Project Title: Integrated control of brown marmorated stink bug

Report Type: Final Project Report

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Project Duration: 3 Years

Total Project Request for Year 1 Funding: $96,326
Total Project Request for Year 2 Funding: $99,851
Total Project Request for Year 3 Funding: $103,517

Other related/associated funding sources: Awarded
Funding Duration: 2017-2022
Agency Name: USDA-NIFA-SCRI
Amount: $156,047 for WSU/Beers
Notes: 2017 – 2021, plus a 1 -year NCE due to COVID

Other related/associated funding sources: Awarded
Funding Duration: 2019
Amount: $26,675
Agency Name: Washington State Commission on Pesticide Registration

Other related/associated funding sources: Awarded
Funding Duration: 2020
Amount: $16,505
Agency Name: Washington State Commission on Pesticide Registration

Budget 1
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Item	2019	2020	2021	2022 (NCE)
Salaries[1]	$53,395	$55,531	$57,752	
Benefits[2]	$21,166	$22,012	$22,893	
Wages[3]	$7,800	$8,112	$8,436	
Benefits[4]	$725	$754	$785	
Equipment				
Supplies[5]	$3,000	$3,000	$3,000	
Travel[6]	$5,200	$5,200	$5,200	
Miscellaneous				
Plot Fees[7]	$5,040	$5,242	$5,451	
Total	**$96,326**	**$99,851**	**$103,517**	**$0**

Footnotes: [1]Research Technician (Smytheman), 1.0 FTE, [2]Benefits 39.6%. [3]Time-slip wages 13 weeks@$15/hr., [4]Benefits, 9.3% [5]Laboratory, field and office supplies, electronics. [6]Motor Pool rental, April-October.
[7]Plot fees for Sunrise Orchard apples

Objectives

1. *Investigate the efficacy and non-target effects of insecticide infused netting as a means of monitoring and control of BMSB.* Insecticide-infused netting has several potential applications in monitoring BMSB, and also as a component of behavioral controls. However, the active ingredient in the netting is broad spectrum, thus non-target effects are a possible negative attribute.
2. *Redistribute Trissolcus japonicus (the samurai wasp) where established BMSB populations are identified and monitor its establishment and non-target effects. T. japonicus* was found for the first time in Washington in 2015, allowing us to re-distribute this adventive population; the APHIS permit to release the quarantine strain has not yet been approved. Permit approval is largely based on risk assessment of non-target effects, and the adventive population in Washington provided a rare opportunity to validate laboratory tests in the wild.
3. *Determine development of BMSB on shrub-steppe plants.* BMSB first reached outbreak levels in the US in the mid-Atlantic region, but little is known of its ecology in the semi-arid interior of Washington.
4. *Track the invasion of BMSB in Washington State*. Tracking the spread of an invasive species is key to understanding its invasion ecology. The advent of widely accessible GPS georeferencing, and the combination of targeted sampling and citizen scientist reporting has allowed us to develop a detailed record of the extent and nature of its spread.

Significant Findings

- Captures of BMSB in interior traps in blocks protected by attract and kill (A&K) traps were consistently lower than in blocks not protected by traps. Fruit damage in the protected blocks was 50% lower than the unprotected blocks.
- The use of an insecticide-infused panel trap baited with pheromone provided a significant enhancement to capture over the 'ghost' trap (draped netting). The addition of lights to pheromone traps did not increase trap capture.
- A total of ≈16,000 *T. japonicus* were released in Washington from 2017-2022, with release sites including tree fruit growing areas (mid-Columbia, Yakima, Rock Island, Walla Walla, Prosser), and urban centers (Seattle, Puyallup, Spokane, and Tri-Cities). Yellow sticky cards were deployed to determine if the wasp became established, but only a single specimen was recovered in eastern Washington (Yakima). The original populations in Vancouver, however, are still flourishing.
- Using PCR and morphological methods, we found that *T. japonicus* (samurai wasp) had higher total impact (reproductive and non-reproductive) on the native spined soldier bug (a predator) than on BMSB. Effects on other native stink bug species (all pests) was present, but at lower levels.
- In two years of studies, Washington's native shrub-steppe plants as a diet for BMSB constituted a clear developmental penalty for nymphs reared on native plants in comparison to either a colony diet, or plants prevalent in the mid-Atlantic region. Further, adults experienced substantial reductions in longevity and fecundity on the native diet. This appears to be a clear indication that without crop plants, BMSB will not build to high levels in unmanaged areas of Washington.
- The database tracking the spread of BMSB across Washington has 1,617 records as of December 2022. Thirty of 39 counties have reported BMSB, with the greatest numbers of reports and individual bugs coming from the I-5 corridor centered on Seattle. 2022 was the most active reporting year to date, with 218 reports and ≈9,500 bugs recorded.

Results and Discussion

Obj. 1: Investigate the efficacy and non-target effects of insecticide-enhanced netting as a means of monitoring and control of BMSB

1a. Attract-and-kill for control of BMSB. Much of the initial research on BMSB in the mid-Atlantic area focused on determining the efficacy of various insecticides; this research was critical for enabling growers to prevent crop damage in the short term. Since that time, research efforts have transitioned to exploring longer-term solutions, especially biological control. Although biological control is expected to provide some overall population suppression, it is likely that vulnerable crops will still need a more direct form of protection. Most of the insecticide options will be highly toxic to the samurai wasp and limit its impact in orchards; the primary impact will be in unmanaged habitats. Thus, development of tactics that are compatible with biological control are the highest priority for BMSB.

