategy (Kamminga et al. 2012; Kuhar et al. 2012; Leskey et al. 2012d, 2014; Lee et al. 2013a, 2014c; Bergmann and Raupp 2014; Mathews and Barry 2014; Aigner et al. 2015; Kuhar and Kamminga 2017; Morehead and Kuhar 2017; Morrison et al. 2017d). Of the seven identified research priorities, all were either fully or partially accomplished (Table 1). Ultimately, the amount of funding provided by the BMSB SCRI ($10.7 million) and through leveraged projects was critical to this success. Leveraged funding obtained by SCRI team members was greatest in 2012, totaled $8.4 million USD, and was spread across 96 funding sources (Table 2). The average grant awarded from 2010–2016 was $87,625.63 USD.

Long-Term Priorities

Longer-term research priorities identified by the Working Group that became objectives of the previous and current *H. halys* SCRI projects and other leveraged projects included developing IPM tactics and reestablishing IPM programs (Blaauw et al. 2015; Soergel et al. 2015; Morrison et al. 2016, 2019; Nielsen et al. 2016b; Mathews et al. 2017; Short et al. 2017), the evaluation and use of native natural enemies (Jones et al. 2014, 2017; Cornelius et al. 2016a,b; Herlihy et al. 2016; Morrison et al. 2016, 2017a; Ogburn et al. 2016; Dieckhoff et al. 2017; Fraga et al. 2017; Lowenstein et al. 2018), and classical biological control agent *T. japonicus* (Talamas et al. 2015a,b, 2017; Milnes et al. 2016; Hedstrom et al. 2017; Jentsch 2017; Kaser et al. 2018; Morrison et al. 2018; McIntosh et al. 2019; Milnes and Beers 2019; Quinn et al. 2019a,b). In addition, as biological control was considered one of the most important priorities by the BMSB IPM Working Group and both SCRI projects, significant outreach efforts were and continue to be made on this topic. To enable research and Extension personnel to properly identify *H. halys* parasitoids, an annual workshop was held for the scientific community beginning in 2013. These 2-d workshops led by taxonomy experts have proven to be essential to researchers involved in natural enemy surveys for *H. halys*. This workshop has been held for seven consecutive years to date and averaged 17 attendees per workshop, and in April 2019, an equivalent workshop was conducted in Montpellier, France for European researchers. Outreach efforts for the general public included a public display of *H. halys* and *T. japonicus* at the National Museum of Natural History Insect Zoo from April 2014 to July 2018, with an estimated 7.5 million visitors to the Insect Zoo during that time period.

Regulatory Priorities

There were fewer regulatory priorities overall, and those consistently appearing in the top five in most years included: expanding uses for existing registered products, increasing new product testing and labeling, and clearly defining the economic and ecological threat posed by *H. halys* (Table 3). In total, there were seven regulatory priorities that appeared at least once in the top five ranking. Approximately 80% of the top identified regulatory priorities were either fully or partially accomplished.

Table 2. Additional funding leveraged from other programs and extramural sources by the SCRI Project Team, including number of additional projects and total amounts awarded by year during the SCRI Project (2012–2016)

Grants	2012	2013	2014	2015	2016	Total
Amount	$3,229,180	$2,001,271	$1,245,067	$1,936,542	$215,244.00	$8,412,060
Number awarded	18	28	23	22	5	96

Table 3. Regulatory priorities generated by the BMSB IPM Working Group and the corresponding frequencies that each priority was ranked on a 1–5 scale by participants

Regulatory priority	Frequency of regulatory priority rankings					Total years in the top five[a]	Accomplished?
	1	2	3	4	5		
Expansion of uses of existing registered products	1	1	0	4	1	7	Fully
Product testing and labeling for new products	3	1	2	0	1	7	Fully
Definition of the economic and ecological threat posed by BMSB	0	1	4	2	0	7	Not undertaken
Interagency coordination and interdisciplinary funding	0	1	2	0	2	5	Fully
Use of toxins in combination with attractants (regulatory status)	3	2	0	0	0	5	Partially

Shown above are research priorities that ranked in the top five two or more times from 2010 to 2016.

[a]Priorities that were tied in rank for a year may result in summations that exceed the total number of years that the BMSB IPM Working Group met. This is not a calculation error.

Table 4. Consumer priorities generated by the BMSB IPM Working Group and the corresponding frequencies that each priority was ranked on a 1–5 scale by participants

Consumer priority	Frequency of consumer priority rankings					Total years in the top five[a]	Accomplished?
	1	2	3	4	5		
Defining period of movement to homes and triggers for movement	2	0	3	0	0	5	Fully
Preventative measures for reducing entry into human-made structures	0	3	2	0	0	5	Partially
Important biological control agents around residential areas	0	0	0	4	0	4	Fully
Development of IPM-friendly management strategies	3	0	0	0	0	3	Not undertaken
Factors associated with selection of overwintering sites	0	0	1	0	1	2	Fully
Forecasting population size	0	1	0	0	1	2	Partially
Evaluate efficacy of insecticides/killing agents for homeowners	0	0	0	0	2	2	Fully

Shown above are research priorities that ranked in the top five two or more times from 2012 to 2016.

