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BS1847: Review of the biology, ecology and management of the brown marmorated stink bug *(Halyomorpha halys)* with reference to kiwifruit *(Actinidia chinensis)*

Puketapu A

March 2019

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BS1847: Review of the biology, ecology and management of the brown marmorated stink bug (*Halyomorpha halys*) with reference to kiwifruit (*Actinidia chinensis*)

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Plant & Food Research Te Puke

March 2019

Halyomorpha halys (Stål, 1855) (brown marmorated stink bug, BMSB) is native to East Asia with an extensive distribution throughout North America, Canada, Europe and more recently Chile. This invasive insect is a significant economic pest of fruit and vegetable crops. Damage caused by BMSB includes: fruit drop, malformed or distorted fruit, internal tissue damage and skin discoloration. Feeding injury varies in response to host plant phenology, BMSB density and life stage/s present. All nymphal stages, except the first instar, and adults feed on plant structures. Feeding by late instars and adults causes proportionately more damage than earlier nymph stages.

The BMSB life cycle consists of three main stages: egg, nymph (five instars) and winged adults. Late-season adults move to suitable overwintering grounds in late autumn; dispersing again in late spring to feed and mate. The number of BMSB generations per year varies in response to local conditions (temperature, photoperiod); one to two generations is common in invaded regions and China, however four to six generations were reported in Kwangtung (Guangdong) province, China.

BMSB is highly polyphagous with over 300 host plants identified across 62 plant families (identified in this review). BMSB is considered as an arboreal species but also feeds on a wide range of ornamental, wild and horticulturally/agriculturally important crops. Economically important crop hosts include; *Glycine max* (soybean), *Phaseolus* spp. (beans), *Pisum sativum* (pea), *Malus domestica* (syn. *M. pumila*) (apple), *Prunus armeniaca* (apricot), *Prunus domestica* (plum), *Prunus incam* (cherry), *Prunus persica* (peach), *Prunus serotina* (black cherry), *Pyrus* spp. (pear), *Capsicum annuum* (bell-pepper, capsicum), *Actinidia deliciosa* (syn*. A. chinensis* var. *deliciosa)* (Chinese gooseberry, kiwifruit), *Secale cereale* (cereal rye), *Triticum aestivum* (wheat), *Citrus* spp. (lemons, lime, madarins, oranges), and *Solanum lycopersicum* (tomato). BMSB move between crops during the summer growing season based on the availability of suitable host plants. Feeding on multiple host species may support normal development.

Brown marmorated stink bug management

BMSB control at present relies heavily on multiple applications (sometimes weekly) of broad-spectrum insecticides, particularly in North America. This is unsustainable and more integrative control options are required to prevent toxic chemical residues, secondary pest outbreaks, development of pesticide resistance and to avoid harming natural enemies. BMSB is susceptible to a range of broad-spectrum insecticides including those belonging to the neonicotinoid, organophosphate, organochlorine, pyrethroid and carbamate chemical groups.

Pheromone baited traps (pyramid or clear sticky traps) are largely used to identify and monitor the presence of BMSB. The stimuli included in these traps are based on the male-produced aggregation pheromone that attracts BMSB to the area and not the exact location of deployment. It is recommended to use timed visual inspections and/or beating of vegetation in the area surrounding the lure for a more accurate indication of local population numbers. Visual inspection may also be useful to identify the presence of overwintering BMSB populations and to monitor trap crops.

In the absence of prescribed cultural control methods specific to BMSB, general cultural control methods may help in reducing pest populations. Trap cropping has been explored and a mixture of sorghum (*Sorghum bicolor* L.) and sunflower (*Helianthus* L.) has been demonstrated to be effective for BMSB. *Trissolcus japonicus*, a parasitoid of BMSB, has been identified as the best candidate for classical biological control. Adventive populations of *T. japonicus* have appeared in North America and Switzerland.

Integrated pest management (IPM) strategies are currently under development for BMSB, many of which involve the use of pheromone stimuli in various attract and kill strategies or combined with traps (ground deployed pyramids) as indicators of action thresholds. Field trials have validated some of these methods in peach and apples crops in North America.

Damage to kiwifruit

BMSB is a reported pest of kiwifruit in China, Korea, Italy, and more recently Greece. Anecdotal reports from China and Korea estimate >30% crop losses due to BMSB injury. European growers have reported similar crop damage and large BMSB infestations (M. Suckling pers. comm.) Kiwifruit damage associated with BMSB includes; fruit, flower and bud drop, fruit deformation and internal tissue damage.

In the event of BMSB establishing in New Zealand, the kiwifruit industry is likely to face a number of challenges including; possible limits to export markets, disruption of current management systems due to increased chemical use, potential issues with chemical residues and exceeding international minimum residue levels (MRLs) and increased production costs (packaging, labour, crop protection and control).

Management in kiwifruit

Control options suitable for use or adaptation in the current kiwifruit management systems in New Zealand include chemical, cultural and biological strategies.

Many of the insecticide sprays identified as efficacious against BMSB overseas belong to chemical groups either prohibited from use in New Zealand and/or the current Zespri® Crop Protection Programme (CPP). The use of unpermitted chemicals would likely result in impeded access to export markets and social licence to operate, as well as disrupt the current IPM programme. Of the insecticides used or tested offshore against BMSB, bifenthrin, thiacloprid, pyrethrum and spinosad could be applied against BMSB as these are currently permitted within the CPP at certain periods in the cropping cycle. Of these products only bifenthrin showed good activity against BMSB.

Currently pheromone stimuli are the most efficacious and widely available BMSB attractants. Should the BMSB establish in New Zealand, these will be widely used to monitor for BMSB presence and could also be used as attractants in various attract and kill (AK) strategies for BMSB control. General cultural control techniques including the removal of alternate hosts may help to reduce BMSB abundance. Crop netting may provide a degree of protection from feeding damage, however negative effects (on fruit dry matter, pollination, secondary pest outbreaks) associated with the use of these nets may outweigh the benefit of their use; hence these limitations need to be addressed. Many of these cultural practices could be adapted into organic kiwifruit growing systems.

Pre-emptive classical biological control measures have already been approved in New Zealand for the release of *T. japonicus* in eradication attempts; approval for widespread release has not yet been achieved.

Some control methods would be relatively easy to adopt in a short period of time (less than three years) including surveying, pheromone trapping and integration of insecticides currently permitted in the CPP and alternate host plant removal. Other methods will take longer to implement due to current knowledge gaps and lack of available technologies.

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1 BIOLOGY AND ECOLOGY

1.1 Classification and nomenclature

Preferred Scientific Name

Halyomorpha halys (Stål).

Preferred Common Name

Brown marmorated stink bug.

Synonyms

Halyomorpha brevis
Halyomorpha mista
Halyomorpha remota
Pentatoma halys Stål.

This species has had a long and confusing history in terms of classification, with *Halyomorpha halys* (Stål, 1855) recognised as the longest serving (Rider et al. 2002) and widely accepted name for this insect. Since this original classification, *H. halys* has been recorded as *H. mista, H. brevis* (Lee et al. 2013, Rider et al. 2002, CABI 2017) and *H. remota* (Rider et al. 2002, CABI 2017). *H. mista* is sometimes still used in Japan (Soergel 2014, Rider et al. 2002). In China *H. halys* was misidentified or confused with *H. picus*, an Indian species (Rider et al. 2002, Soergel 2014), however Josifov and Kerzhner (1978) determined that there is only a single *Halyomorpha* species present in China, Japan and Korea, *H. halys* (Stål) (Rider et al. 2002, Lee et al. 2013), hence “all references to *Halyomorpha* from these locations are considered synonymous with *H. halys*” (Lee et al. 2013 p. 628).

This review document will use the classification *Halyomorpha halys* (Stål, 1855) and the common name brown marmorated stink bug, shortened to BMSB, from this point forward.

International Common Names

English:	yellow brown marmorated stink bug, yellow-brown stink bug (CABI 2017)
French:	punaise diabolique (CABI 2017), punaise marbrée (CABI 2017, EPPO 2018)
German:	Marmoriete Baumwanze (CABI 2017, EPPO 2018)
Italian:	cimice marmorizzata grigio-marrone (EPPO 2018)
Russian:	Коричнево-мраморный клоп (EPPO 2018).

English Acronym

BMSB (CABI 2017).

Taxonomic Tree (CABI 2017)

Domain: Eukaryota
Kingdom: Metazoa
Phylum: Arthropoda
Subphylum: Uniramia
Class: Insecta
Order: Hemiptera
Suborder: Heteroptera
Family: Pentatomidae
Genus: Halyomorpha
Species: *Halyomorpha halys.*

1.2 Geographical distribution

1.2.1 Native range

The BMSB is native to parts of Asia including China, Japan, Korea, Taiwan (Hoebeke and Carter 2003, Lee et al. 2013) Myanmar and Vietnam (Yu and Zhang 2007, Musolin et al. 2017) (Figure 1).

The BMSB is reported to be present in the following Chinese provinces: Anhui, Fujian, Guangdong, Guangxi, Guizhou, Hebei, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Jilin, Liaoning, Nei Mongol (Inner Mongolia), Shaanxi, Shandong, Shanxi, Sichuan, Xizhang (Tibet), Yunnan, and Zhejiang (CABI 2019).

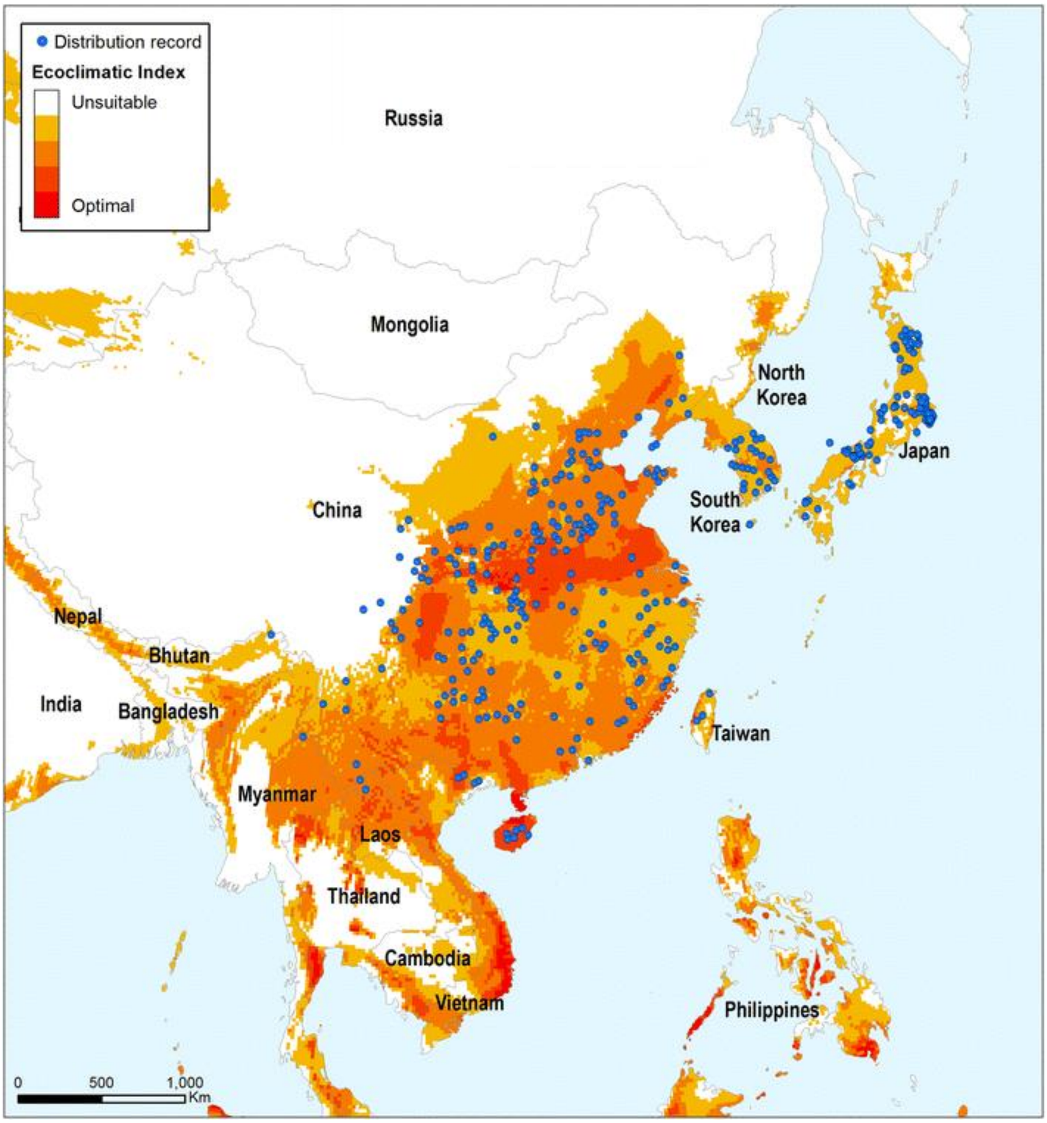


Figure 1. Modelled climate suitability (CLIMEX Ecoclimatic Index) for *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug (BMSB)) within its native range, including reported distribution locations (Source: Kriticos et al. 2017: p. 1036). Please note that permission would be required from the journal if this content was to be used outside of this review.