Behavioral controls have been the most intensively researched alternatives for BMSB control in the past 10 years. The most prevalent of these has been variations on a technique known as attract-and-kill (A&K). The attraction component has been the dual BMSB lure (currently available from Trécé); the means of killing them can be more variable, but often centers on an insecticide component. Initial experiments tested spraying baited trees at frequent intervals, but more recent efforts have focused on the use of long-lasting insecticide nets (LLIN) to cause mortality. This avoids the necessity of weekly sprays; in fact, the toxicity of the netting is projected to last several years.

Methods: We tested a perimeter of A&K traps using 3 pheromone lures and LLIN (Plate 1) to protect an orchard from BMSB fruit damage. Traps were deployed every 50 m (164 ft) on the orchard border next to wooded areas (the latter is presumed to be a major source of BMSB). The traps were deployed in early July and checked every other week until late October. In addition, 3 sticky traps were placed near the center of the orchard to determine penetration of BMSB into the orchard interior. The A&K plots were compared to untreated sections of the same block, separated by a 55 to 756 ft buffer zone (sticky traps only). Adults and nymphs of BMSB retained by the traps were recorded, and a preharvest fruit damage sample (80 fruit/plot) was taken in early August and assessed after ca. 12 weeks of cold storage.

Plate 1. LLIN net in a pear tree

Results and Discussion: Captures in A&K border traps in 2020 were 93 to 99% lower (1 to 3 BMSB/traps/season) than the same blocks in 2019 (44 to 104 BMSB/trap/season), and interior sticky trap catches in 2020 were 61% of those in 2019, indicating lower overall bug pressure in 2020 in this orchard. The A&K traps caught <1 BMSB/trap through most of the season, with no consistent seasonal trend. Surprisingly, the A&K traps caught less than the interior traps throughout the season. The interior sticky traps behind the protective perimeter of A&K traps caught consistently fewer BMSB (Fig. 1), resulting in significantly lower fruit damage at harvest (Fig. 2).

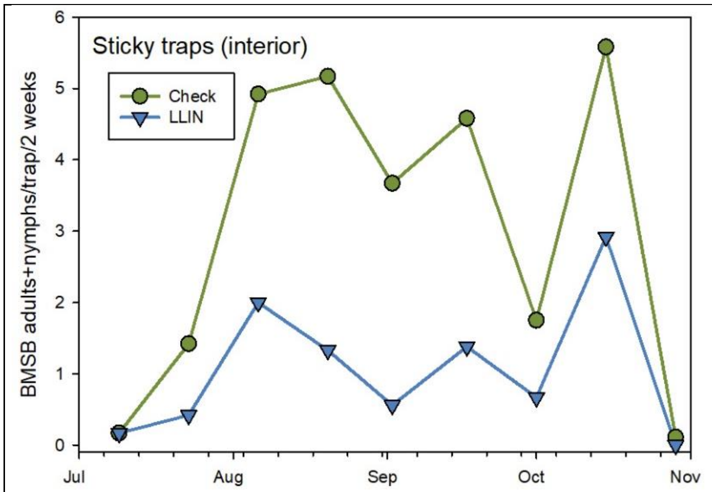


Fig. 1. BMSB captured in the interior of plots protected by A&K traps (LLIN) versus the unprotected (check) plots.

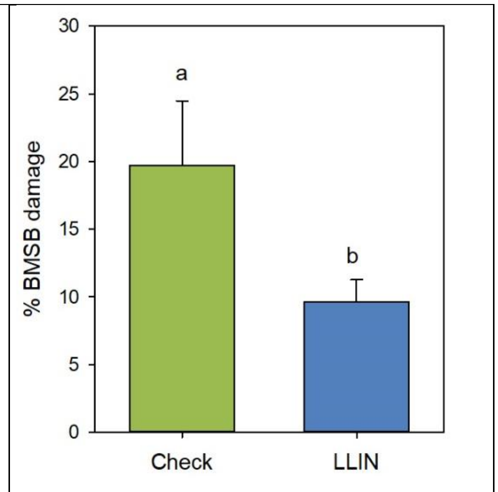


Fig. 2. Fruit damage caused by BMSB in LLIN versus check plots.

1b. Physical exclusion, net barriers. Net barriers were tested to determine if they could intercept stink bugs immigrating into orchards from native habitat. Native stink bugs were used as a proxy for BMSB until populations expanded to a testable level. We built 12 ft high x 150 ft long shade net barriers (white, 20% shade, 2 x 5 mm openings) between apple orchards and unmanaged areas of native habitat (Plate 2a), and studied the movement between the two, and the damage occurring with or without a net. The barriers had a triple row of flaps to retain stink bugs landing on the net and moving upwards. In the second year of the study, the barriers were enhanced with the addition of strips of insecticide infused netting to reduce the possibility of escape of the intercepted bugs (Plate 2b).

Stink bug populations in the orchard were lower in the control plots than in the two barrier treatments, although the differences were not statistically different. Fruit damage was lowest in the deltamethrin net treatment, again without statistical differences. About 6-fold more stink bugs were killed by the deltamethin vs plain net barriers (non-significant), however, higher numbers of some non-target species (Neuroptera, Coccinellids, and Hymenoptera) were also killed by the deltamethrin-augmented nets.