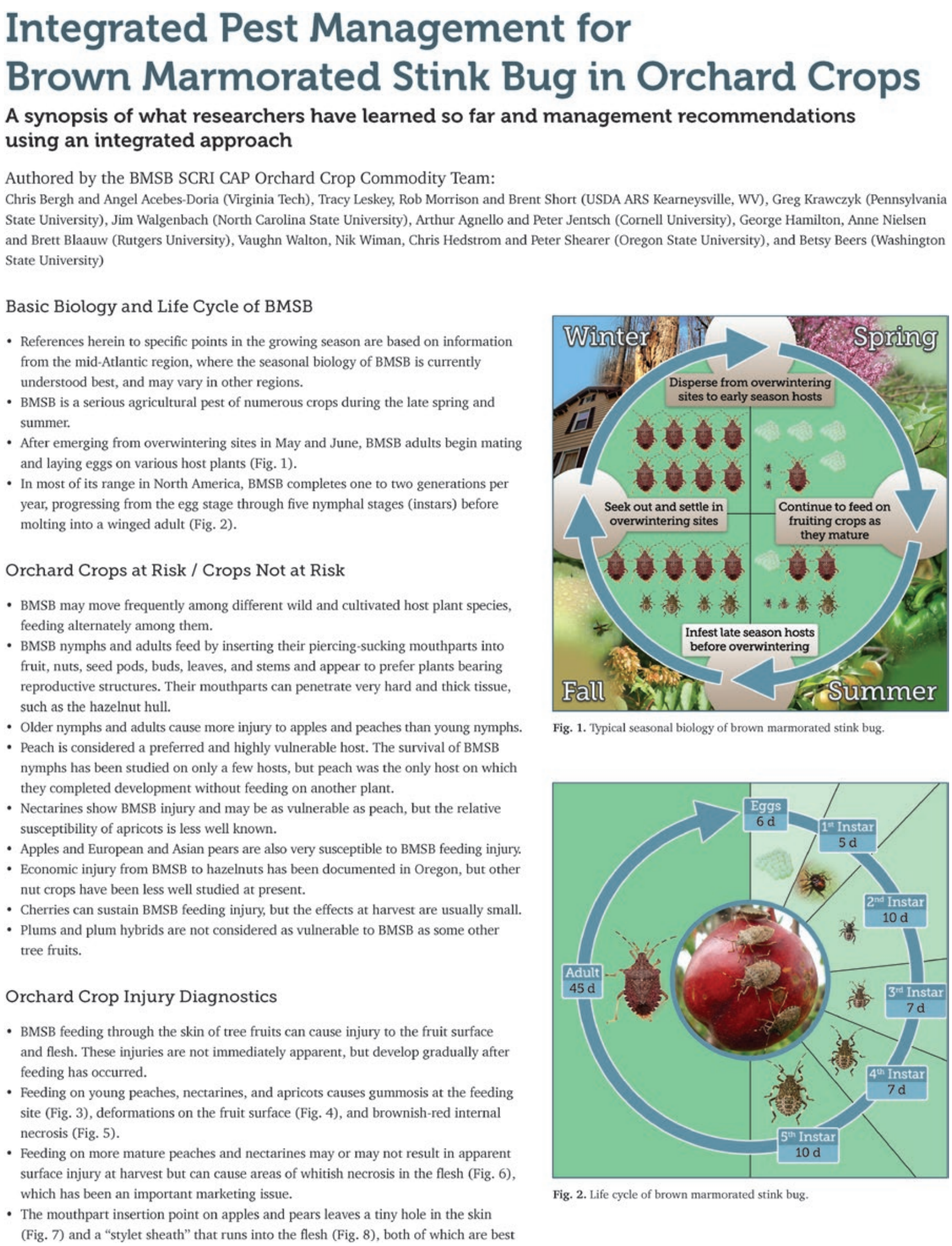
[a]Priorities that were tied in rank for a year may result in summations that exceed the total number of years that the BMSB IPM Working Group met. This is not a calculation error.