1.2.2 Global distribution

This invasive pest has spread throughout the northern hemisphere and is now a recognised agricultural pest in many parts of the US, Canada and Europe (Figure 2 and Table 1 below). The first established BMSB population detected in the southern hemisphere was in Chile in 2017 (Faudez and Rider 2017). The global distribution has largely been attributed to human-mediated movement or via BMSB ‘hitchhiking’ on imported/exported cargo.

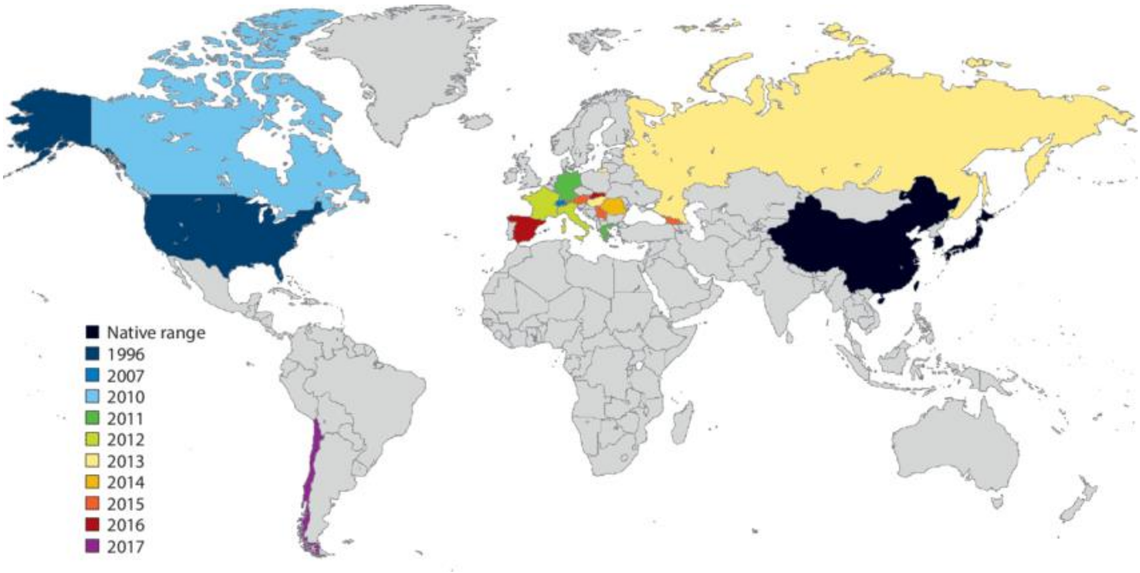


Figure 2: Global distribution of established (as reported in February 2018) *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug (BMSB)) populations in pests native and invaded range by year of detection. Year of detection is based on the earlier of published reports or European and Mediterranean Plant Protection Organization reporting. (Source: Leskey and Nielsen 2018: p. 601). Please note that permission would be required from the journal if this content was to be used outside of this review.

In the United States (US) and Canada BMSB have been intercepted at multiple points of entry. The first reports of established US populations were in 1996 in Allentown, Pennsylvania; however specimens were misdiagnosed as *Euschistus servus*, the native brown stink bug (Hoebeke and Carter 2003, Rice et al. 2014, Leskey and Nielsen 2018). Insect specimens were later sent to Cornell University and formally identified as BMSB (Hoebeke and Carter 2013). BMSB has since spread to 45 states including Hawaii (Table 1) where the pest is considered both an agricultural and nuisance pest.

The first reports of BMSB in Canada were in 1993 in British Columbia, with additional interceptions noted sporadically from Asia and the US (Rice et al. 2014). It is thought that BMSB had established in parts of Canada by 2010 following reports of the bug entering homes (Rice et al. 2014, Leskey & Nielson 2018), and this was confirmed with the first detection of BMSB eggs in Hamilton, Ontario in 2012. BMSB remains for the most part a nuisance pest in Canada but concerns are being raised due to the proximity of existing populations to major fruit-growing regions (Rice et al. 2014).

Table 1: Geographical distribution of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB), categorised by continent, showing countries or states where BMSB has either established or been detected/intercepted. Countries where kiwifruit (*Actinidia chinensis*) is grown commercially have been noted in italics.

Continents	Countries where BMSB has been intercepted or established
Asia	*China*, *Korea*, *Japan*, Taiwan
Africa	Not present.
North America	Canada - Alberta, Ontario, Quebec. USA - Alabama, Arizona, *California*, Connecticut, Delaware, District of Columbia, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, Wyoming.
South America	*Chile* (Faúdez and Rider 2017)
Europe	Austria, Croatia (Sapina and Seric Jelaska 2018) *France*, Germany, Georgia (namely Abkhazia) (Musolin et al. 2017), *Greece*, Hungary, *Italy*, Liechtenstein, Romania, Russian Federation, Serbia, Slovakia, Slovenia, *Spain*, Switzerland
Oceania	Australia (not established), Guam, *New Zealand* (not established)
Antarctica	Not present.

Source: CABI 2017, EPPO 2013, 2018 unless otherwise stated.

In 2007 BMSB was officially recorded as an established pest in Zurich, Switzerland (Rice et al. 2014, Leskey and Nielson 2017) and is a likely source of further populations detected in neighbouring countries including Liechtenstein, Germany, France and Italy (Rice et al. 2014). BMSB is, for now, deemed as a nuisance pest only in Switzerland despite its presence there for 12 years. However like Canada there is potential for BMSB to become a serious agricultural pest in Europe (Rice et al. 2014).

The most recent record of BMSB establishment, and a first for the southern hemisphere, was in Santiago, Chile in 2017 (Faudez and Rider 2017, Astorga 2018), where BMSB interceptions increased from 2010. The first in-land detection was of a single specimen in the Qunita Normal Commune; this initiated regional and national surveillance programmes (Astorga 2018). So far BMSB has remained restricted to Santiago (G. Avila, pers. comm.).

Borisade et al. (2017) reported the presence of BMSB aggregations in Nigeria, however uncertainty remains around the correct identification of the insect pest included in these reports (Corceoi et al. 2017, Astorga 2018). This would be the first report of BMSB on the African continent and hence requires verification (Corceoi et al. 2017).

1.2.3 Potential Global distribution

Kriticos et al. (2017) used the climate modelling package CLIMEX to explore the potential global expansion range of BMSB. CLIMEX “explores the effects of climate on invasive species to estimate their potential distributions in novel climates” (Kriticos et al. 2017: p. 1034).

The CLIMEX model shows that many of the climes suitable for BMSB are quickly being occupied (Figure 3). Expansion into the southern hemisphere remains, for the moment, restricted to Chile, however large parts of South America have been identified as highly suitable for BMSB occupation. The same can be said for the central and southern parts of Africa.

Increasing border interceptions of BMSB in Australia and New Zealand provide potential for continued expansion. Figures 3 and 4 shows that the eastern and southern coasts of Australia and northern Tasmania are most suitable for BMSB establishment, as are much of the North Island and northern parts of the South Islands of New Zealand and the many surrounding island nations (Figures 3 and 4). For both Australia and New Zealand these climes include important agricultural and horticultural landscapes.

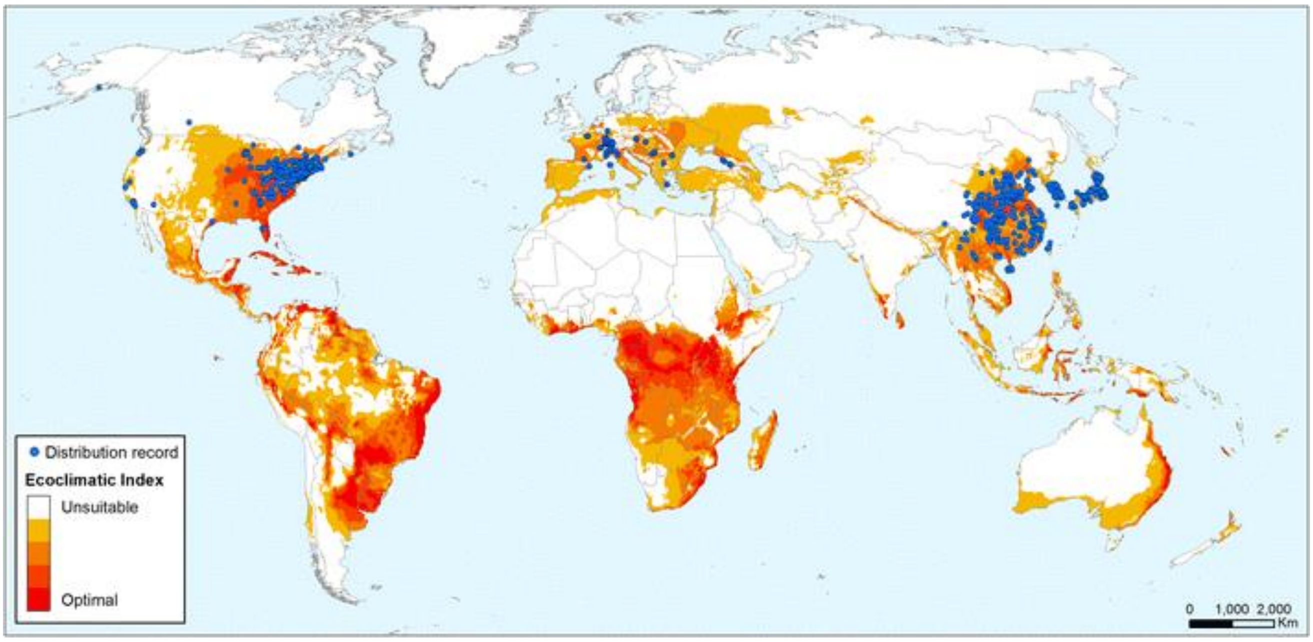


Figure 3. Modelled climate suitability (CLIMEX Ecoclimatic Index) for *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) globally, including reported distribution locations. Note the three outlying distribution records in the USA and Canada have been investigated and found to be transient populations associated with human transportation. (Source: Kriticos et al. 2017: p. 1040). Please note that permission would be required from the journal if this content was to be used outside of this review.

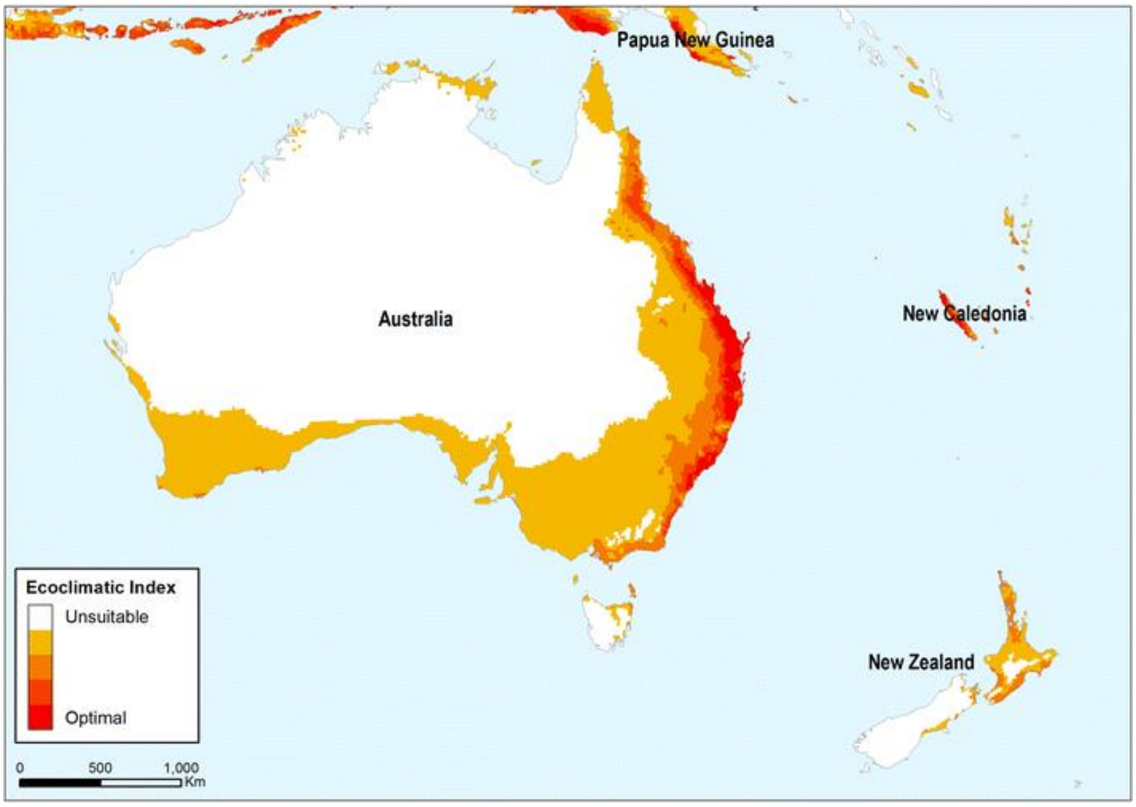


Figure 4. Modelled climate suitability (CLIMEX Ecoclimatic Index) for *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in Australasia. (Source: Kriticos et al. 2017: p. 1041). Please note that permission would be required from the journal if this content was to be used outside of this review.