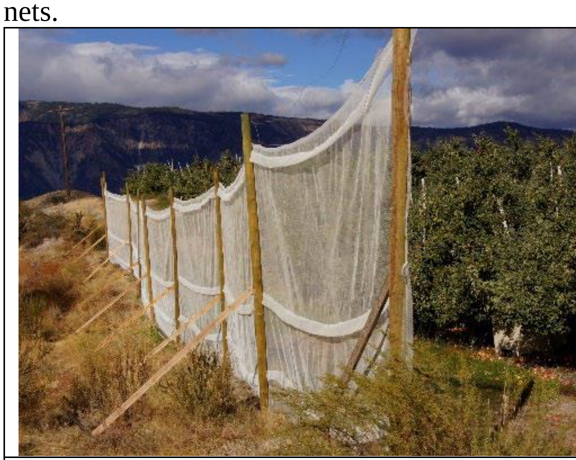


Plate 2a. Net barriers with flaps

Plate 2b. Insecticide-infused netting (black) sewn into flaps of net barrier.

Objective 2: Redistribute *Trissolcus japonicus* (the samurai wasp) where established BMSB populations are identified, and monitor its establishment and non-target effects

2a. Redistribute the samurai wasp in Washington State.

Methods: T. japonicus was found for the first time in Washington State (Vancouver) in 2015, and we have reared it in colony continuously since that time. Most of the colony's production has been for re-distribution to other parts of Washington. While our initial target was the tree fruit growing areas east of the Cascades, we later expanded that to urban areas which had established BMSB populations. We released *T. japonicus* (mostly as adults, occasionally as parasitized eggs close to hatch) from 2017 to 2022. Our goal for release in urban sites is that when BMSB spread from urban to agricultural areas (the pattern observed in other parts of the nation), their parasitoid will move with them. This may effectively constitute a *pro-active* release for agriculture. In addition, we released *T. japonicus* in two agricultural areas in Klickitat County, and two in Douglas County. As a follow-up to our releases, we deployed yellow sticky traps to determine establishment of *T. japonicus* in several previous release sites.

Plate 3. Release of the samurai wasp in Washington

Results: We released a total of **15,488** adult *T. japonicus* in from 2017-2022, in Prosser (455), Puyallup (700), Rock Island (2,910), Seattle (2,288) Spokane (3,840), Tri-Cities (1,239), Walla Walla (448), White Salmon (3,090), and Yakima (518) (Plate 3, Fig. 3). The numbers released were dependent on the availability of egg masses from the BMSB colony. All of the 2021-22 releases were from the 2020 *T. japonicus* collection from one of the original sites in Vancouver.

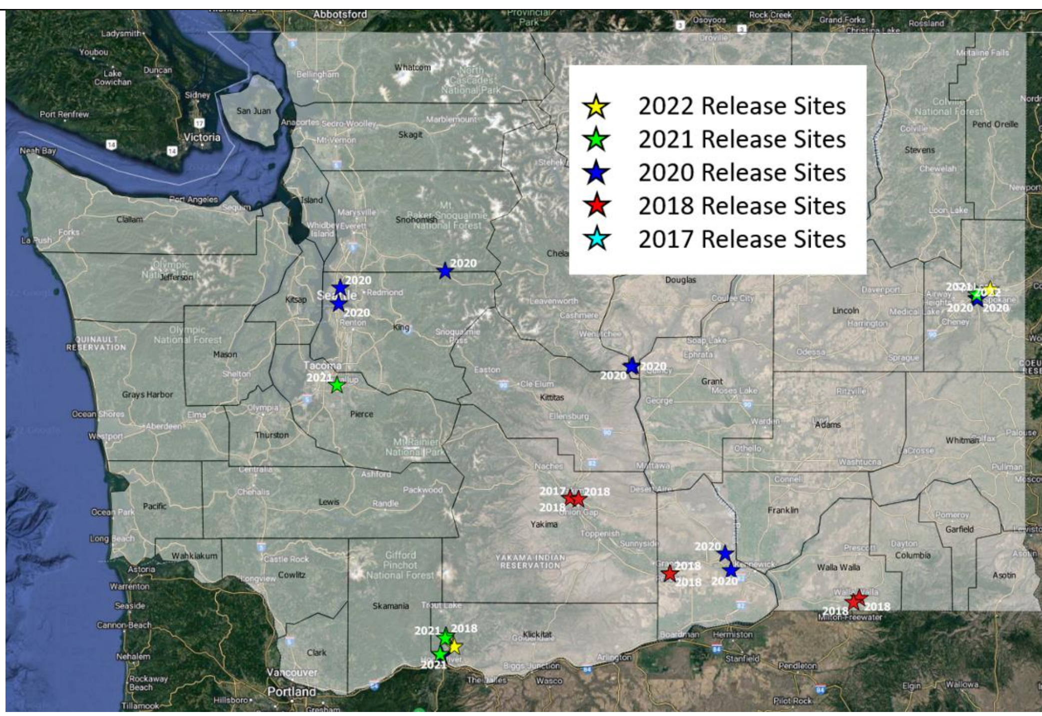


Fig. 3. Release sites of the samurai wasp in Washington, 2017-2022.

From all the years of sampling for recovery of released *T. japonicus*, only a single specimen was recovered from a yellow sticky trap (Yakima, 2022). It is difficult to determine at this point in time if the populations failed to establish, or if they are merely below the threshold of detection. We resampled two of the original sites in Vancouver where *T. japonicus* was first found in 2015-2016. Populations were still present and flourishing; this indicates that at least some of Washington's microclimates are suitable for this parasitoid species. It also validates the use of sticky traps for monitoring recovery of released populations.