Table 5. Extension priorities generated by the BMSB IPM Working Group and the corresponding frequencies that each priority was ranked on a 1–5 scale by participants

Extension priority	Frequency of extension priority rankings					Total years in the top five[a]	Accomplished?
	1	2	3	4	5		
Educating professionals to pest ID and diagnosis of injury	0	1	0	3	3	7	Partially
Education programs to growers and the general public	5	1	0	0	0	6	Partially
Develop revised and unified management plans	1	1	4	0	0	6	Fully
Coordinate efforts of state and regional extension programs	0	3	0	3	0	6	Fully
Deliver economic injury thresholds	0	2	2	0	1	5	Fully

Shown above are research priorities that ranked in the top five two or more times from 2010 to 2016.

[a]Priorities that were tied in rank for a year may result in summations that exceed the total number of years that the BMSB IPM Working Group met. This is not a calculation error.



Integrated Pest Management for Brown Marmorated Stink Bug in Orchard Crops

A synopsis of what researchers have learned so far and management recommendations using an integrated approach

Authored by the BMSB SCRI CAP Orchard Crop Commodity Team:
Chris Bergh and Angel Acebes-Doria (Virginia Tech), Tracy Leskey, Rob Morrison and Brent Short (USDA ARS Kearneysville, WV), Greg Krawczyk (Pennsylvania State University), Jim Walgenbach (North Carolina State University), Arthur Agnello and Peter Jentsch (Cornell University), George Hamilton, Anne Nielsen and Brett Blaauw (Rutgers University), Vaughn Walton, Nik Wiman, Chris Hedstrom and Peter Shearer (Oregon State University), and Betsy Beers (Washington State University)

Basic Biology and Life Cycle of BMSB

- References herein to specific points in the growing season are based on information from the mid-Atlantic region, where the seasonal biology of BMSB is currently understood best, and may vary in other regions.
- BMSB is a serious agricultural pest of numerous crops during the late spring and summer.
- After emerging from overwintering sites in May and June, BMSB adults begin mating and laying eggs on various host plants (Fig. 1).
- In most of its range in North America, BMSB completes one to two generations per year, progressing from the egg stage through five nymphal stages (instars) before molting into a winged adult (Fig. 2).

Orchard Crops at Risk / Crops Not at Risk

- BMSB may move frequently among different wild and cultivated host plant species, feeding alternately among them.
- BMSB nymphs and adults feed by inserting their piercing-sucking mouthparts into fruit, nuts, seed pods, buds, leaves, and stems and appear to prefer plants bearing reproductive structures. Their mouthparts can penetrate very hard and thick tissue, such as the hazelnut hull.
- Older nymphs and adults cause more injury to apples and peaches than young nymphs.
- Peach is considered a preferred and highly vulnerable host. The survival of BMSB nymphs has been studied on only a few hosts, but peach was the only host on which they completed development without feeding on another plant.
- Nectarines show BMSB injury and may be as vulnerable as peach, but the relative susceptibility of apricots is less well known.
- Apples and European and Asian pears are also very susceptible to BMSB feeding injury.
- Economic injury from BMSB to hazelnuts has been documented in Oregon, but other nut crops have been less well studied at present.
- Cherries can sustain BMSB feeding injury, but the effects at harvest are usually small.
- Plums and plum hybrids are not considered as vulnerable to BMSB as some other tree fruits.

Orchard Crop Injury Diagnostics

- BMSB feeding through the skin of tree fruits can cause injury to the fruit surface and flesh. These injuries are not immediately apparent, but develop gradually after feeding has occurred.
- Feeding on young peaches, nectarines, and apricots causes gummosis at the feeding site (Fig. 3), deformations on the fruit surface (Fig. 4), and brownish-red internal necrosis (Fig. 5).
- Feeding on more mature peaches and nectarines may or may not result in apparent surface injury at harvest but can cause areas of whitish necrosis in the flesh (Fig. 6), which has been an important marketing issue.
- The mouthpart insertion point on apples and pears leaves a tiny hole in the skin (Fig. 7) and a "stylet sheath" that runs into the flesh (Fig. 8), both of which are best

Fig. 1. Typical seasonal biology of brown marmorated stink bug.

Fig. 2. Life cycle of brown marmorated stink bug.

Fig. 3. Example of the provisional guidance document for orchard crops that were developed by the SCRI CAP Project Team based on input from the SAP and published by the Northeastern IPM Center in 2016.