1.2.4 Interceptions in New Zealand

BMSB was first detected in New Zealand (NZ) in 2005; this interception originated from Asia. Since this initial find BMSB border interceptions and post-border detections have increased. Furthermore the origin of these detections has widened with the continued global expansion of the pest. Establishment of the pest here in New Zealand would cause widespread losses to the agricultural and horticultural industries and likely place sanctions on global exports.

The high-risk period for border BMSB interceptions in New Zealand is September to April. This period corresponds to the northern hemisphere autumn and winter months when BMSB form large aggregations in sheltered environments to overwinter (MPI 2015, 2017, KVH 2017a). This behaviour causes nuisance problems in residences in parts of the US and Europe, and is important in the global movement of BMSB as a ‘hitchhiker’ pest in luggage and posted goods. Incoming vehicles, travellers’ personal effects and freight containers have been identified as key incoming items associated with BMSB detections in New Zealand (Nixon & Bedoya 2016) (see Table 2).

Local and national government and industry bodies are well aware of the risks associated with BMSB in New Zealand and many pre-emptive steps have been taken to deter the establishment of the BMSB here. Large efforts have been placed on national pest awareness, educational and research programmes aimed at pest identification, efficient and effective border detection and pre- and post-border control treatments/methods. An example of this is the successful application to the governmental body, the Environmental Protection Authority (EPA) of New

Zealand, to import and release the samurai wasp (*Trissolcus japonicus*), a successful natural enemy (see Section 1.7.9 Natural Enemies) of the BMSB in its native range, in the event of a BMSB incursion (EPA 2018). This is considered a world first in pre-emptive national biosecurity.

At the time of writing this review BMSB, had not established in New Zealand or Australia.

Table 2. Pathways of entry of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in New Zealand and Australia (Source: Ormsby 2018: p. 10).

Commodity/Pathway	Description
Car/machinery parts	Containerised spare parts for vehicles or machinery
Consumer goods	Manufactured goods in containers, such as tiles, furniture, glass etc.
Fresh fruit (hosts)	Fresh fruit in containers (usually boxed or bagged)
Mail	Posted mail including packages
New vehicles	New (unused) cars, trucks or machinery e.g. tractors, trains
Used vehicles	Used cars, trucks or machinery e.g. tractors, trains
Passenger baggage	Baggage arriving with passengers at airports
Personal effects	Household goods in containers
Sawn timber	Wood arriving in containers or as break bulk
Sea containers	The inside of a sea container which is either empty, or BMSB were not associated with the goods therein.
Vessels	A ship or boat arriving independently (not as cargo)

1.3 Pest Description

The BMSB, like all stink bugs, are hemipterans, colloquially referred to as the order of piercing and sucking insects. Hemipterans possess modified mouthparts (stylets) specialised for piercing tissues and sucking/feeding on cell contents or interstitial fluids. The BMSB life cycle consists of an egg stage, five nymphal instars and a winged adult stage. As with other pentatomid species, the adult female is larger than the adult male.

1.3.1 Eggs

Barrel-shaped eggs are laid by mated females in a raft of between 20–30 eggs. Eggs are usually laid on the underside of leaves (CABI 2017, Utah State University 2017) and “toward the upper and interior tree canopy” (Funayama 2002 in Lee et al. 2013: p. 630). Eggs are light green in colour, changing to white as they mature (Rice et al. 2014) (Figure 5), smooth, and approximately 1.3 mm in diameter and 1.6mm in length” (CABI 2017).

As the eggs mature, a black triangle appears above the developing nymph head. This is known as the egg burster (Utah State University 2017). Eggs mature in 3–7 days depending on temperature (Utah State University 2017).

Figure 5. *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) egg raft laid on the underside of a leaf. The black triangle is known as the egg burster and sits above the first instar nymph. (Source: Utah State University 2017).

1.3.2 Nymphs

First instar nymphs emerge with brightly coloured reddish-brown abdomens with black markings and a black head (Rice et al. 2014, CABI 2017, Stop BMSB 2018). They feed on the remains of the eggs' shells until they reach the second instar (Rice et al. 2014) (Figure 6). Nymphs moult or shed their exoskeleton between each instar to increase body size (Utah State University 2017).

**Figure 6. *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) first instar nymphs.
(Source: Stop BMSB 2018).**

During the second instar stage, nymphs "leave the egg mass and feed on hosts plants" (Rice et al. 2014). The abdomen of the second instar nymph appears lighter in colour than the first, and the double white banding on the antennae becomes evident at this stage (Figure 7).

Third instar nymphs appear darker in colour than first and second instar nymphs. During this stage the white banding on the forelegs becomes more evident, as well as the dark yellow/light brown markings on the back of the abdomen and pronotum (see Appendix II –*Halyomorpha halys* morphology). The fourth and fifth instar nymphs are similar in appearance and all phenological markings become more apparent including the white banding on the antennae and legs, and the characteristic marmorated pattern at the base of the abdomen (see Figures 7 and 8).

Figure 7. Four nymphal (second to fourth) stages of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) and an adult male (left) and adult female (right). (Source: Stop BMSB 2018).

1.3.3 Adults

The large winged adults are mottled brown in appearance. This coloration serves as camouflage in arboreal environments. The characteristic features that distinguish BMSB from other brown pentatomid species are the light yellow/tan and dark brown triangle patterning or marmorations on the base of the abdomen and the double white banding on the legs and antennae (See Figures 7 and 8).

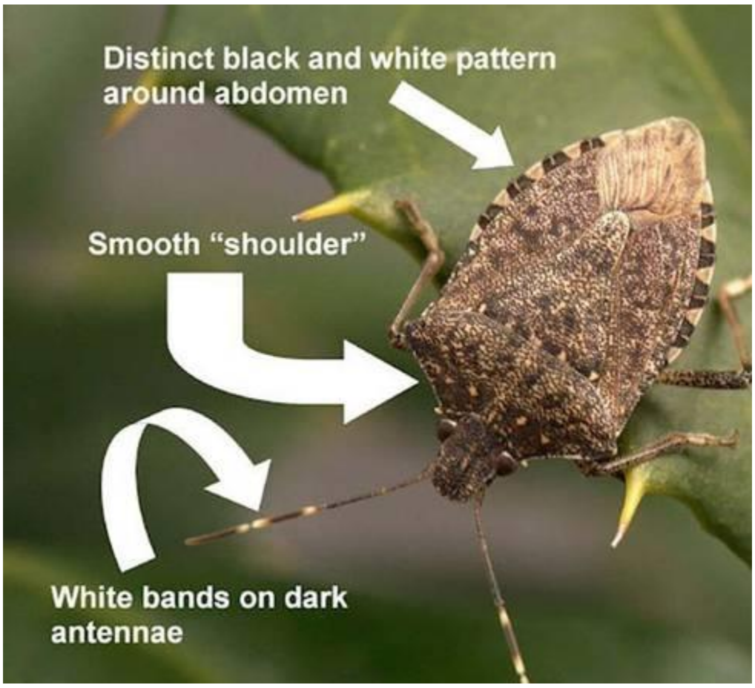


Figure 8. Distinguishing morphological characteristics of the *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) adult including the double white bands on the antennae and the black and white marmorated pattern on the base of the abdomen. (Source: Michigan State University, 2015).

Adult BMSB range from 12–17mm (MPI 2019) in length with the adult female being larger than the male (see Figure 7). BMSB adults are also larger than many of the pentatomid species present in New Zealand (see Figure 9). The introduced pest, *Nezara viridula* or the green vegetable bug (GVB, syn. Southern green stink bug), is the most similar in size to adult BMSB; this similarity may lead to the brown or russet GVB form being mistaken for BMSB (Figure 9).

Brown marmorated stink bug adults are strong flyers and have two pairs of wings (fore and hind wings) which are hidden at rest under the hemelytron (see Appendix II – *Halyomorpha halys* (Stål, 1855) morphology).

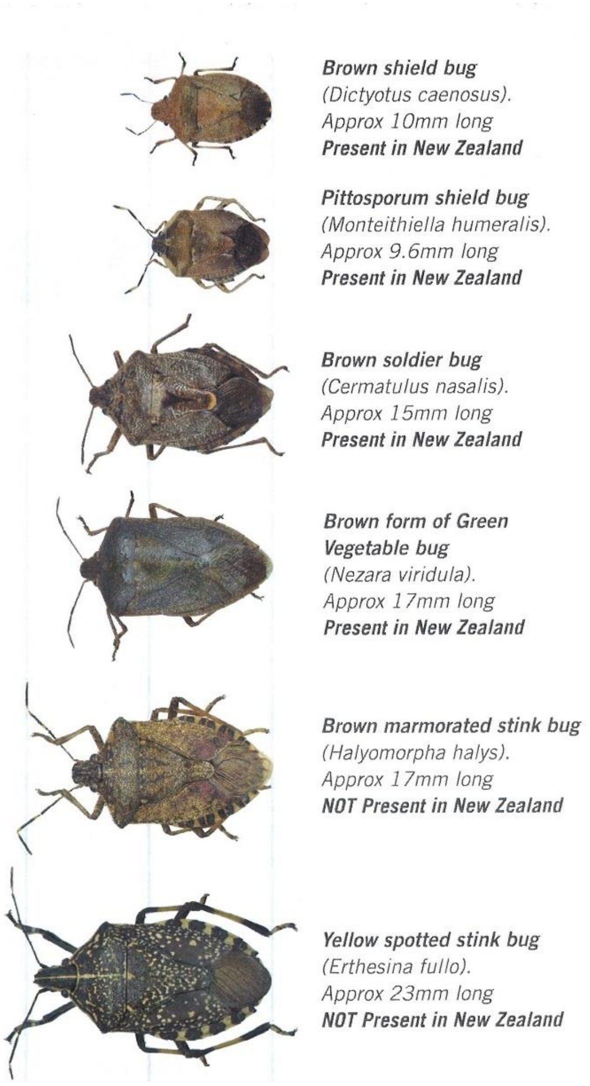


Figure 9. Size comparisons of four pentatomid (shield or stink bug) species present in New Zealand and two Asian invasive species: *Halyomorpha halys* ((Stål, 1855) (brown marmorated stink bug, BMSB) and *Erthesina fullo* (Thunberg.) (yellow spotted stink bug). (Source: MPI 2019).

1.4 Host Plants

BMSB is highly polyphagous and is reported to feed on over 300 host plants including a wide range of ornamental, wild and horticulturally/agriculturally important host plants (see Table 3). Adults move between host plants during the growing season (Wang & Wang 1988; Fujisawa 2001; as reviewed by Lee et al. 2013) based on the availability of fruiting structures, host suitability and acceptability (Hoffman 1931; Oda et al. 1980; Funayama 2002, 2004; Yu and Zhang 2007; Bea et al. 2009; as reviewed by Lee et al. 2013). As an arboreal species, BMSB also feeds on woody structures such as tree trunks (Shrewsbury et al. 2011). Feeding on multiple host species and plant structures may be a necessary requirement for normal development (Funuyama 2002, 2004; in Lee et al. 2013) and this strategy is employed in artificial BMSB rearing systems.

Not all host plants are equally preferred. Some are used for sustenance only (feeding hosts) whilst others are capable of supporting the entire BMSB life cycle (reproductive hosts) (Oda et al. 1980 in Lee et al. 2013). Primary hosts are those that BMSB shows a preference for. These support the entire life cycle (egg to adult) and are often heavily infested by BMSB (Table 3). In the US, BMSB has been reported to feed more on Angiosperms than Gymnosperms, (Bakken et al. 2015, Bergmann et al. 2016, Leskey and Nielson 2018) and is more commonly found on non-Asian hosts than Asian host plants (Martinson et al. 2016 in Leskey and Nielson 2017: p. 603).

Table 3. Primary host plants of the *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) and their use/host classification (horticultural or agricultural crop, ornamental, wild host or other). Primary host plants are those that BMSB shows a preference for, that support the entire life cycle (egg to adult), and are often heavily infested by BMSB.

Family	Botanical name (common name)	Host classification
Amaranthaceae	*Amaranthus caudatus* (amaranth)	Horticultural crop, ornamental
Aquifoliaceae	*Ilex aquifolium* (holly)	Ornamental
Bignoniaceae	*Catalpa* spp. (catalpa)	Wild, ornamental
Fabaceae	*Glycine max* (soybean), *Phaseolus lunatus* (lima bean), *Phaseolus* spp. (beans), *Phaseolus vulgaris* (common bean), *Pisum sativum* (pea)	Horticultural crop
	Mimosa spp. (mimosa)	Wild host
Magnoliaceae	*Magnolia stellata* (star magnolia)	Ornamental
Moraceae	*Morus alba* (white mulberry, mora)	Wild host
Poaceae	*Zea mays* (maize), *Zea mays* subsp. *mays* (sweetcorn)	Horticultural crop
Rhamnaceae	*Ziziphus sativa* (sativa)	Horticultural crop
Rosaceae	*Malus baccata* (siberian crab apple), *Malus sargentii* (Sargeant's crab apple)	Ornamental
	Malus domestica (syn. *M. pumila*) (apple), *Malus zumi* (zumi), *Prunus armeniaca* (apricot), *Prunus avium* (sweet cherry), *Prunus domestica* (plum), *Prunus incam* (cherry), *Prunus persica* (peach)*Prunus serrulata* (Japanese flowering cherry), *Prunus subhirtella* (weeping Japanese cherry), *Prunus serotina* (black cherry), *Pyrus* spp. (pear)	Horticultural crop
	Prunus cerasifera (cherry plum), *Prunus incisa* (Fuji cherry)	Ornamental
	Prunus laurocerasus (cherry laurel)	Other
Rutaceae	*Citrus junos* (yuzu)	Horticultural crop, ornamental
Scrophulariaceae	*Paulownia tomentosa* (princesstree, paulownia)	Wild host, forestry crop
Simaroubaceae	*Ailanthus altissima* (tree-of-heaven)	Wild host
Solanaceae	*Capsicum annuum* (bell-pepper, capsicum)	Horticultural crop

Source: Lee et al. 2013, EPPO 2018, CABI 2017, 2019, Stop BMSB 2018.