2b. Determine permeability of net enclosures to *T. japonicus*. A study was done in 2019 at the Sunrise Research Orchard using released *T. japonicus* from our colony. We used the same 3-tree shade net cages that had been used for BMSB exclusion studies in the past. Sentinel BMSB egg masses (from our colony) were placed in the canopy of an apple tree either inside or outside the net cages. Twenty *T. japonicus* females were released a few feet from the egg mass, with six replicates/treatment. Despite the close proximity of egg masses to the released females, none of the BMSB eggs were parasitized, thus no conclusion can be drawn about net permeability.

2c. Determine the effects of host plant and canopy height by *T. japonicus* (foraging behavior). This objective was explored in two experiments, one in 2019, and one in 2022. The 2019 experiment was performed as described in objective 2b but varying the host plant (apple vs pepper) or the height (1 and 3 meters [3.3 and 9.8 ft] from the ground) in the canopy of an apple tree. Of the 861 sentinel eggs deployed, only 6 were parasitized, all from a single egg mass on pepper, thus no conclusions could be drawn about foraging preferences of *T. japonicus* in relation to egg mass height or host plant (apple vs pepper).

The 2022 experiment was performed at 7 sites in the Vancouver, WA area, which were known or suspected to have an established adventive population of *T. japonicus*. While *T. japonicus* is thought to be arboreal, it can also attack egg masses in vegetable crops (e.g., peppers). Pairs of egg masses were deployed from 3 August to 13 September in adjacent plant canopies either high (6 ft) or low (2 ft) to simulate a tree crop or a vegetable crop. Of the 20 replicate pairs of egg masses deployed, only 4 masses were parasitized (from only 3 sites). Two were from the high treatment, and two from the low treatment. While the attack rate was too low to draw definitive conclusions, *T. japonicus* appears equally capable of finding and parasitizing egg masses regardless of height.

2d. Determine the non-target effects of the samurai wasp on native stink bugs.
Methods: In the summer of 2019 we deployed sentinel stink bug egg masses of three native stink bugs (*Euschistus conspersus Chinavia hilaris*, and *Podisus maculiventris*) and compared them to BMSB to determine attack rate of *T. japonicus*. After allowing completion of egg hatch or development of parasitoids, we characterized the eggs individually using a combination of morphological and PCR methods. The morphological methods used a classification scheme based on appearance where a normally hatched egg and one producing an adult parasitoid were assessed; unhatched eggs were classed based on appearance and subjected to PCR with the new *T. japonicus* primer developed by my lab (Dr. Kacie Athey). The combination of these methods allowed us to evaluate both reproductive (emerged adult parasitoid) and non-reproductive (egg is killed by the parasitoid, but no adult parasitoid is produced) impacts. The latter can be a hidden, but potentially very important non-target effect of a parasitoid, and is an emerging criterium in evaluating natural enemies for classical biological control programs.

Results. *Euschistus conspersus* was not successfully attacked by *T. japonicus* during the course of this study (no adult parasitoids produced); however, it suffered a fairly high rate of non-reproductive effects (22.7%). *Chinavia hilaris*, another pest species, was attacked the least often (7.1% of eggs), with most of the effects being non-reproductive (5.4%). BMSB eggs (*H. halys*) suffered much higher total levels of impact (31%), with most of that successfully producing an adult parasitoid (25.5%). However, the highest level of attack was experienced by the native predator, *Podisus maculiventris* (67.2%), with higher levels of non-reproductive impacts (43.2%) versus reproductive (24.0%) (Fig. 5).

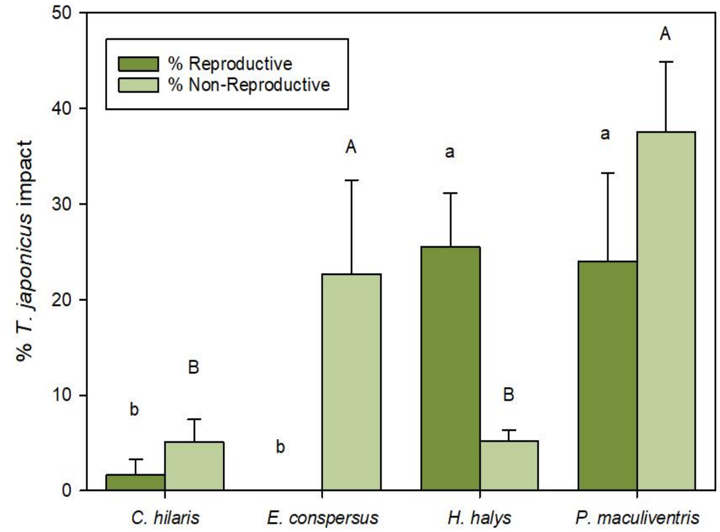


Fig. 5. Total parasitoid impact of *T. japonicus* on BMSB (*H. halys*) and 3 native stink bugs.