Consumer Priorities

The three most highly ranked consumer priorities were 1) defining the period of movement into homes and cues to stimulate movement, 2) developing preventative measures for reducing entry into human-made structures, and 3) evaluating important biological control agents around residential areas. In 2015, to determine if consumer priorities were being met, members of the general public were asked about *H. halys* nuisance issues. Of those who responded to the survey (n = 527), 92% indicated that invasion by *H. halys* in their home was the primary source of problems compared with businesses or other areas (e.g., gardens, exterior of the house, storage units, or other structures). More than 71% of respondents (n = 482) indicated that problems had been ongoing for 1–3 yr. Nearly 34% reported the problem as 'bad' or 'extremely horrible'. Individual estimates of the number of *H. halys* inside a home were as follows: not sure (15.03%), 1–99 (44.68%), 100–999 (26.51%), 1,000–9,999 (11.69%), and 10,000 or more (1.87%). According to the multivariate model, respondents with 1,000 or more *H. halys* were five times more likely to report the issue as bad or horrible compared with those with 99 or less. Length of invasion also had an impact on perception of the problem, with those experiencing problems for more than 1 yr characterizing them as 'bad' or 'horrible'. Surveyed individuals reported turning to a variety of information sources with exactly half of those using university Extension sources, although 79.7% of these individuals also used an additional source of information. Of the top consumer priorities, 85% were either fully or partially accomplished (Table 4). Some key projects included addressing the efficacy of ready to use products (Bergmann and Raupp 2014) and consumer traps (Aigner 2016), as well as using crowd-sourced data to understand spread (Hahn et al. 2016), alightment on and passage into homes (Hancock et al. 2019, Chambers et al. 2019b), and potential management tactics at overwintering sites (Bergh and Quinn 2018).

The need for educating growers and pest management professionals to identify *H. halys* and injury symptoms accurately was consistently ranked in the top five Extension priorities by the Working Group (Table 5). Development of revised and unified management plans, education programs for growers and the general public, the coordination of state and regional Extension programs, and the delivery of economic injury thresholds were also ranked in the top five Extension priorities five or more times (Table 5). Five other Extension priorities were ranked in the top five just once. Overall, 100% of the top Extension priorities were either fully or partially accomplished.

SAP Recommendations and Extension/Outreach Products

Working Group priorities dovetailed with recommendations that emerged from the BMSB SCRI SAP, including: 1) tools for specialty crop growers to better identify *H. halys* and other pestiferous and beneficial stink bug species based on survey results obtained from specialty crop growers by Extension educators in 2012 (Dellinger et al. 2016) and 2) provisional 'guidance documents' for managing *H. halys* in specialty crops. Based on these recommendations and priorities, pocket-sized stink bug identification guides for North America were created and distributed to over 4,500 stakeholders. Further, provisional guidance documents (Fig. 3) that contained diagnostic damage images for various commodities, *H. halys* life cycle and development diagrams, an illustration demonstrating the landscape-level risk posed by *H. halys*, description of the standard monitoring traps, common natural enemies that attack *H. halys*, and efficacious insecticides were created for orchard crops, vegetables, grapes, and small fruit. Each of these guidance documents was also translated into Spanish. Hard copies of more than 23,000 guidance documents as well as associated stink bug ID kits were distributed to researchers and stakeholders in the United States and abroad, with

Table 6. Number of hardcopy outreach documents distributed to researchers and stakeholders in the United States and internationally during the first SCRI project

Documents	Number distributed
Management recommendation fact sheets	
Halyomorpha halys in vegetables [English]	3,774
Halyomorpha halys in orchard crops [English]	5,664
Halyomorpha halys in grapes [English]	2,964
Halyomorpha halys in small fruit [English]	3,184
Halyomorpha halys in vegetables [Spanish]	804
Halyomorpha halys in orchard crops [Spanish]	984
Halyomorpha halys in grapes [Spanish]	494
Halyomorpha halys in small fruit [Spanish]	544
Other outreach tools	
Field Guide to Stink Bugs	3,241
Stink Bug ID kits	1,327
DVDs (tracking the brown marmorated stink bug)	200
Total	23,180

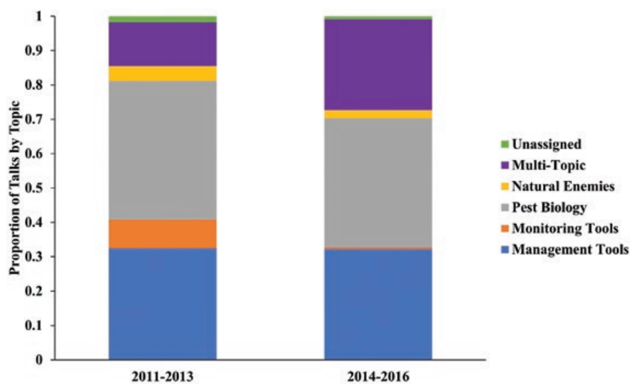


Fig. 4. Extension and outreach talks categorized by the topic from 2011–2013 and 2014–2016 during the first SCRI CAP.