Table 4. Secondary host plants of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB). Secondary host plants are those that are used occasionally for feeding and resting but do not support the complete development from egg to adult (see Appendix I for further information on secondary host plants).

Family	Botanical name (common name)
Aceraceae	*Acer buergerianum* (trident maple), *Acer campestre* (field or hedge maple), *Acer circinatum* (vine maple), *Acer fremanii* (Freman maple), *Acer griseum* (paperback maple), *Acer japonicum* (full-moon maple), *Acer macrophyllum* (broadleaf maple), *Acer negundo* (box elder), *Acer palmatum* (Japanese maple), *Acer pensylvanicum* (striped maple), *Acer platanoides* (Norway maple), *Acer rubrum* (red maple), *Acer saccharinum* (silver maple), *Acer saccharum* (sugar maple), *Acer spp.* (maple), *Acer tegmentosum* (East Asia stripe maple)
Actinidiacdeae	*Actinidia deliciosa* (syn. *A. chinensis* var. *deliciosa)* (Chinese gooseberry, kiwifruit)
Adoxaceae	*Sambucus recemosa* (red elderberry)
Amaranthaceae	*Beta vulgaris* (beet), *Beta vulgaris* ssp. *cicla* (Swiss chard), *Celosia argentea* (celosia), *Celosia* spp. (cock's comb)
Anacardiaceae	*Pistacia chinensis* (Chinese pistache), *Rhus typhinastaghorn* (staghorn sumac)
Annonaceae	*Asimina triloba* (pawpaw-apple)
Asparagaceae	*Asparagus officinalis* L. (asparagus)
Asteraceae	*Arctium minus* (common burdock, lesser burdock), *Artemisia argyi* (Argyi wormwood), *Chrysanthemum morifolium* (Chrysanthemum), *Helianthus* spp. (sunflower)
Balsaminaceae	*Impatiens balsaminia* (rose balsam)
Basellaceae	*Basella alba (*syn. *B. rubra)* (malabar spinach)
Berberidaceae	*Mahonia aquifolium* (Oregon grape)
Betulaceae	*Betula nigra* (river birch), *Betula papyrifera* (paper birch), *Betula pendula* (common silver birch), *Betulaceaealnus* spp. (Alder), *Carpinus betulus* (hornbean), *Corylus colurna* (filbert hazelnut), *Corylus* spp. (hazelnut)
Boraginaceae	*Symphytum* spp. (comfrey)
Brassicaceae	*Armoracia rusticana (*horseradish), *Brassica juncea* (wild mustard), *Brassica napus* (rape), *Brassica oleracea* (cabbage, cauliflower, collard greens)
Canabaceae	*Cannabis sativa* (hemp), *Humulus lupulus* (syn. *H. scandens*) (hop)
Caprifoliaceae	*Abelia grandiflora* (glossy abelia), *Heptacodium miconioides (*seven sons flower), *Lonicera* spp. (honeysuckle), *Lonicera tatarica (*tatarian honeysuckle), *Viburnum burkwoodii* (viburnum), *Viburnum dilatatum* (viburnum), *Viburnum prunifolium* (viburnum), *Viburnum* spp. (viburnum), *Waigela hortensis* (Japanese weigela)
Celastraceae	*Euonymus japonicus* (Japanese spindle)
Cercidiphyllaceae	*Cercidiphyllum japonicum* (katsura)
Family	Botanical name (common name)
Chenopodiaceae	*Chenopodium berlandieri (*pitseed goosefoot), *Chenopodium* spp. (goosefoot)
Cornaceae	*Cornus florida* (flowering dogwood), *Cornus kousa* (kousa dogwood), *Cornus macrophylla* (large leaf dogwood), *Cornus officinalis* (Asiatic dogwood), *Cornus racemosa* (grey dogwood), *Cornus sericea* (redosier dogwood), *Cornus* spp. (dogwood)
Cucurbitaceae	*Cucumis sativus* (cucumber), *Cucurbita pepo* (marrow, pumpkin)

Family	**Botanical name (common name)**
Cupressaceae	*Chamaecyparis obtusa* (Japanese cypress), *Cryptomeria* spp. (Japanese red-cedar), *Cupressus* spp. (cypress), *Juniperus virginiana* (eastern red cedar), *Metasequoia glyptostroboides* (dawn redwood), *Platycladus orientalis* (oriental arborvitae)
Ebenaceae	*Diospyros kaki* (persimmon)
Elaeagnaceae	*Elaeagnus angustifolia* (Russian olive), *Elaeagnus umbellata* (autumn olive)
Ericaceae	*Vaccinium corymbosum* (blueberry)
Euphorbiaceae	*Veronica fordii* (tung tree)
Fabaceae	*Albizia julibrissin* (sensitive plants), *Astragalus sinicus* (milk-vetch), *Baptisia australis* (blue wild indigo), *Caragana arborescens* (Sinerian pea-tree), *Cercis canadensis* (eastern redbud), *Cercis canadensis* ssp. *Texensis* (Texas redbud), *Cladrastis kentukea* (syn. *C. lutea*) (American yellowwood), *Gleditsia triacanthos* (honey locust), *Gleditsia triacanthos* ssp. *Inermis* (thornless common honeylocust), *Pueraria montana* var. *lobata* (kudzu), *Robinia pseudoacacia* (black locust), *Sophora japonica* (Japanese pagoda tree), *Trifolium* spp. (clover), *Vigna angularis* (adzuki bean), *Vigna sesquipedalis* (Chinese long bean), *Vigna unguiculata* (cowpea), *Wisteria sinensis* (Chinese wisteria)
Fagaceae	*Chastanea* spp. (chestnut), *Quercus alba* (white oak), *Quercus coccinea* (scarlett oak), *Quercus robur* (common oak), *Quercus rubra* (northern red oak)
Ginkgoaceae	*Ginkgo biloba* (Ginko)
Hamamelidaceae	*Hamamelis japonica* (invasive witch-hazel), *Hamamelis virginiana* (Virginian witch-hazel), *Liquidambar styraciflua* (sweetgum)
Hippocastanaceae	*Aesculus carnea* (red horse chestnut), *Aesculus glabra* (Texas buckeye)
Juglandaceae	*Carya illinoinensis* (pecan), *Carya ovata* (shagbark hickory), *Juglans nigra* (black walnut)
Lamiaceae	*Clerodendrum trichotomum* (harlequin gloryblower), *Vitex negundo* (Chinese chaste tree)
Lardizabalaceae	*Akebia* spp. (chocolate vine)
Lauraceae	*Cinnamomum camphora* (camphor tree), *Sassafras albidum* (common sassafras)
Lythraceae	*Lagerstroemia indica* (Indian crape myrtle), *Lythrum salicaria* (purple loosestrife), *Punica granatum* (pomegranate)
Magnoliaceae	*Liriodendron tulipifera* (tuliptree), *Magnolia grandiflora* (Southern magnolia)
Malvaceae	*Abelmoschus esculentus* (okra), *Firmiana platanifolia* (Chinese parasol tree), *Gossypium hirsutum* (upland cotton), *Hibiscus moscheutos* (crimson eyed-mallow), *Hibiscus rosa-sinensis* (China rose), *Hibiscus syriacus* (hibiscus)
Family	Botanical name (common name)
Moraceae	*Ficus carica* (common fig), *Morus* spp. (mulberry tree)
Oleaceae	*Chionanthus retusus (*Chinese fringetree), *Chionanthus virginicus* (white fringetree), *Forsythia suspensa* (weeping forsythia), *Fraxinus americana* (white ash), *Fraxinus chinensis* (Chinese ash), *Fraxinus pennsylvanica* (downy ash), *Ligustrum japonicum* (Japanese privet), *Ligustrum sinense* (Chinese privet), *Olea oleaster* (wild olive), *Syringa pekinensis* (Pekong tree lilac), *Syringa* spp. (lilac)
Orchidaceae	*Brassia* spp. (orchid), *Phalaenopsis* spp. (moth orchid)
Phytolaccaceae	*Phytolacca americana* (American pokeweed)
Pinaceae	*Larix kaempferi* (syn. *L. leptolepis*) (Japanese larch), *Tsuga canadensis* (eastern hemlock)
Platanaceae	*Platanus occidentalis* (American sycamore)

Family	Botanical name (common name)
Poaceae	*Panicum miliaceum* (common millet), *Secale cereale* (cereal rye), *Setaria italica* (pearl millet), *Sorghum bicolour* (sorghum), *Triticum aestivum* (wheat)
Polygonaceae	*Polygonum perfoliatum (*mile-a-minute weed)
Rhamnaceae	*Rhamnus cathartica* (buckthorn), *Ziziphus jujuba* (jujube)
Rosaceae	*Amelanchier laevis* (syn. *A. grandiflora*) (Allegheny serviceberry), *Chaenomeles speciosa* (quince), *Crataegus laevigata* (smooth hawthorn), *Crataegus monogyna* (oneseed hawthorne), *Crataegus pinnatifida* (Chinese hawthorne), *Crataegus viridis* (green hawthorne), *Eriobotrya japonica* (loquat), *Fragaria ananassa* (strawberry), *Photinia* spp. (syn. *Aronia* spp.) (chokeberry), *Chaenomeles speciosa* (quince), *Prunus grayana* (Japanese bird cherry), *Prunus pseudocerasus* (Chinese sour cherry), *Pseudocydonia sinensis* (Chinese quince), *Pyracantha* spp. (firethorn), *Pyrus calleryana* (bradford pear), *Pyrus communis* (European pear), *Pyrus pyrifolia* (oriental oear tree), *Rosa canina* (dog rose), *Rosa multiflora* (multiflora rose), *Rosa rugosa* (rugosa rose), *Rubus fruticosus* (blackberry), *Rubus idaeus* (raspberry), *Rubus phoenicolasius* (wine raspberry), *Rubus* spp. *(raspberry, blackberry), Sorbus americana* (American mountainash), *Sorbus aria* (whitebeam), *Spiraea* spp. (spiraea)
Rubiaceae	*Cephalanthus occidentalis* (common buttonbush)
Rutaceae	*Citrus* spp. (lemons, lime, mandarins, oranges), *Tetradium daniellii* (syn. *Euodia hupehensis*) (Korean euodia)
Salacia	*Celastrus orbiculatus* (Asiatic bittersweet)
Saliaceae	*Populus tomentosa* (Chinese white poplar), *Salix* spp. (willow)
Sapindaceae	*Koelreuteria paniculata* (goldenrain tree)
Scrophulariaceae	*Antirrhinum majus* (snapdragon), *Buddleia davidii* (butterfly bush), *Buddleia* spp. (butterfly bush)
Solanaceae	*Lycium babarum* (boxthorn), *Nicotiana alata* (jasmine tobacco), *Solanum lycopersicum* (tomato), *Solanum melongena* (eggplant), *Solanum nigrum* (black nightshade)
Styracaceae	*Halesia tetraptera* (mountain silverbell), *Styrax japonicus* (japonica)
Family	Botanical name (common name)
Taxaceae	*Taxus cuspidata* (Japanese yew)
Theaceae	*Camellia oleifera* (oil seed camellia), *Camellia sinensis* (Chinese tea), *Stewartia koreana* (Korean stewartia), *Stewartia pseudocamellia* (Japanese stewartia)
Tiliaceae	*Tilia americana* (basswood), *Tilia cordata* (small-leaf lime), *Tilia tomentosa* (silver lime)
Ulmaceae	*Celtis koraiensis* (Korean hacknerry), *Celtis occidentalis* (hackberry), *Celtis* spp. (nettle tree), *Ulmus americana* (American elm), *Ulmus parvifolia* (Chinese elm), *Ulmus procera* (syn. *U. minor*) (English elm), *Ulmus pumila* (elm), *Zelkova* spp. (Japanese zelkova)
Vitaceae	*Cayratia japonica* (bushkiller), *Vitis riparia* (riverbank grape), *Vitis vinifera* (grapevine)

Source: Lee et al. 2013, EPPO 2018, CABI 2017, 2019, Stop BMSB 2018.

1.5 Damage

Pentatomids feed by inserting their straw like stylet (see Section 1.7.2 Feeding) into host tissues, injecting a solidifying saliva and sucking up the cell contents and/or interstitial fluids. Injury resulting from BMSB feeding varies from host to host and crop physiology at the time of feeding. BMSB, like many other pentatomids, feed on many different plant parts including "buds, leaves and stems, but prefer reproductive structures such as fruits and seed pods" (Utah State University 2017: p. 2, Rice et al. 2014).

Crop injury associated with BMSB feeding includes: malformed or distorted fruit, formation of internal spongy or corky tissue and skin discoloration. Feeding injury expression and type is dependent on host plant phenology, BMSB density and life stage (Leskey and Nielson 2017). Feeding by late instars and adults inflicts proportionately more damage in comparison with earlier nymphal stages (Acebes-Dora et al. 2016).