Objective 3: Determine development of BMSB on shrub-steppe plants

Methods: In 2019, we compared BMSB raised from the egg to the adult stage on either a typical colony diet (carrots, sunflower seeds, peanuts, bean plants) or plants native to Eastern Washington's sagebrush steppe habitat. Understanding the dietary limitations for development in different regions of the country should help us predict the relative risk of population buildup. The 2019 results indicated clearly that nymphs were slower to develop to the adult stage when fed on native plants, adult weights were lower, and that survivorship was significantly reduced. However, BMSB is unlikely to encounter a typical 'colony' diet in the wild (they do not have access to carrots and peanuts), so we followed up in 2020 with a similar study using plants typical of the mid-Atlantic region compared to our native plants. The mid-Atlantic (or 'Eastern' plants) were cuttings taken from residential areas of Wenatchee, while the native or 'Western' plants were cuttings taken from unmanaged habitats (No. 2 Canyon, Horse Lake Preserve). The assemblage of Eastern plants was fairly consistent throughout the study (maple, tree of heaven, catalpa), while the Western plant assemblage changed as the various species bore fruit. The Western diet was more varied, and included serviceberry, chokecherry (Plate 4), bitterbrush, currant, Oregon grape, elderberry, snowberry, and wild rose at various points during the season. In all cases, both foliage and fruit structures were included in the cuttings; the latter is believed to be essential for the development of BMSB. We followed the nymphal development from 1st instars through adults, noting developmental time, adult weight, and survivorship. Adult weight is believed to associated with reproductive success of the adult; to test this, we took 10 male/female pairs from each of the two diet regimes (continuing with the same diet as the nymphs experienced) and allowed them to mate and lay eggs until the death of the female. This gave us the important measures of fecundity (eggs/female) and longevity.

Plate 4. BMSB nymph on chokecherry.

Results. The survivorship of the Western nymphs to the adult stage was about half the survivorship of those fed the Eastern diet (Fig. 6). The Eastern nymphs reached the adult stage in 42 to 43 days, while the Western nymphs required 49 to 50 days, and their adult weight was 13-15% lower (Fig. 7). The same trends continued for the adults reared on these two diets; the Eastern females laid over twice as many eggs as the Western females (Fig. 8) and lived 59 vs 37 days (Fig. 9). The longevity of the males was 36.1 vs 35.7 days and was not affected by diet.

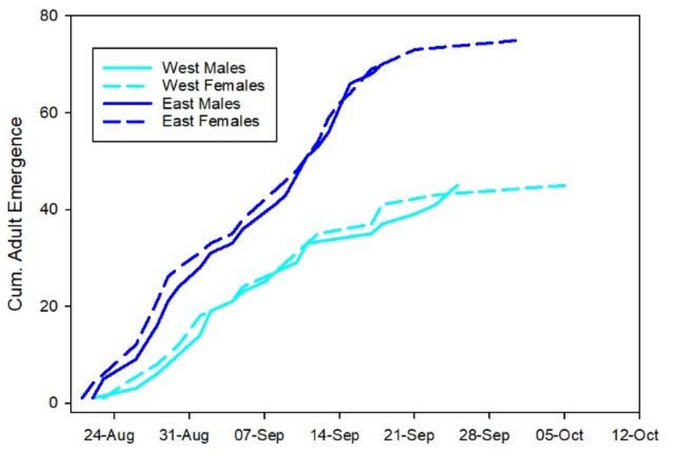


Fig. 6. Adult emergence and survivorship of nymphs fed on host plants from the eastern US vs the arid western US.

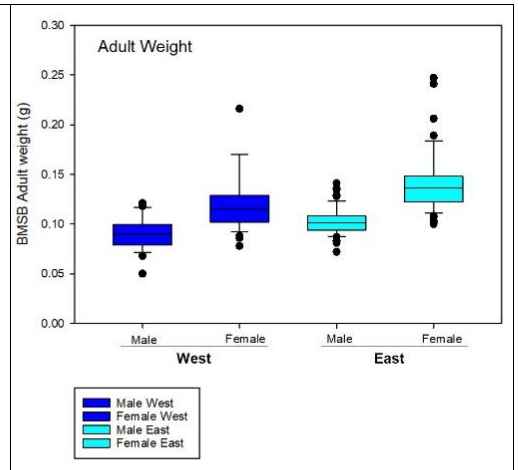


Fig. 7. Weight of surviving adults fed Eastern and Western plant diets (2020).

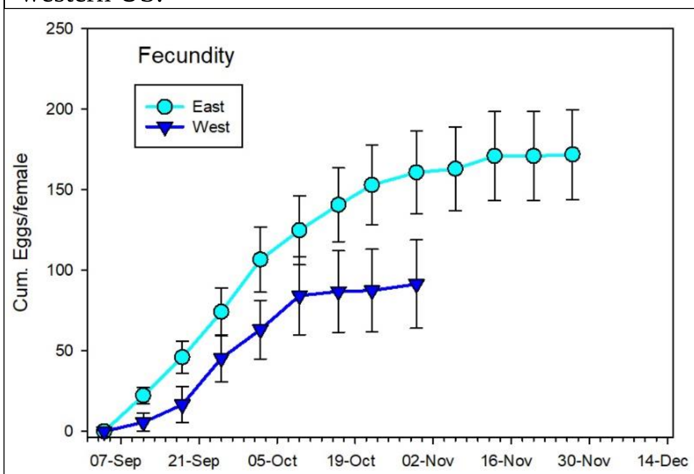


Fig. 8. Fecundity (cumulative eggs/female) from BMSB adults fed on either Eastern or Western plant diet.

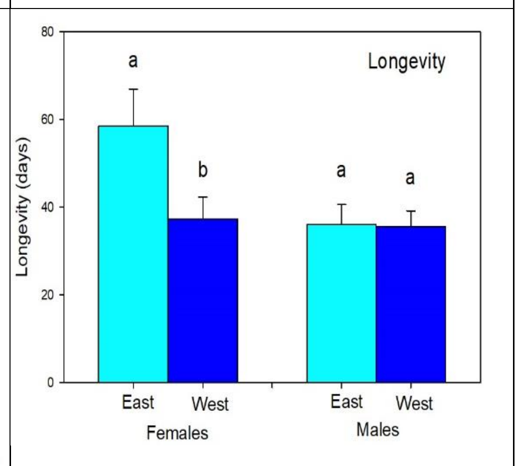


Fig. 9. Adult longevity of BMSB fed on either Eastern or Western plant diet.