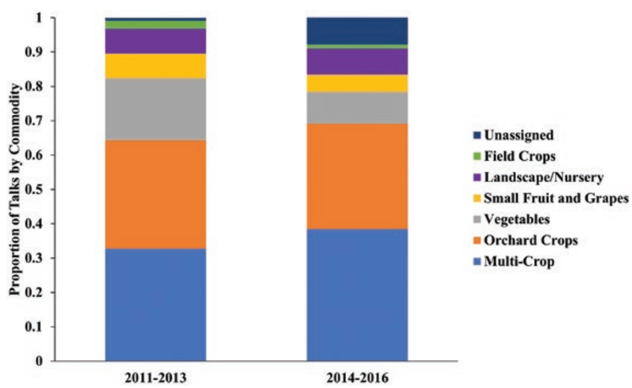


Fig. 5. Extension and outreach talks categorized by crop from 2011–2013 and 2014–2016 during the first SCRI CAP.

Table 7. Per acre insecticide costs for a sample of apple growers in the Mid-Atlantic region, 2009–2012*a*

Year	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	Average change
2009	$691	$336	$481	$491	$528	$385	$533	$345	$345	
2010	$739	$438	$422	$698	$599	$575	$301	$597	$445	+$75
2011	$1,325	$475	$485	$507	$690	$373	$324	$829	$435	+$70
2012	$951	$674	$542	$551	$547	$604	$423	$965	$507	+$35

[a]Spray records for apple and stone fruit growers in West Virginia, Maryland, Pennsylvania, and New Jersey provided by Tracy Leskey (USDA-ARS), Greg Krawczyk (Penn State University), and Dean Polk (Rutgers University).

Table 8. Per acre insecticide costs for a sample of stone fruit growers in the Mid-Atlantic region, 2009–2012*a*

Year	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	Average change
2009	$462	$399	$660	$398	$281	$232	$751	$237	$245	$403	n.d.[b]	n.d.[b]	
2010	$662	$302	$617	$268	n.d.[b]	$274	$442	$360	$255	$313	n.d.[b]	n.d.[b]	–$33
2011	$740	$249	$640	$337	$248	$178	$570	$414	$236	$405	$473	$298	+$31
2012	$887	$305	$666	$316	$357	$196	$460	$314	$267	$497	$547	$461	+$40

[a]Spray records for apple and stone fruit growers in West Virginia, Maryland, Pennsylvania, and New Jersey provided by Tracy Leskey (USDA-ARS), Greg Krawczyk (Penn State University), and Dean Polk (Rutgers University).
[b]n.d. indicates that spray records were not available for that particular grower and year.

Table 9. Summary of damage reported by growers for surveys administered on an annual basis between 2015 and 2016 at meetings in five Mid-Atlantic U.S. States (Maryland, New Jersey, Pennsylvania, Virginia, West Virginia)

Year[a]	% Growers		% Growers			% Growers		*N*
	With damage	No damage	# Min affected ha[b]	Interested in AK[c]	Believe AK is effective	Interested in PT[c]	Have or will use PT	
2015	76.2	23.8	5,523	80.4	46.9	47.3	18.4	228
2016	74.8	25.2	2,221	60.1	66.7	53.0	20.1	138
2017	69.4	30.6	9,881	50.4	37.4	65.0	27.6[d]	131

[a]2017 survey question for % of growers interested in/thought AK was effective was structured differently, which may have contributed to the different response rate compared with prior years, see Supp Appendices 1–3 (online only).
[b]Minimum number of reported ha with damage.
[c]AK = attract-and-kill, PT = pheromone-baited traps.
[d]Percentage of growers that believe pheromone-baited traps are effective.

the great majority (>80%) consisting of the English language provisional recommendations fact sheets (Table 6).

SCRI Output Topics

SCRI Team members reported 792 Extension and outreach talks; the focus of most Extension talks from 2011–2013 and 2014–2016 were on basic pest biology of *H. halys* and management tools, respectively (Fig. 4). As the relative risk posed by *H. halys* became known for each specialty crop commodity, researchers refocused their efforts to address the needs of the most vulnerable specialty crops with the greatest numbers of talks either covering orchard crops or multiple crops at most meetings (Fig. 5). An estimated 22,000 direct stakeholder contacts were made via presentations by the SCRI team.

Identifying Short-Term Control Options

When *H. halys* outbreak populations were discovered in the Mid-Atlantic, there were no Extension recommendations available for any cropping system. Thus, there was variability in how growers managed the initial threat in the absence of information, and it was clear that the number of insecticide applications made by growers increased (Leskey et al. 2012a). On average, spray costs for the nine apple growers increased by $181 per acre ($447 per ha) from 2009 to 2012, representing a 52% increase in management costs (Table 7). There was geographical variation in pest pressure and responses differed by individual growers across the region. Overall, 89% of apple growers had costs that increased from 2009 to 2012. The situation was quite different for stone fruit (peach) growers, with average spray costs increasing by $20 per acre ($49 per ha) from 2009 to 2012, representing a 5% increase in costs (Table 8). Following 2010, many insecticide efficacy experiments were conducted to enable specific management recommendations for *H. halys*. This work was used to support EPA Emergency Use Exemptions (Section 18) for dinotefuran and bifenthrin use in tree fruits primarily for states in the Mid-Atlantic. In addition, this information was incorporated into state and regional pest management guides for more than 85,000 acres (34,398 ha) of specialty crop production.