Feeding injury on immature tree fruits can lead to fruit malformation, an example of this is cat-facing (Figure 10). This type of damage occurs when the cells surrounding a feeding site die, inhibiting growth, whilst the rest of the fruit continues to grow at a normal rate (Pennsylvania State University 2019). Fruit appear malformed and distorted and are ultimately unsuitable for commercial markets.

Figure 10. Cat-facing injury on a peach (*Prunus persica*) in response to *Halyomorpha halys* (Stål, 1855) (Brown marmorated stink bug, BMSB) feeding (Source: University of Florida 2019a).

Feeding damage on fruits, nuts and vegetables (Leskey and Nielsen 2018) includes sunken lesions or discoloration on the fruit skin and internal tissue corking. Corky lesions result from cell death or necrosis beneath the dermal layer. In apples, black spots may develop on the outer skin directly above internal feeding wounds (Lee et al. 2013). White corky damage in fleshy fruits (e.g. tomatoes) and beans can be detected externally but in other crops such as kiwifruit (*Actinidia chinensis*) this is difficult and internal inspection is required.

In hazelnuts, when BMSB injury occurred before kernel expansion, kernels ceased to grow, resulting in empty shells (Hedstrom et al. 2014: p. 1858). When BMSB fed during kernel expansion, damaged nuts were distorted or malformed, and in mature kernels corky lesions appeared (Hedstrom et al. 2014).

Figure 11. Injury associated with *Halyomorpha halys* (Stål, 1855) (Brown marmorated stink bug, BMSB) brown marmorated stink bug (*Halyomorpha halys* Stål) feeding on A) a ‘Cripps Pink’/Pink Lady® apple, B) tomato and, C) and D) an ear of sweet corn. Note the sunken area on the tomato skin and corky lesions on the apple. (Source: Utah State University 2017).

In addition to reduced fruit quality, crop yields may be further affected by low fruit set through flower and young fruit abortion (Rice et al. 2014) and fruit abscission. Fruit drop has been reported for some crops including kiwifruit, peaches and persimmon (Lee et al. 2013).

Excreta or droppings on fruit surfaces can produce an unpleasant taste when ingested and have been reported to taint wine when deposited on wine grapes (Rice et al. 2014). Small mould growths have been observed developing on the excreta of *Nezara viridula* (the green vegetable bug syn. southern green stink bug) on kiwifruit in cool storage (Puketapu and Logan, unpublished data). Excreta produced by pentatomids is unsightly and difficult to remove from fruit surfaces once dried.

Pentatomids are also implicated in the transmission of bacterial and fungal pathogens that cause disease or fruit rot. Pathogens can be carried on the stylet and transmitted to healthy plants during feeding. Pathogens associated with BMSB include: *Eremothcium coryli* (Rice et al. 2014), a fungal pathogen implicated in late fruit rot of tomatoes, and Paulownia witches broom *Phytoplasma* (PaWB) (Lee et al. 2013). Voshell et al. (2014) showed that BMSB increased the incidence of *Colletotrichum cocodes* rot in tomatoes when BMSB nymphs were exposed to the fungal pathogen before being introduced to clean tomato fruit. *C. cocodes* infection increased with increasing BMSB frequency.

1.5.1 Damage to kiwifruit

The brown marmorated stink bug is a reported kiwifruit pest in China (KVH 2017a, Teulon & Xu 2018), Italy, Korea and more recently Greece (Andreadis et al. 2018). BMSB damage was first reported in Italy in 2016 despite the pest being present there for nine years prior (KVH 2017a). BMSB may feed on kiwifruit leaves, fruit and fruit stems, flowers, fruit buds, plant shoots and even the woody trunk (KVH 2017a). Kiwifruit growers in China and Korea have reported fruit loss greater than 30% in response to BMSB feeding through fruit drop and storage rot (KVH 2017a). However, this estimate remains anecdotal and requires further research to understand the true risk that BMSB poses to kiwifruit.

BMSB have been shown to feed on both Zespri® Green (*A. chinensis* var. *deliciosa* 'Hayward') and Zespri® SunGold (*A. chinensis* var. *chinensis* 'Zesy 002') kiwifruit in laboratory studies, however no clear preference for either variety was observed (KVH 2017a, Lara et al. 2018). Feeding on kiwifruit leaves may result in yellow-green spots while feeding on flowers and buds may cause rot and/or flower and bud drop (KVH 2017a). Early fruit feeding can cause fruit malformation (KVH 2017a). Feeding on ripening kiwifruit results in the formation of white corky lesions beneath the fruit skin (KVH 2017a, Lara et al. 2018), as seen in other tree fruit and vegetables (Figure 12).

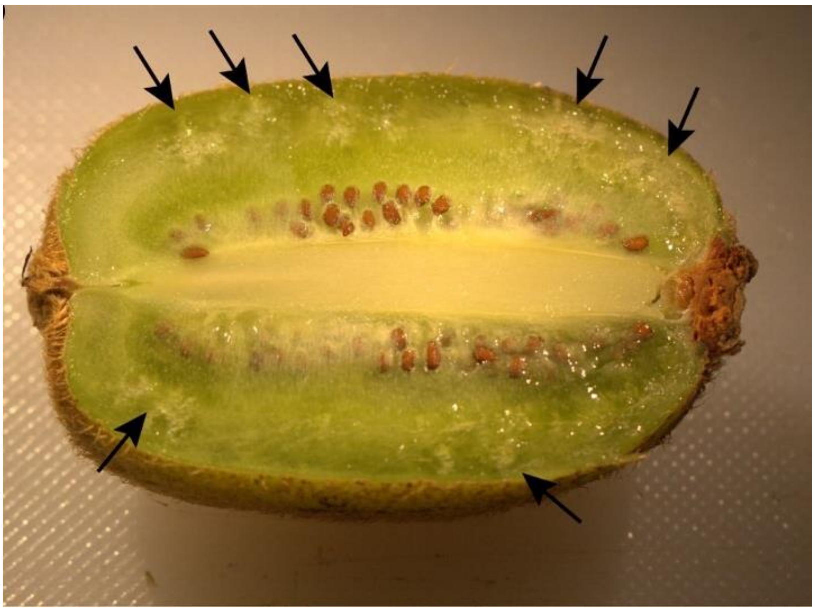


Figure 12. Internal damage caused by *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) feeding in a Zespri® Green kiwifruit (*Actinidia chinensis* var. *deliciosa* 'Hayward') (Source: Lara et al. 2018: p. 16). Please note that permission would be required from the journal if this content was to be used outside of this review.

Recent reports of BMSB damage in two green kiwifruit varieties Zespri® Green and ENZA™ 'Megakiwi™' or 'Tsechelidis' (*A. chinensis* var. *deliciosa*) in parts of Greece include dark sunken regions on the exterior of infested fruit near the stalk (Figure 13), fruit deformation and internal tissue damage (white corky lesions) (Andreadis et al. 2018). Furthermore, both adults and nymphs were observed feeding directly on the fruit (Andreadis et al. 2018). Egg laying was observed on the leaves in late May to mid-June and on the fruit from the end of July to mid-August (Andreadis et al. 2018). Vast numbers of BMSB adults were also observed moving into kiwifruit from other crops in August–September (Andreadis et al. 2018).

Figure 13. Dark, sunken areas on the skin of a green variety of kiwifruit (*Actinidia chinensis* var. *deliciosa*) near the fruit stalk associated with *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) infestation. (Source: Andreadis et al. 2018: p. 404). Please note that permission would be required from the journal if this content was to be used outside of this review.

1.6 Pest Status

The BMSB has invaded many US states, Canada and Europe and, as interceptions of the pest increase here in New Zealand, the possibility of establishment intensifies. BMSB is implicated in causing severe damage to a wide range of economically important fruit, field, nut and vegetable crops. In 2010 some stone fruit growers in the US lost >90% of their crops due to BMSB (Leskey and Hamilton 2010b in Rice et al. 2014). In the same year BMSB damage caused US$37 million in losses in mid-Atlantic apples in the US (America/Western Fruit Grower 2011 in Rice et al. 2014).

1.6.1 Pest status in kiwifruit

Kiwifruit damage caused by BMSB in China has anecdotally been estimated at >30%, attributed to fruit drop and storage rot (KVH 2017a). In Korea growers have reported amplified damage effects in the SunGold (*A. chinensis* var. *chinensis* 'Zesy002') variety in the field (S. Max pers. comm.) and laboratory assessments have shown no clear kiwifruit varietal preference (Lara et al. 2018). European growers have reported similar crop damage and large BMSB infestations (M. Suckling pers. comm.).

In the event of BMSB establishing in New Zealand, the kiwifruit industry is likely to face a number of challenges including; possible limits to export markets, disruption of current management systems due to increased chemical use, potential issues with chemical residues and exceeding international minimum residue levels (MRLs) and increased production costs (packaging, labour, crop protection and control).

1.6.2 Nuisance pest impacts

BMSB is a public nuisance pest in residential and industrial areas as it overwinters in walls, insulation, attics, garages and other buildings (Inkley 2012). Reports of large aggregations of BMSB entering homes and other man-made structures seeking shelter during the cooler months have been reported in the US, Canada and invaded parts of Europe. A homeowner in Maryland, US, removed 26,205 BMSB adults from her residence in June 2011 (Inkley 2012). Once inside homes, BMSB may be hard to remove and can cause unsightly spotting or release a pungent odour when disturbed (Inkley 2012, Leskey et al. 2012a, Lee et al. 2013).

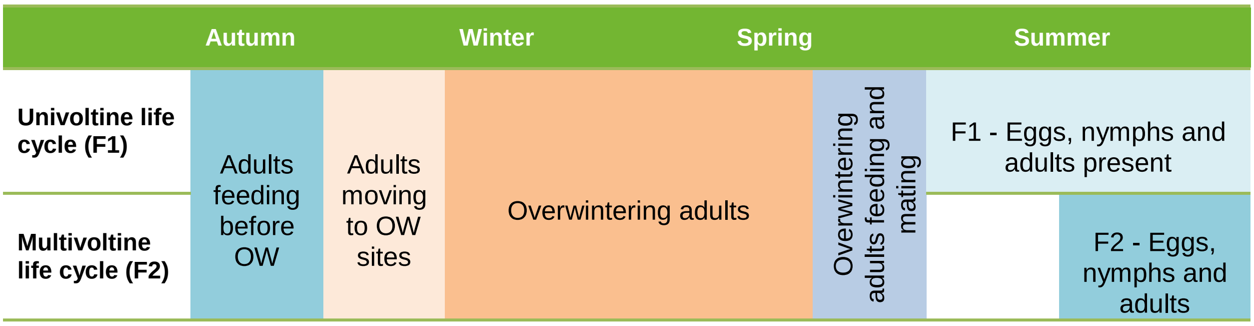
1.7 Biology and ecology

1.7.1 Life history and development

BMSB development is governed by many biological factors including temperature, photoperiod and host plant phenology. “Minimum and maximum temperatures for BMSB development in the US are 14.4°C and 35.76°C, and 12.97°C and 36.5°C in Europe” (Haye et al 2014; Nielsen et al. 2008a; as reviewed by Leskey and Nielsen 2018:p. 602). Total development (egg lay to adult emergence) of a BMSB cohort requires 537.62 - 588.24 day degrees (DD) (Haye et al. 2014, Nielsen 2014). Nielsen (2008a) reported that a further 147.65DD was required before female oviposition was initiated (pre-oviposition period). At a constant 25°C the total development period for a single BMSB cohort is reported to be 41.32 - 42.3 days (Haye et al. 2014, Nielsen 2008a) and the pre-oviposition period was on average 13.35 ± 0.72 days (Nielsen 2008a). Mean adult longevity has been estimated at 301 (Zhang et al. 1993 in Lee et al. 2013) to >365 days (Wang & Wang 1988 in Lee et al. 2013).

The actual number of BMSB generations per year varies in response to local conditions and factors such as photoperiod and temperature. Four to six BMSB generations have been documented in Kwangtung (Guangdong) province, China (Hoffman 1931 in Lee et al. 2013), however many other sources report one to two generations per year (Qin 1990; Zhang et al. 1993; Li et al. 1996; Chu et al. 1997; as reviewed by Lee et al. 2013). One or two generations have been reported in much of the invaded North American states (University of Florida 2019a) while Haye et al. (2014) reported that BMSB is univoltine in Switzerland. In New Zealand “it is likely that BMSB would probably develop through 1-2 generations per year, dependant on temperature, humidity and food plant availability” (Charles 2015: p. 10).

First-generation eggs (F1) are laid by post-overwintering adults in late spring in Chinese bivoltine BMSB populations (Wang & Wang 1988; Zhang et al. 1993; Qiu 2007; as reviewed by Lee et al. 2013). F1 adults then lay eggs (F2) in mid-summer (Qin 1990; Zhang et al. 1993; Qiu 2007; as reviewed by Lee et al. 2013) with F2 adults present in late summer/early autumn (Qin 1990; Zhang et al. 1993; Qiu 2007; as reviewed by Lee et al. 2013) (Figure 14).