Objective 4. Track the invasion of BMSB in Washington State

Methods: We used a combination of targeted sampling with pheromone traps in eastern Washington fruit production areas and logging reports from citizen scientists from around the state to track the spread and relative abundance of BMSB across the state. As of December 2022, the database has 1617 records beginning in 2010 when BMSB was first recorded in Vancouver by K. Sheehan, and in Yakima by Pete Landolt and Dave Horton in 2012. The majority of the records in the database were identified by Peter Smytheman from submitted photographs, and the person submitting the record was asked for a street address; this was used as the georeference point for the maps.

Results: BMSB has been found in 30 (out of 39) counties in Washington state; Island County had its first BMSB report in 2022 (Figure 10).

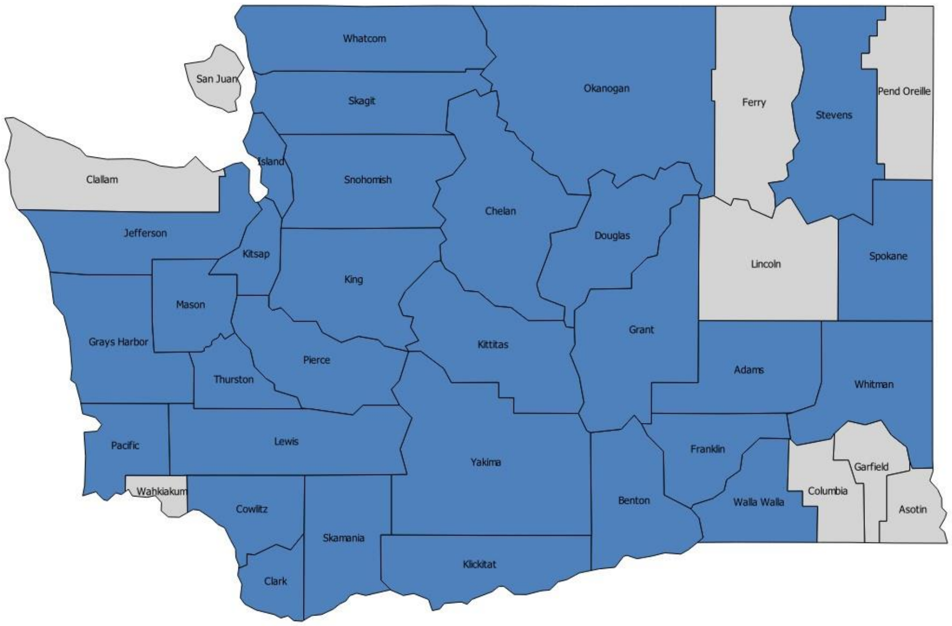
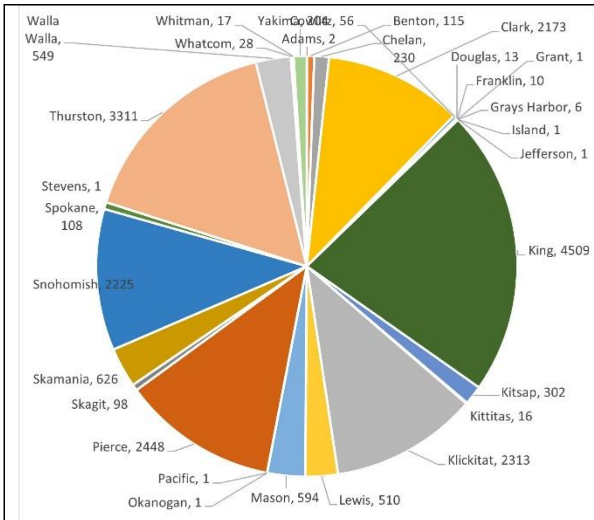


Fig. 10. Counties in blue have recorded one or more BMSB during the reporting period of 2010-2022.



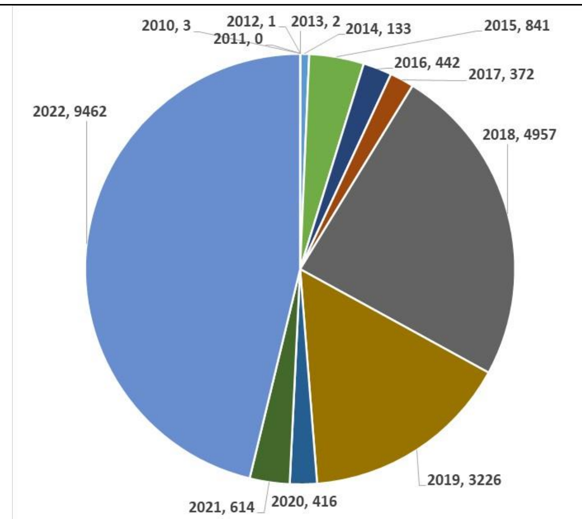


Fig. 11. BMSB reported by county.	**Fig. 12.** BMSB reports by year.

Unsurpisingly, the urban counties on the west side of the state had the highest numbers of bugs reported, led by King, Pierce, Thurston, and Snohomish counties. Along the Columbia River, Clark and Klickitat also had numerous BMSB reported (Fig. 11). The number of reports fluctuated greatly from year to year (Fig. 12), with 2018, 2019, and 2022 having the most bugs reported. In general, the number reported may be a less stable metric than the number of reports, but these two metrics were roughly correlated.