Reestablishing Long-Term IPM Programs

There was a dramatic need to reduce insecticide inputs among growers, as some were spraying over 20 times per growing season to protect vulnerable crops, resulting in increased costs and secondary pest outbreaks (Leskey et al. 2012a). From 2015 to 2017, growers were surveyed regarding their perceptions and adoption of pheromone-based technology in apple orchards in the Mid-Atlantic United States to reduce insecticide inputs. Survey responses were received from 497 growers over 3 yr (Table 9). Over the course of 3 yr, most surveyed growers (69–76%) reported damage from *H. halys*. In 2017, about 50% and 65% of growers were interested in adopting AK and pheromone-baited monitoring traps, respectively. This difference in adoption interest is likely due to the labor commitment of weekly sprays required for AK programs (Morrison et al. 2019). When the stakeholder interest in pheromone-technology is taken together with growers who have reported that they are already currently using or will use pheromone technology in the next year, this represents almost 93% of all apple growers surveyed (Table 9). In 2017, almost 70% of growers reported that their *H. halys* Extension needs were being met at an above average or best level by available information. Finally, in 2017, tree fruit growers reported an overall average of 16.5% injury from *H. halys*, which, while still high, was much lower than in 2010 and 2011 when Extension recommendations and monitoring traps were not available (Leskey et al. 2012a).

Table 10. Resources that growers would like to hear more about in the future relative to *H. halys* at the end of the SARE-funded project in 2016

Topics	% Growers[a]
Most effective insecticides	57
Timing of insecticide sprays	49
Protecting beneficial insects	45
Monitoring traps or other sampling techniques	32
Predict future outbreaks or time periods of risk	32
Treatment thresholds	30
Organic control methods	29
Perimeter-based management	22
Stink bug identification and/or identification of injury	16
I do not want to hear more about *H. Halys*	1

[a]Out of *N* = 134 growers in five Mid-Atlantic States.

At the end of the study, growers reported they were most interested in receiving information about the most effective insecticides, optimal timing for insecticide applications, and methods to protect beneficial insects (Table 10).

National Outreach Efforts

A unique aspect of the SCRI project was its national reach. For example, the comprehensive StopBMSB.org website was launched in September 2012 and utilized by 204,241 visitors through 30 September 2016 (Table 11). All institutions participating in the SCRI project contributed to resources on the website, making it a comprehensive national resource for information on *H. halys*. A popular feature of the website continues to be the *H. halys* distribution and pest status map for North America. This map was updated at least once annually at the BMSB IPM Working Group meeting and documented the status of BMSB as its range expanded (Fig. 6). A recent addition to the website includes a map that documents years and locations where *T. japonicus* was recovered. During the original SCRI project there were 39,810 downloads from StopBMSB.org with 95%, 4%, and 1% of those being the *H. halys* distribution maps, infographic of crops at risk, and provisional guidance documents for BMSB management in specialty crops, respectively. The StopBMSB.org site was accessed by residents in all 50 states in the United States during the original SCRI project, with 36% of visits originating from New York, Ohio, Pennsylvania, California, and Virginia. During the same period, there were 46,826 views of the short form videos, with 41%, 15%, and 7% of those for videos about the history and identification, biological control, and overwintering and spread being most popular, respectively (Table 12). As of 6 March 2019, 409,299 people have visited StopBMSB.org and 71,520 downloads have occurred.

Additionally, many members of the SCRI team participated in *H. halys* news stories produced by mainstream media. The reach of these stories is estimated at ~626 million people (Supp Table 2 [online only]). Major outlets that covered the project included

Table 11. Summary of visitors and downloads for StopBMSB.org since it went live during the SCRI Project