	Autumn		Winter	Spring	Summer	
Univoltine life cycle (F1)	Adults feeding before OW	Adults moving to OW sites	Overwintering adults	Overwintering adults feeding and mating	F1 - Eggs, nymphs and adults present	
Multivoltine life cycle (F2)						F2 - Eggs, nymphs and adults

Figure 14. Seasonality of multivoltine and univoltine *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) life cycles in China (Lee et al. 2013). (OW = overwintering).

1.7.2 Feeding

BMSB nymphs and adults feed on a wide range of host plants (Tables 3 and 4). During feeding BMSB insert their straw-like stylet into plant tissues, holding it in place with the rostrum (Figure 15 and Appendix II). BMSB secrete a thick salivary compound which forms a protective sheath around the stylet (Leskey & Nielsen 2018). This sheath may stay intact on the fruit surface and is a characteristic sign of BMSB feeding (Figure 16). Salivary sheaths have been used in laboratory studies to quantify feeding frequency on host materials (Lara et al. 2018). Without these sheaths feeding is hard to detect in thicker skin fruits/vegetables, such as kiwifruit, with the naked eye. Fruit peeling is the only other way to gain confirmation of BMSB feeding in kiwifruit. A watery saliva is injected via the stylet into the plant tissue; this contains digestive enzymes which aid in cell degradation (Peiffer & Felton 2014, Leskey & Nielsen 2018). BMSB feed on the liquefied contents of these tissues.

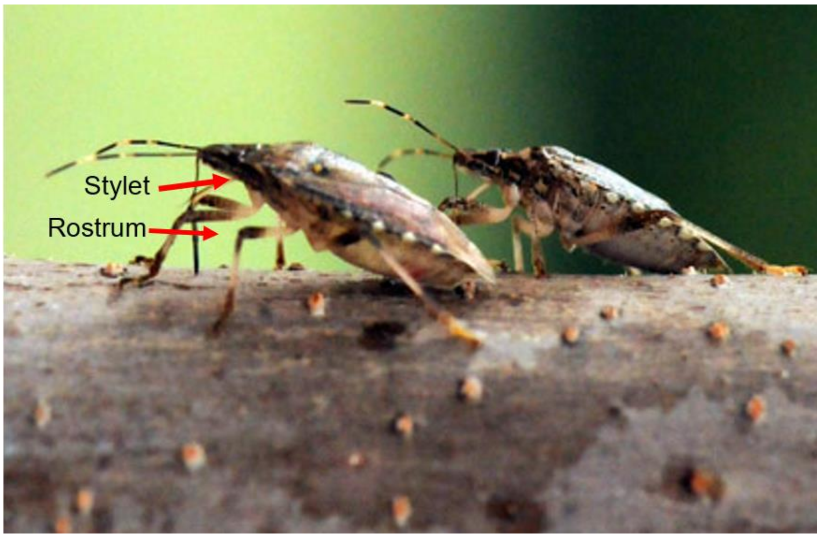


Figure 15. *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) adults feeding on an elm tree (*Ulmus* sp.), showing the location of the stylet and rostrum. (Source: Stop BMSB 2019).

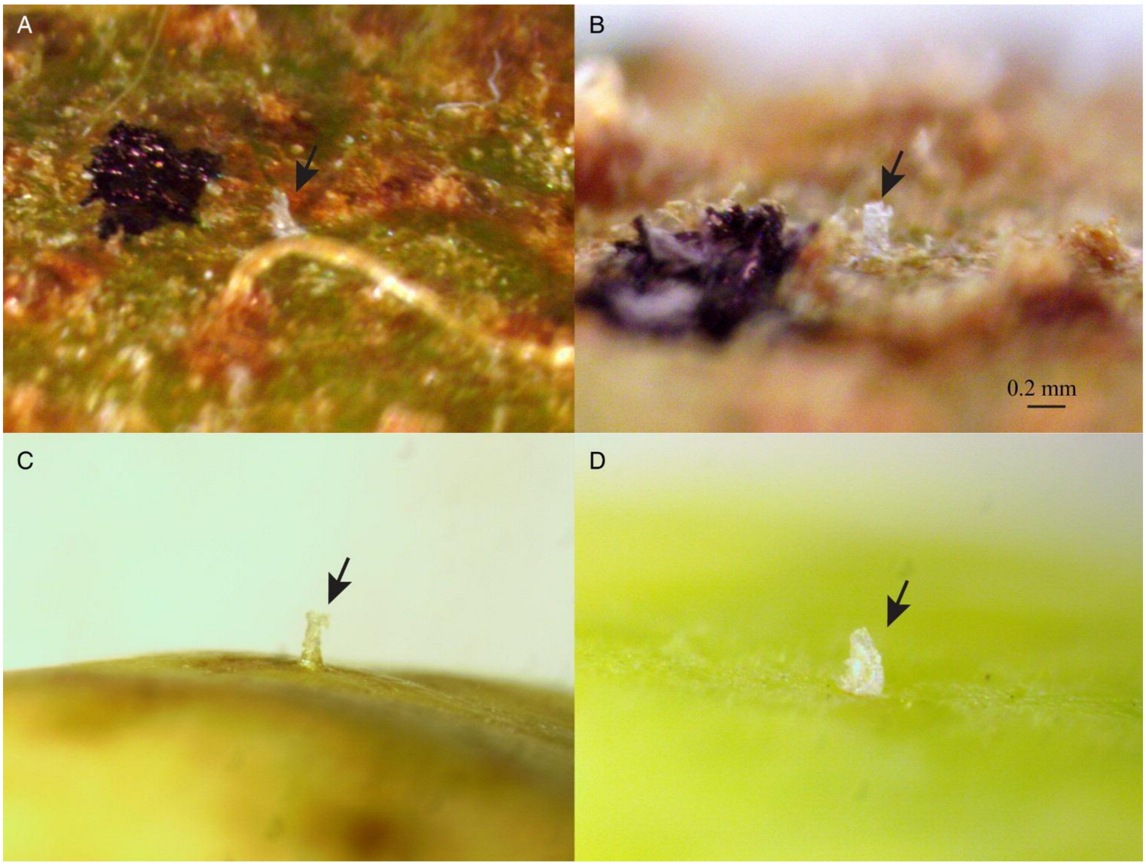


Figure 16. **Examples of salivary sheaths (arrows) deposited by *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) on the external surface of different foodstuffs. A–B, Green kiwifruit; C, pistachio nut; D, table grape. (Source: Lara et al. 2018: p. 15). Please note that permission would be required from the journal if this content was to be used outside of this review.**

1.7.3 Dispersal

Both adults and nymphs are capable of localised dispersal. First instar nymphs commonly remain on or near the egg case, however all other nymphal stages are capable of dispersal. Mobile nymph stages have “strong walking capacity on horizontal and vertical surfaces” (Lee et al. 2015: p. 647). In field observations, fifth instar nymphs were capable of walking two times the distance of third instars (Lee et al. 2015).

Adult BMSB are strong fliers. Most BMSB adults (89%) will fly less than 5km per day, however some individuals are capable of much longer flights (Lee & Leskey 2015). The maximum flight distance recorded by a single BMSB adult (under laboratory conditions) was 117km (Lee & Leskey 2015). BMSB adults fly during the day and at night; night flying activity includes mate seeking and searching for alternate food sources (CABI 2017).

Global BMSB dispersal has been achieved via human-mediated means and the ‘hitchhiker’ tendencies of the pest. In all invaded countries BMSB first established in small numbers in urban landscapes before moving into agricultural areas several years later (KVH 2017a).

It is forecasted that the most likely pathway for BMSB entry into New Zealand is via new and used vehicles from North America as infestation levels detected on other pathways are low in comparison (Ormsby 2018). Auckland is the most likely site for initial establishment as the greatest number of BMSB are intercepted here (Ormsby 2018) but other towns, such as Tauranga in the Bay of Plenty, with busy ports are also potential establishment sites.

1.7.4 Reproduction and oviposition

Reproductive development is governed by diet, photoperiod and temperature (Lee et al. 2013). Adult BMSB reach sexual maturity approximately two weeks post adult emergence (Wantanabe 1979; 1980; Yanagi & Hagihara 1980; Kawada & Kitamura 1983; Qiu 2007; Bae et al. 2009; as reviewed by Lee et al. 2013). Mating occurs at any time and the females are polyandrous (Kawada & Kitamura 1983 in Lee et al. 2013). BMSB “copulation duration is between 5-14 minutes” (Saito et al. 1964; Kawada & Kitamura 1983; Wang & Wang 1988; as reviewed by Lee et al. 2013: p. 630) and the average interval between oviposition events is approximately 4–5 days (Nielsen et al. 2008a, Lee et al. 2013).

Adult male BMSB, like other pentatomid species possess claspers (Figure 17) at the base of the abdomen which bind the adult pair during copulation (Figure 18).

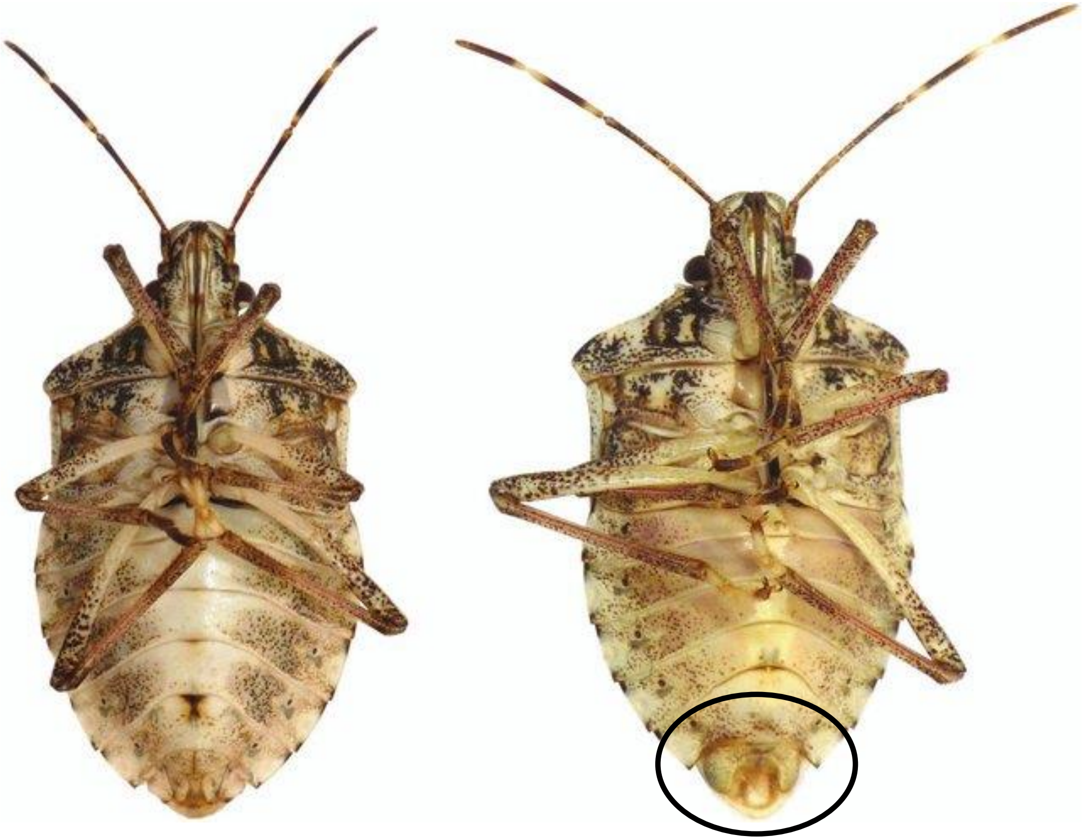


Figure 17. Adult female (left) and male *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) adults. Males have claspers (circled in the above image) on the terminal abdominal segment which serve to bind reproductively mature BMSB adult pairs during copulation (Source: Rice et al. 2014: p. A3). Please note that permission would be required from the journal if this content was to be used outside of this review.

Figure 18. Mating *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) adults with the male on the left and the female adult on the right. Mating pairs are bound together during copulation using specialised claspers as the base of the abdomen. (Source: BugGuide 2019).

Substrate-borne vibrational communication is used by pentatomids especially for mate location (Polajnar et al. 2016, Mazonni et al. 2017). Three male (MS-1, MS-2 and MCrS) and two female (FS-1, FS-2) produced vibrational signals or songs play an integral role in BMSB mate location (Polajnar et al. 2016). In order to find a mate and initiate reproduction, male adults first release an aggregation pheromone, followed by the male insect issuing Male Song 1 (MS-1). This signal can last almost 30 seconds, which is longer than any other vibrational signal described for other pentatomid species (Polajnar et al. 2016). The female then responds with FS-1 followed by FS-2, to which the males respond with MS-2 and then initiate searching behaviours moving only in the pauses between female signals (Polajnar et al. 2016). This pattern can be repeated multiple times until the pair meet (Polajnar et al. 2016).

During the final phases of this behaviour the female remains silent while the male emits the Male Courtship Song (MCrS). When the pair come into contact, the male emits a pheromone and initiates tactile stimulation via antennation and head butting. This is followed by genital contact and eventually copulation (Polajnar et al. 2016). Before genital contact is made, male BMSB tremulate and walk sideways, butting the female abdomen to coerce her to raise it ready for copulation (Polajnar et al. 2016). The female-produced FS-2 signal has been shown to attract males when artificially reproduced (Mazzoni et al. 2017). Adult male BMSB were able to locate the source of the signal and tended to dwell near the source (Mazzoni et al. 2017). This behaviour could possibly be exploited in attract and kill strategies.