The overwhelming majority (63%) of BMSB reports came from either the interior or exterior of houses (Fig. 13, 14). The next most popular categories were backyards and urban host plants. Only 11% of the reports were from agricultural crops; these numbers are somewhat inflated by the targeted sampling done by my program.

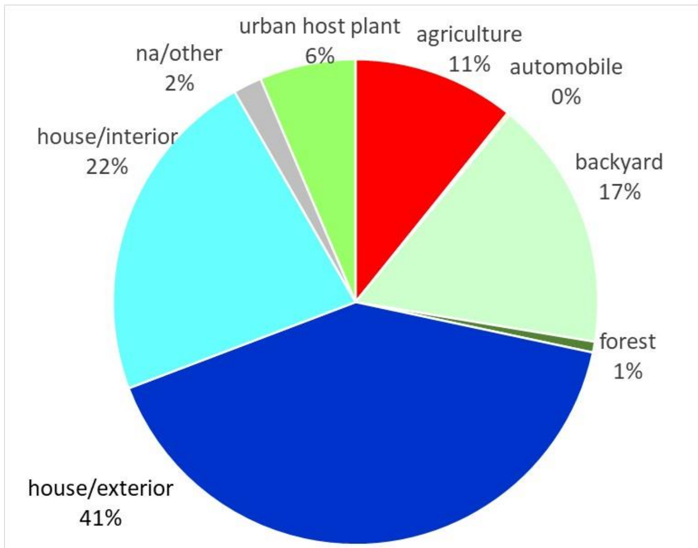


Fig. 13. BMSB reports by location of sighting.

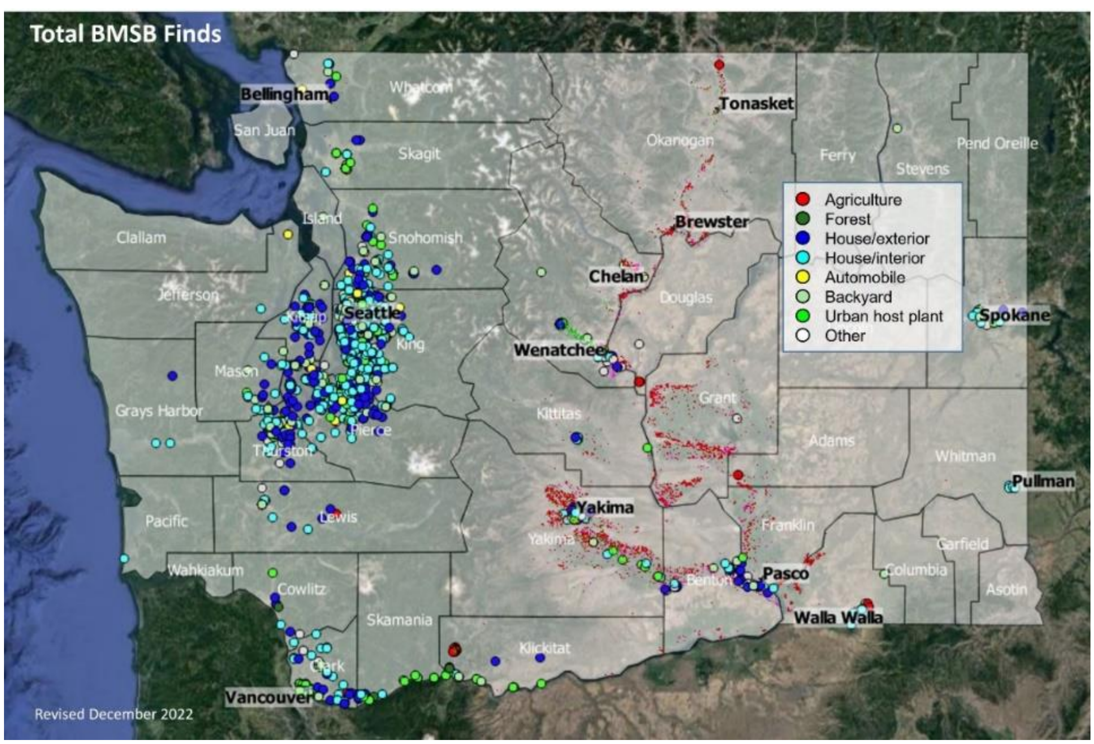


Fig 14. BMSB detection by GPS location. Red, green and magenta pixels represent apple, pear, and sweet cherry acreage, respectively.

The highest concentration of both reports and insects found are from I-5 corridor centered around major urban areas (Seattle, Vancouver). Records east of the Cascades are sparser and more scattered; while it is clear BMSB has invaded the state's interior, populations appear to be localized and relatively small. Most of the finds are in non-native landscaping, where more appropriate host plants are the most plentiful (Fig. 15).