Pages	SCRI Phase I	After Phase I	Total
	1 Sept. 2012 to 30 Sept. 2016	1 Oct. 2016 to 6 Mar. 2019	1 Sept. 2012 to 6 Mar. 2019
Downloads			
Crops at risk (views + downloads)	1,628	4,096	5,724
Crops at risk (PDF downloads)	[not tracked separately]	373	373
Halyomorpha halys distribution map (views + downloads)	37,717	22,254	59,971
Halyomorpha halys distribution map (PDF downloads)	[not tracked separately]	289	289
Samurai wasp fact sheet[a]		622	622
Trissolcus japonicus brochure[a]		403	403
Management recommendations[b]			
Halyomorpha halys in vegetables [English]	243	572	815
Halyomorpha halys in orchard crops [English]	137	661	798
Halyomorpha halys in grapes [English]	36	397	433
Halyomorpha halys in small fruit [English]	37	340	377
Halyomorpha halys in vegetables [Spanish]	9	23	32
Halyomorpha halys in orchard crops [Spanish]	3	19	22
Halyomorpha halys in grapes [Spanish]	0	20	20
Halyomorpha halys in small fruit [Spanish]	0	18	18
Total downloads	39,810	30,087	69,897
Total visitors to StopBMSB.org	204,241	207,215	409,299

[a]Not added to StopBMSB.org until *after* the first SCRI project.
[b]Not created until the last year of the first SCRI project.

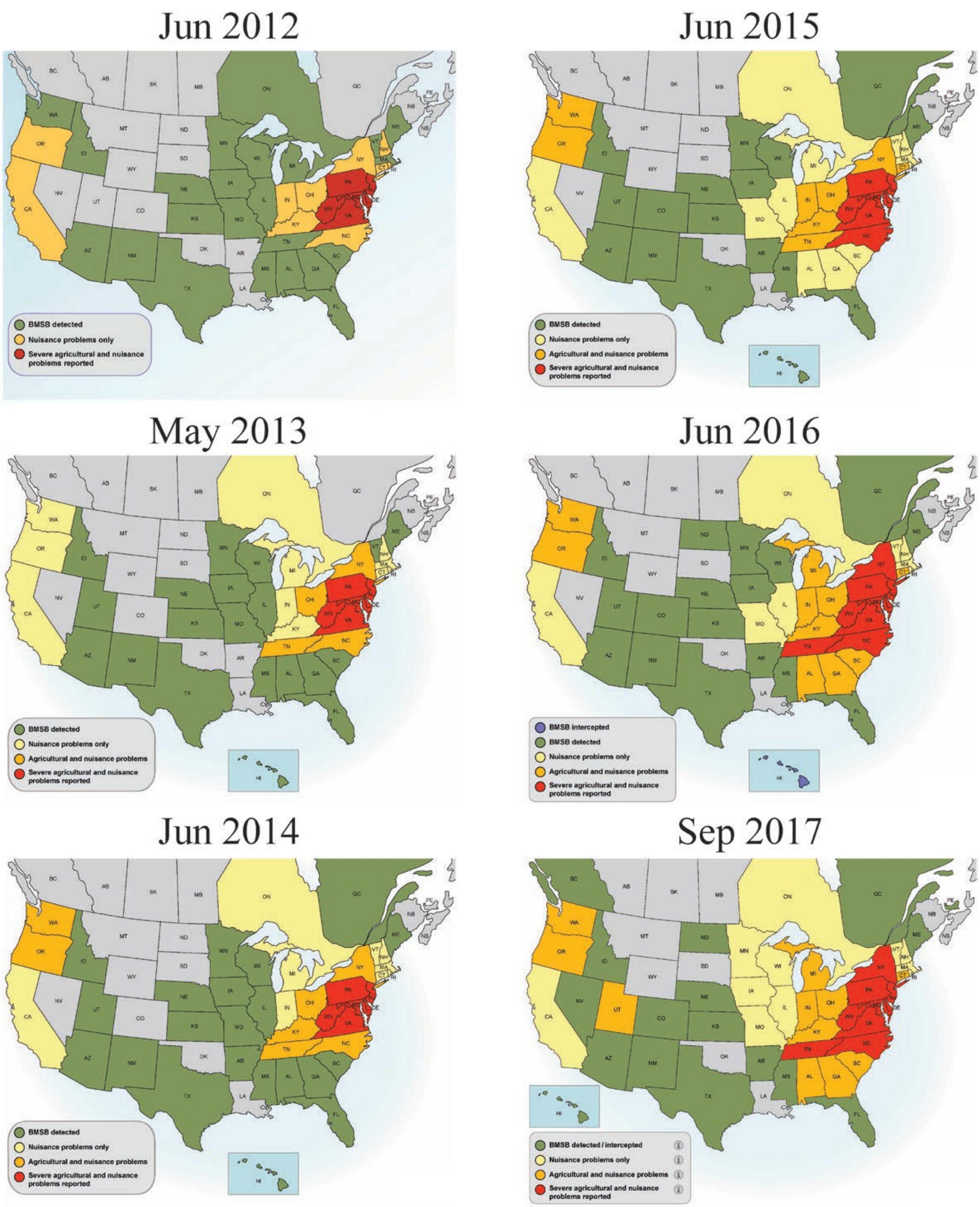


Fig. 6. Distribution map of the brown marmorated stink bug throughout the United States and Canada. The pest status for the insect in each state and province is reported and updated by the BMSB IPM Working Group. Colors represent *H. halys* intercepted (purple), *H. halys* present but not damaging (e.g., detected; green), nuisance problems only (yellow), agricultural and nuisance problems (orange), and severe agricultural and nuisance problems (red).

the New York Times, Washington Post, Wall Street Journal, USA Today, National Geographic, NPR, BBC, CSPAN, and Discovery Channel (Supp Table 2 [online only]). Greatest coverage occurred in 2013, with an estimated reach of 470 million people, and there was a particularly high peak in commodity press coverage that same year.