Eggs are laid in rafts of 20–30 eggs (CABI 2017) and are light green in colour changing to white (Rice et al. 2014) (Figure 6) as they mature. Eggs are usually laid on the underside of leaves (CABI 2017, Utah State University 2017) and “toward the upper and interior tree canopy” (Funayama 2002 in Lee et al. 2013: p. 630). Adult females lay eggs over their whole lifespan, however this declines with age and reduced health (Kawada & Kitamura 1983 in Lee et al. 2013). In a life table analysis conducted by Nielsen et al. (2008a) mated females laid on average 212.24 (±31.04) eggs.

1.7.5 Overwintering

Overwintering behaviours are triggered by abiotic cues such as cooling temperature and by shortening day length. In Japan, Korea and China BMSB adults move to suitable overwintering grounds in September through to November (Saito et al. 1964; Kobayashi and Kimura 1969; Watanabe et al. 1978; Yanagi and Hagihara 1980; Kawada and Kiatamura 1992; Zhang et al. 1993; Funuyama 2012; as reviewed by Lee et al. 2013). BMSB will rarely leave the overwintering grounds (Tomaya et al. 2011 in Lee et al 2013), “unless stored nutrients are depleted” (Funuyama 2012 in Lee et al. 2013: p. 628).

Lee et al. (2014a) reported that BMSB adults prefer cool, dry overwintering sites and in natural landscapes were found on dry surfaces within dead, standing trees. In deciduous forests overwintering adults were found mostly in dead, standing oak (*Querus* spp.) and locust (*Robinia* spp.) trees (Lee et al. 2014a). This preference for dry, cool sites may account for the insects’ affinity for man-made structures (Lee et al. 2014a) (Figure 19) and furthermore this association may enhance overwintering survivorship (Kiritani 2006 in Leskey & Nielsen 2018).

Figure 19: *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) adults infesting a residence in the United States. (Source: Entomological Society of America 2019).

Dispersal from the overwintering sites is temperature and photoperiod dependant and can also be signalled by the depletion of resources. Overwintered adults start to disperse in spring when ambient temperatures are greater than 10°C (Qin 1990 in Lee et al. 2013). In Southern Europe BMSB adults were observed exiting overwintering habitats when temperatures exceeded 14°C with a photoperiod of 13 hours (Costi et al. 2017).

Overwintered adults are “significantly more susceptible to insecticides than F_1 adults” (Brown Marmorated Stink Bug Working Group 2011 in Lee et al. 2014a) and subsequent generations. This fact may be key in significantly reducing pest populations.

1.7.6 Mortality factors

Mortality is due to senescence, parasitism and predation: the latter two topics are discussed in Section 1.7.9 Natural Enemies of this review.

Relatively few studies report mortality factors. In North America BMSB egg mortality averaged 54% in field samples with approximately 35.8% attributed to egg parasitism, 7% to chewing and sucking predation and 11.2% to unknown factors (Jones et al. 2017). The latter category includes egg malformation and discoloration caused by unidentified influences. Nielsen et al. (2008a) reported an average egg mortality rate of 18.4% under laboratory conditions. Costi et al. (2017) reported 86% mortality in overwintering adult BMSB in Italy, which is relatively high when compared with 39% reported in BMSB populations in Switzerland (Haye et al. 2014). Mortality was likely due to exposure to very low temperatures (Costi et al. 2017, Wermelinger et al. 2008 in Ormsby 2018) and exhaustion of resources. Adults that leave overwintering sites early tend to perish soon after emergence, possibly due to the lack of resources in late winter/early spring (Costi et al. 2017).

1.7.7 Chemical ecology

a) Volatiles

BMSB, like other pentatomids, emits a wide array of volatile chemicals, including hydrocarbons, aldehydes and oxo-aldehydes (Weber et al 2017). Volatile compounds are secreted from the abdominal and metathoracic glands of pentatomid nymphs and adults respectively (Lopes et al. 2015, Weber et al. 2017).

Aldehydes and alkenes contained in the pungent odour produced by pentatomids when disturbed are allomones or defensive compounds (Weber et al. 2017). Third instar nymphs and adults of BMSB produce the aldehyde (E)-2-decanal which was identified as an alarm pheromone (Harris et al. 2015, Weber et al. 2017). The odour associated with this compound is said to be similar to that of coriander (*Corriandrum sativum* L.) (Weber et al. 2017).

Volatile detection technologies have been explored to aid in BMSB overwintering site location in an array of situations including cargo (Weber et al. 2017). Canine detector dogs have been trained to detect BMSB volatiles (Lee et al. 2014a) and in New Zealand these dogs have been used to investigate border and post-border BMSB interceptions (MPI 2018).

Volatiles produced by pentatomids have been shown to have antifungal or antibacterial properties which aid in their defences against microbial infection. The aldehydes, (E)-2-decanal and (E)-2 –octanal, have fungistatic properties which “inhibit fungal spore germination of the entomopathogenic fungi *Metarhizium*, *Beauvaria* and *Isoria* (Pike 2014 in Weber et al. 2017: p. 955).

Volatiles produced by pentatomids can also be exploited by natural enemies; these act as kairomones that aid in the location of the pest species.

b) Pheromones

The aggregation pheromone produced by male BMSB consists of a 3:5:1 mix of the two (cis and trans) stereoisomers, (3*S*,6*S*,7*R*,10*S*) -10,11-epoxy-1-bisabolene-3-ol and (3*R*,6*S*,7*R*,10*S*) -10,11-epoxy-1-bisabolene-3-ol) (Khrimian et al. 2014). This compound is commonly referred to as PHER. Both nymphs and adults are responsive to synthetic formulations of the aggregation pheromone (Khrimian et al. 2014) which now plays an integral role in BMSB population monitoring and management strategies.

BMSB are also attracted to the aggregation pheromone of *Plautia stahli* (Hemiptera: Pentatomidae, the brown-winged green stink bug, (methyl-(2*E*,4*E*,6*Z*)-2,4,6-decatrienoate or MDT)) (Khrimian et al. 2014, Weber et al. 2017) and, prior to the discovery of PHER, was used to monitor BMSB populations. However MDT was discovered to be attractive only to BMSB adults later in the growing season when populations were larger, missing the opportunity to control smaller or post-overwintering populations earlier in the season (Leskey et al. 2012a).

Weber et al. (2017) found that combining PHER and MDT in baited traps produced a synergistic effect, whereby more adults and nymphs were caught in traps baited with both pheromone components in comparison to traps baited with each component alone. Furthermore, when combined with PHER, MDT remained attractive to BMSB throughout the growing season (Weber et al. 2017). It is now common for the two-component pheromone complex to be commercially marketed and sold in combination (Weber et al. 2017).

The BMSB sex pheromone remains unknown.

1.7.8 Genetic haplotypes

A total of 45 BMSB haplotypes (H1-23, H30-51) have been identified across 10 different countries using *cytochrome c oxidase subunit I* (COI) sequence analysis (Gariepy et al. 2014b, 2015; Cesari et al. 2015; in Lee et al. 2018). Of these 18 were detected in Korea, 16 of which were novel and two novel haplotypes were detected in the US (H50-H51) (Lee et al. 2018). Haplotype 22 is prominent in Korea; H22 is also present in China and Greece (Lee et al. 2018). Haplotype 1 is prominent in Greece, Hungary, Italy, Canada, the US and China indicating that established BMSB populations in these invaded countries most likely originated from China (Lee et al. 2018). H3 is dominant in France and Switzerland (Lee et al. 2018).

Based on haplotype diversity, Korean BMSB populations were genetically distinct from those detected in China, the US and Europe, suggesting that they were not part of the invasion events in these countries (Lee et al. 2018). BMSB populations in Greece comprise H1 and H22, suggesting that the resident population is derived from both China and Korea.

Table 5. *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) haplotypes identified by Lee et al. (2018) utilising cytochrome c oxidase subunit I (COI) sequence analysis on BMSB specimens collected from East Asia, Europe and North America. Novel haplotypes are shown in bold text (Source: Lee et al. 2018: p. 51). Please note that permission would be required from the journal if this content was to be used outside of this review.

			Haplotype																																										Total
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	30	31	32	33	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	
Native range	East Asia	Korea		15																				41						2	1	1	1	1	5	2	1	1	3	1	1	1	1	1	1			80
		China	75	1	14	1	1	1	3			1	1	1	3	1	1	1	1	1	1	1	1																									110
		Japan																							1																							1
Non-native range	Europe	France	1		136					2																																						139
		Greece	18		4																			2		1	1	8	23																			57
		Hungary	83		1																																											84
		Italy	32		7					1																																						40
		Switzerland	2		191					31	1																																					225
	North America	Canada	49					1								1																																51
		USA	25																																										1	1	27
Total			285	16	353	1	1	2	3	34	1	1	1	1	3	2	1	1	1	1	1	1	1	43	1	1	1	8	23	2	1	1	1	1	5	2	1	1	3	1	1	1	1	1	1	1	1	814

1.7.9 Natural enemies

Known BMSB natural enemies include egg, nymph and adult parasitoids, chewing and sucking predators, entomopathogenic fungi and an intestinal virus.

a) Parasitoids:

Several natural enemies and predators have been reported for the BMSB in its native range (Table 6), the most specialised and effective of these belong to the *Trissolcus* genus (Arakawa & Namura 2002; Arakawa et al. 2004; Qiu 2007; Yang et al. 2009; as reviewed by Lee et al. 2013). Many of these parasitic wasps target BMSB eggs. Two species *Bicyrtes quadrafaciata* and *Trichopoda pennipes* target late instar nymphs or adults, whilst predatory insects feed on all BMSB life stages. In parts of Asia, 63–85% egg parasitism has been reported by members of the *Trissolcus* and *Anastatus* genera (Zhang et al. 1993; Qiu 2007; Qiu et al 2007; Yang et al. 2009; Hou et al. 2009; Talamas et al. 2013; as reviewed by Rice et al. 2014). An egg parasitism survey conducted in the mid-Atlantic region of the US and Oregon using sentinel BMSB egg rafts showed that egg parasitism by indigenous species is low (<1–11%) in comparison to those reported in Asia (Leskey et al. 2012a, Rice et al. 2014). Parasitism presence also varied in response to ecosystem (Leskey et al. 2012a).

Trissolcus japonicus (syn. *T. halyomorphae*) was reported to be the predominant parasitic wasp in Beijing, China (Yang et al. 2009 in Lee et al. 2013). Up to 80% BMSB egg parasitism by *T .japonicus* has been reported (KVH 2017a). Two adventive populations of *T. japonicus* have occurred in North America and Switzerland. It is thought that this natural enemy entered the US via parasitised eggs on imported plant material (University of Florida 2019b). The importation and release of *T. japonicus* as a means of classical biological control has been approved by the Environmental Protection Authority of New Zealand as an early BMSB eradication tool.

Table 6. Documented parasitoids of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in the pests native range (Asia) and North America, and the BMSB life stage that each natural enemy attacks.

Agent	Host stage affected	Country of origin
Parasitoids		
Acroclisoides sp.	Egg	China
Anastatus sp.	Egg	China
Anastatus gastropachae Ashmead	Egg	Japan
Anastatus mirabilis	Egg	Delaware, Maryland
Anastatus pearsalli	Egg	Delaware, Maryland, Pensylvania
Anastatus reduvii	Egg	Delaware, Maryland
Bicyrtes quadrafaciata	Late instars	Pennsylvania
Bogosia sp.	Egg	Japan
Gryon obesum	Egg	Maryland
Gryon japonicum	Egg	Japan
Ooencyrtus nezarae Ishii	Egg	Japan
Ooencyrtus sp.	Egg	China, Delaware, Maryland
Telenomus nigripedius Nakagawa	Egg	Korea
Telenomus mitsukurii (Ashmead)	Egg	China
Telenomus podisi	Egg	Maryland, Pennsylvania
Telenomus sp.	Egg	China
Telenomus utahensis	Egg	Virginia
Trichopoda pennipes	Adult, late instars	Pennsylvania
Trissolcus brochymenae	Egg	Delaware, Maryland, Virginia
Trissolcus edessae	Egg	Delaware, Maryland, Virginia
Trissolcus euschisti	Egg	Delaware, Maryland, Oregon
Trissolcus itoi Ryu (bassionym)	Egg	Japan
Trissolcus favipes Thomson	Egg	China
Trissolcus halyomorphae Yang	Egg	China
Trissolcus japonicus (syn. *T. halyomorphae*)	Egg	East Asia, North America, Switzerland
Trissolcus mitsukurii (Ashmead)	Egg	Japan, China
Trissolcus plautiae (Watanabe)	Egg	Japan
Trissolcus thyantae	Egg	Virginia
Trissolcus utahensis	Egg	Oregon

Sources: CABI 2017, Lee et al. 2013, Rice et al. 2014.

b) Predators:

Egg predation of up to 40–70% has been reported in corn and soy bean crops in Pennsylvania, Maryland and New Jersey (Rice et al. 2014). *Harmonia axyridis* and earwigs (Forficulidae) were identified as the main predators in Pennsylvanian orchard systems (Biddinger et al. 2012 in Rice et al. 2014). Conversely, Ogburn et al. (2016 in Leskey and Nielsen 2018) reported that BMSB egg predation in organic farms across the US did not exceed 10%. Predation on BMSB nymphs and adults has not been quantified.