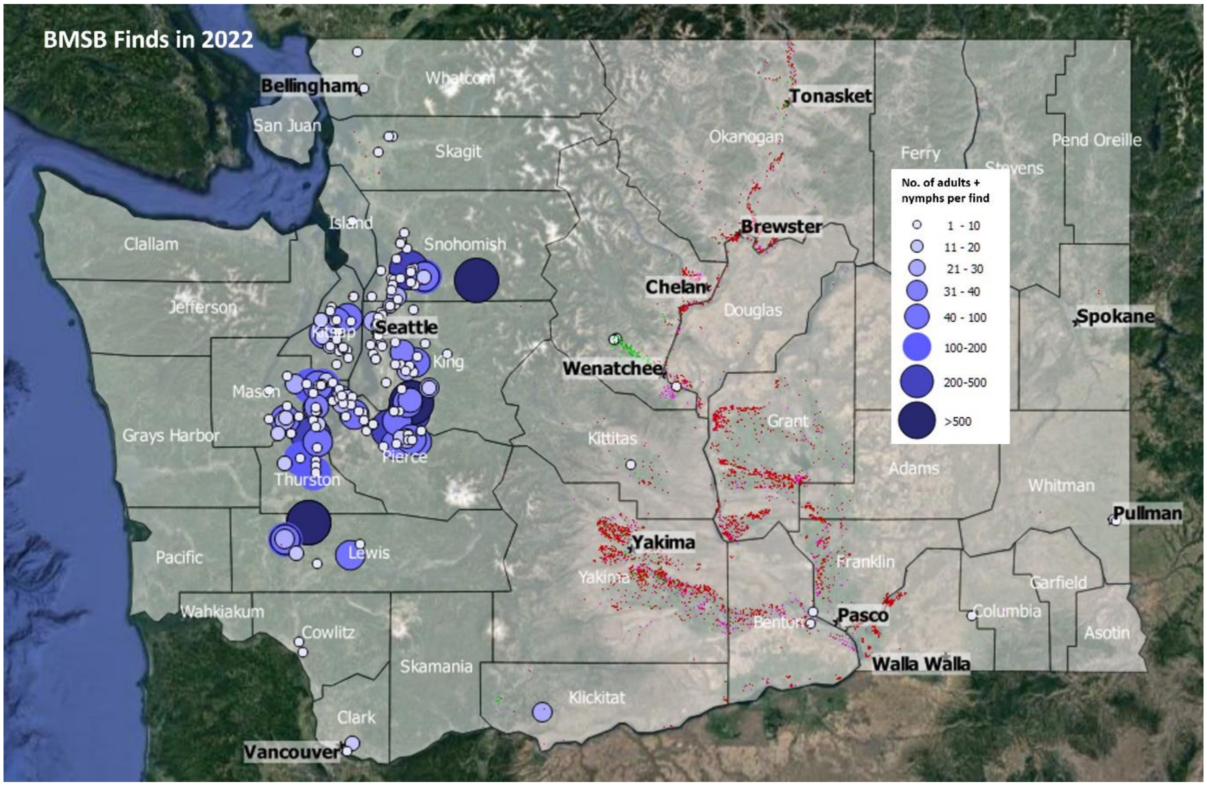


Fig. 15. BMSB reports in 2022; 218 individual reports, totaling 9,500 bugs.

Based on discussions with Justin Bush of the Washington Invasive Species Council (WISC), the BMSB reporting function will be transferred to this organization starting January 1, 2023. This organization has an ongoing mission to track a wide range of invasive species, with greater mapping capability (viz., EDDMapS). Because the WTFRC and SCRI projects are nearing completion, the WISC can provide a long-term archive for this information.

Executive Summary

Project Title: Integrated control of brown marmorated stink bug

Keywords: Invasive species, physical control, biological control, behavioral control, IPM

Brown marmorated stink bug on apple

Abstract: This project, along with the preceding WTFRC grant (CP-16-101), the leveraged projects funded by the USDA-SCRI program and the WSCPR, have established the baselines for a new invasive pest in Washington. We have tracked its spread throughout the state, studied its phenology and nutritional ecology, developed more efficient monitoring tools, explored behavioral and physical controls, and promoted classical biological control where native natural enemies were inadequate. Importantly, we have benefitted by, and contributed to, a national and international research and outreach effort by our colleagues.

The reporting database has established that BMSB is by far more numerous in urban areas west of the Cascades. This may provide a significant advantage for Washington's large agricultural industries which lie primarily east of the Cascades. The most likely explanation is that the semi-arid climate of the interior and its associated flora are inhospitable to this species, and may limit its population growth if not its spread. What remains to be seen is whether the current division we see is permanent, or merely reflecting a delay in invasion and population increase. We can also only speculate whether build-up in unmanaged habitats is a key element in the movement to crop fields and orchards, or if BMSB can achieve pest status without this reservoir.

Moreover, we have clearly identified a possible mechanism why this east-west divide occurs: the poor nutrition provided by our shrub-steppe native plants. Feeding exclusively on native plants imposes a severe developmental and reproductive penalty on BMSB nymphs and adults. When these effects are combined with periods of extreme high temperatures and/or low humidity, mortality at various stages plus poor reproductive success predict greatly slowed population increase in comparison to more favorable climates/regions.

We have successfully used native stink bugs as a model to study control of BMSB, with the added benefit that we now have new potential tools for native stink bugs. Studying control methods before a pest reaches critical levels is difficult, but highly advantageous. With chemical controls already thoroughly explored by eastern colleagues, we focused on behavioral controls using net barriers, insecticide infused netting, and pheromones. The initial results are promising, and may reduce the need for broad-spectrum insecticide applications in areas where BMSB reaches damaging levels.

Lastly, we have made important contributions to the non-target effects of *T. japonicus* (the samurai wasp) because of the well-established adventive population in southwestern Washington. This includes employing new PCR methodology to fully evaluate such effects, and underscore the difference between physiological (lab-derived) host range and ecological host range (that which occurs in nature). This advances the science of introduction of classical biological control (CBC) agents, which may be valuable when future invasive species become candidates for this approach. We have also made significant efforts at re-distributing *T. japonicus*, although to date, without success. Recording our efforts will help future scientists evaluate CBC programs for BMSB, with special emphasis on climate matching of the natural enemy to the invaded region. The same factors that currently limit population growth of BMSB may also limit establishment of *T. japonicus*, either through climatic incompatibility, or simple low host densities.