Table 12. Number of views for videos about *H. halys* life history, ecology, and management on StopBMSB.org

Video	SCRI Phase I	After Phase I	Total
	1 Sept. 2012 to 30 Sept. 2016	1 Oct. 2016 to 6 Mar. 2019	1 Sept. 2012 to 6 Mar. 2019
Tracking BMSB 1: History and Identification	19,301	10,223	29,524
Tracking BMSB 2: Overwintering and Spread	3,152	1,375	4,527
Tracking BMSB 3: Monitoring and Mapping	2,646	1,830	4,476
Tracking BMSB 4: Host Plants and Damage in Orchard Crops	1,179	646	1,825
Tracking BMSB 5: Host Plants and Damage in Small Fruit	768	344	1,112
Tracking BMSB 6: Host Plants and Damage in Vegetables	6,022	1,253	7,275
Tracking BMSB 7: Host Plants and Damage in Ornamentals	849	371	1,220
Tracking BMSB 8: Host Plants and Damage in the Pacific Northwest	961	527	1,488
Tracking BMSB 9: Management	2,188	652	2,840
Tracking BMSB 10: Biological Control	6,956	3,776	10,732
Tracking BMSB 4–8	524	123	647
Stop BMSB Research Update: Biological Control	584	716	1,300
Stop BMSB Research Update: Pyramid Traps	786	1,356	2,142
Stop BMSB Research Update: Monitoring and Trapping	535	872	1,407
Stop BMSB Research Update: Management	375	630	1,005
Totals	46,826	24,694	71,520

Lessons Learned

There were several important lessons learned over the course of the BMSB IPM Working Group and SCRI CAP and related projects. First, priorities being pursued by the research and Extension community should be stakeholder-driven and address short-, medium-, and long-term needs. Second, to tackle a massive national threat to specialty crop production, a large and dedicated group of research and Extension personnel willing to openly collaborate was critical. Importantly, this included employing powerful, large-scale cooperative trials that spanned multiple states to demonstrate the utility of new approaches (e.g., Leskey et al. 2015b, Ogburn et al. 2016, Mathews et al. 2017, Morrison et al. 2017e, Acebes-Doria et al. 2019). This also included rearing of *T. japonicus* in APHIS-approved quarantine facilities around the United States, which allowed the rapid screening of its potential host range. This minimized duplication of effort and increased the speed at which progress was made. Third, the expertise of many disciplines and specialties (e.g., insect behavior, ecology, applied entomology, economics, IPM, biological control, systematics, sociology, modeling, Extension) was critical to address short- and long-term needs, and enabled a synergy of scientific effort across the group. Fourth, frequent interactions with grower stakeholders through the BMSB SCRI SAP and Working Group memberships and activities were critical to not only providing the latest information on *H. halys* management, but also ensuring that priorities pursued by the SCRI team were aligned with grower needs. Fifth, access to knowledge generated by the BMSB IPM Working Group and the SCRI Project Team and other projects allowed regions outside the Mid-Atlantic to anticipate potential issues, respond quickly by already understanding the most effective approaches, saving money and time. This was true domestically as *H. halys* spread to new regions of the United States (e.g., Midwest and South), and internationally, as countries such as New Zealand and others have implemented surveillance and preventative programs. Finally, large multidisciplinary projects such as the BMSB SCRI CAP provided a unique opportunity for specialized training of the next generation of scientists and Extension professionals across the United States. This project enabled training for 147 undergraduates and high school students, 39 graduate students, 30 postdoctoral fellows, and 43 technical staff. All graduate and postdoctoral projects were tracked and circulated among SCRI team members to reduce duplication of effort and encourage collaboration among laboratories. At least nine Ph.D. students who were trained as part of this project are now in permanent positions at universities, Federal research facilities, state agricultural departments, industry, or regulatory agencies. Ultimately, the contributions of all these factors produced a highly impactful and successful project that reduced the impact of *H. halys* in specialty crops.

Supplementary Data

Supplementary data are available at *Journal of Integrated Pest Management* online.

Acknowledgments

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