Table 7. Documented predators of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in the pests native range (Asia) and North America, and the BMSB life stage that each natural enemy attacks.

Agent	Host stage affected	Country of origin
Arilus cristatus	Egg, nymph, adult	Maryland, Oregon, Pennsylvania
Arma chinensis (Fallou)	Egg, adult	China
Astata bicolour	Late instars	Oregon
Astata unicolour	Adult, late instar nymph	Pennsylvania
Astochia vigratipes Coquillet	Unknown	China
Bicyrtes quadrifasciatus	Nymph	North America
Geocorsis sp.	Egg, nymph	Maryland, Oregon, Pennsylvania
Harmonia axyridis	Eggs	Pennsylvania
Isyndus obscurus (Dallas)	Nymph, adult	Japan
Misumena tricuspidata (F.)	Egg, adult	China
Nyctereutes procyonoides Gray	Adult	East Asia
Orius sp.	Egg, adult	China, Maryland
Tenodera sinensis	Nymph, adult	Maryland
Unidentifed larvae	Egg, early instar nymph	Maryland, Oregon, Pennsylvania
Arachnida	Egg, nymph, adult	Maryland, Oregon, Pennsylvania
Forficulidae	Egg	Pennsylvania

Sources: CABI 2017, Lee et al. 2013, Rice et al. 2014.

c) Entomopathogens:

Pentatomids possess defence mechanisms which reduce bacterial and fungal infection. These include the production of volatile chemicals that inhibit the growth of entomopathogens on the insect cuticle (1.7.7. Chemical ecology). Lipids contained within the cuticle limit the attachment of pathogens to the integument thereby preventing infection into the insect body (Raafat et al. 2015). Early-stage pentatomid nymphal instars (Parker et al. 2015) and eggs (Da Silva et al. 2015) have been demonstrated to be more susceptible to entomopathogenic fungi than adults, and targeting these life stages may prove efficacious in population reduction/control attempts (Parker et al. 2015). Careful consideration of entomopathogen strain or targeting application during susceptible life stages (e.g. nymphs) is recommended.

The entomopathogenic fungi *Metarhizium anisopoliae* and *Beaevaria bassiana* are reported to be efficacious against BMSB (Table 8). The biopesticide Botaniguard® (active ingredient *B. bassiana* (GHA)) is reported to be efficacious against adults (Gouli et al. 2012) and second instar nymphs (Parker et al. 2015), achieving 67–100% mortality 12 days post treatment for both life stages. Coupling sub-lethal doses of chemical insecticides (thiamethoxam) in combination with the entomopathogenic fungi *M. anisopliae* (Metsch.) produced a synergistic effect and enhanced the mortality and myscosis of *Tibraca limbativentris* (the rice stalk stink bug) (Quintela et al. 2013).

Consideration of fungal strain and improvements in formulation may lead to further increases in entomopathogen efficacy.

Table 8. Documented entomopathogens of *Halyomorpha halys* (Stål. 1855) (brown marmorated stink bug, BMSB) in its native range (Asia) and introduced range North America, and the BMSB life stage that each natural enemy attacks.

Agent	Host stage affected	Country of origin
Beauvaria bassiana ((GHA) 22WP and BotaniGard® ES, ERL 1170 and ERL 1540 strains)	Early nymphs, adults	
Metarhizium anisopliae (Met52, ERL 1540, ERL 1171)	Nymphs, adults	
Ophidiocordyceps nutans (Pat.)	Nymph, adult	Japan
Plautia stahli intestine virus (PSIV)	Nymph, adult	Japan

Sources: Gouli et al. 2012, Lee et al. 2013, Parker et al. 2015, Rice et al. 2014, Skillman et al. 2018.

d) Natural enemies of the New Zealand Pentatomid fauna:

In New Zealand, three species of *Trissolcus* (Table 9) are known parasitoids of the local pentatomid fauna. However it is unlikely that these will attack BMSB (Charles 2015). *Trissolcus maori* is restricted to the Acanthosomatidae whilst *T. basalis* predominately attacks *Nezara viridula* (Charles 2015). Similarly, local predator species have not been shown to play a large role in reducing pest populations (Charles 2015).

Table 9. Documented natural enemies of the pentatomid fauna present in New Zealand and the pentatomid species that each natural enemy attacks.

Agent	Host stage affected	Pentatomid species attacked
Parasitoids		
Acroclisoides sp	Eggs	*Nezara viridula*
Aridelus rufotestaceus Tobias 1986	Nymph, adult	*Nezara viridula, Glaucias amyoti*
Trissolcus basalis	Eggs	*Cermastulus nasalis, Cuspicona simplex, Dictyotus caenosus,Glaucias amyoti, Monteitheilla humeralis, Nezara viridula, Oechalia schellenbergii*
Trissolcus oenone (Dodd 1913)	Eggs	*Cermastulus nasalis, Cuspicona simplex, Dictyotus caenosus,Glaucias amyoti, Monteitheilla humeralis, Oechalia schellenbergii*
Trissolcus maori	Eggs	*Oncacontias vittatus*
Predators		
Birds (e.g. *Sturnis vulgaris*)	Nymphs, adults	*Nezara viridula*
	Nymphs	*Nezara viridula*
German wasps (*Vespula germanica*)	Nymphs	*Nezara viridula*
Rats (*Rattus exulans)*		*Dictyotus caenosus*
Entomopathogens		
Beauvaria malawiensis	Adult	*Monteitheilla humeralis*

Sources: Cummings 2009, Martin 2016a, 2016b, 2017, 2018a, 2018b

2 PEST MANAGEMENT

The global invasion of BMSB has disrupted many crop management programmes and growers have resorted to using repeated applications of broad-spectrum chemical in attempts to control the pest. However a more integrated approach needs to be considered to prevent toxic chemical residues, secondary pest outbreaks, development of pesticide resistance and to avoid harming natural enemies.

Organic control solutions are few and far between but many of the cultural control strategies recommended for BMSB management, including the use of exclusion nets, overwintering site and population destruction, alternate host removal, and trap cropping, can be adapted into these systems. In terms of biological control, the egg parasitoid *Trissolcus japonicus* and the biopesticide Botaniguard® have been documented as the most efficacious biological control agents against BMSB.

This section of the review discusses monitoring techniques and biological, cultural and chemical control methods for use against BMSB.

2.1 Monitoring techniques

Pest population monitoring is an essential part of any cropping system and is important in the crop management decision process. The most effective monitoring methods for the BMSB involve the use of black light traps and pheromone stimuli.

a) Visual inspection

Monitoring crops via visual inspection throughout the growing season, and during winter to locate overwintering populations, is important for management. Visual monitoring of trap crops would also be required if implemented as a BMSB control tool.

b) Light traps

Black, blue and white light traps have been demonstrated to be effective tools in monitoring pentatomid phenology (Chatterjee 1989, Kim & Lee 2008, Kamminga et al. 2009, Leskey et al. 2015a, Rice et al. 2017).

White, blue and black (ultraviolet) light have been identified as the most attractive light wavelengths in both lab and field situations and furthermore, that blue light reduced the amount of non-target catch while white light was more attractive to BMSB (Leskey et al. 2015b). Black light traps, although non-species specific, were efficient at trapping BMSB season long, even early in the growing season when BMSB population densities are low (Nielsen et al. 2013). Black light frequencies have also been identified as the most attractive to *Nezara viridula* (green vegetable bug (GVB) syn. southern green stink bug) (Endo 2016).

Rice et al. (2017) showed that competing light sources associated with anthropogenic structures did not reduce BMSB light (blue) trap catches, hence these traps could be used in urban environments to monitor BMSB populations.

c) Pheromone-based traps

Brown marmorated stink bug adults and nymphs have been shown to be cross-attracted to the aggregation pheromone of the brown-winged green bug (*Plautia stahli*) (methyl (2E,4E,6Z)-decatrienoate, MDT), in both the BMSBs native (Lee et al. 2013) and invaded ranges (Aldrich et al. 2007). The exact mechanism of attraction remains unknown (Leskey and Nielsen 2018). MDT is attractive to BMSB adults late in the growing season (Leskey and Nielsen 2018) but remains attractive to nymphs season long (Leskey et al. 2015a). The need for a season long attractant effective against adults led to the discovery of the male produced BMSB aggregation pheromone (Khrimian et al. 2014). Weber et al. (2014) found that using the two pheromone lures in combination produced a synergistic effect for both adults and nymphs.

Because these compounds are aggregation pheromones, BMSB are drawn to the vicinity of the stimuli and not to the exact location. Morrison et al. (2016) documented that these aggregation lures elicit an ‘attract and arrest’ response in BMSB adults and nymphs, and that bugs can usually be found within approximately 2.5m of the stimuli. Astorga (2018) recommended timed visual inspection and beating of vegetation (Figure 20) around the lure for a more accurate indication of local population numbers.

Combinations of aggregation and sex pheromones, host plants volatiles and/or acoustic cues may improve the efficacy of BMSB trapping methods.

Brown marmorated stink bug pheromone lures are traditionally placed out in the field in ground or small canopy pyramid traps (Figure 21): black ground pyramid traps proved to be the most effective for BMSB capture (Morrison et al. 2015). Recently clear stick traps (Figure 20) have been used as an alternative to the pyramids and are efficient at trapping adults (Pennsylvania State University 2017). Sticky traps are cheaper and more adaptable than the large pyramid in some cropping systems (Stop BMSB 2017a). Although the clear sticky traps have been shown to catch lower numbers of BMSB nymphs and adults than the pyramid traps, they are “equally efficient in detecting BMSB presence, abundance and seasonal activity of BMSB throughout the season” (Stop BMSB 2017a: p. 17). Some pyramid traps are loaded with kill strips impregnated with dichlorvos, 2,2-dichlorovinyl dimethyl phosphate or DDVP) that kill insects caught in the traps.

The aggregation pheromone complex for BMSB is currently being used by the Ministry for Primary Industries (MPI) as a surveillance tool in New Zealand. This specific lure is also being used for research purposes by entomologists at Plant and Food Research in Hawke’s Bay to investigate lure by-catch.

Figure 20. Left: Clear sticky trap coupled with Trècè Inc. *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) pheromone lures in Chile, Santiago and right: vegetation beating as part of BMSB surveillance effort in Chile, Santiago. (Source: Astorga 2018).

Figure 21. A pheromone baited pyramid trap used to monitor *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) populations. The fins of the pyramid provide a substrate for BMSB adults and nymphs to arrest on and walk to the tip of the cone, at which a collection container with the pheromone lure is placed. Dichlorvos-impregnated (2,2-dichlorovinyl dimethyl phosphate or DDVP) kill strips may be deployed in the collections containers as well as a means of killing invading insects. (Source: Oregon State University 2016).

2.2 Chemical

2.2.1 Pre-border

The detection of BMSB on goods imported from North America prompted changes in the national Import Health Standards for vehicles, machinery and high-risk containerised goods (Ormsby 2018) entering New Zealand (Table 2). In 2017 vehicles, all machinery and sea containers with goods originating from or travelling via Italy were required to be treated in response to increased BMSB interceptions on Italian exports here in New Zealand. In 2018, the same sanctions were placed on vehicles and machinery arriving from Japan. MPI standards for these commodities include heat treatment and chemical fumigation either in the country of origin or in transitional facilities here in New Zealand.

Chemical fumigant treatments for incoming goods from sanctioned countries include:

- Methyl bromide fumigation at 48 g/m3 at 10–15°C for 24 hours
- Methyl bromide fumigation at 40 g/m3 at 15–21°C for 24 hours
- Sulphuryl fluoride fumigation at 32g/m3 at 21–25° for 24 hours
- Sulphuryl fluoride fumigation at 40g/m3 at 16–20° for 24 hours
- Sulphuryl fluoride fumigation at 16g/m3 at 10° or greater for 12 hours with a 50% end point reading.

Recommendations made in 2018 in a review by Ormsby (2018), included:

- for methyl bromide, a fumigation rate of >140g.h/m3 at 10°C and >120g.h/m3 t 15°C applied over a 12–24 hour period should ensure (at the 95% level of confidence) no more than one BMSB adult survives in 1000 exposed adults (99.9% control),
- for sulphuryl fluoride, a fumigation rate of 0.135g.h/m3 for treatments at >10°C applied over a 12 hour period at a minimum concentration of 8g/m3, should ensure (at the 95% level of confidence) no more than one BMSB adult survives in 1000 exposed adults (99.9% control).

This review also found that overwintering BMSB adults were more tolerant to fumigant treatments.

2.2.2 Post-border

The BMSB is difficult to control with pesticides and attempts to do so have disrupted integrated pest management programmes (IPM) across multiple cropping systems (Rice et al. 2014). In general, multiple applications of foliar broad-spectrum insecticides, especially those belonging to the carbamate, pyrethroid and neonicotinoid chemical groups (Lee et al. 2013, Leskey and Nielsen 2018, Stop BMSB 2017b, Utah State University 2017) (Table 10), have been used in attempts to control BMSB in the field. Broad-spectrum insecticides affect both pest and natural enemy species and may lead to secondary pest problems. Furthermore foliar insecticides have short residual activity against BMSB (Leskey and Nielsen 2018), hence the need for multiple sprays as BMSB continue to invade from the crop surrounds.

Pyrethroids, particularly; bifenthrin, fenpropathin, permethrin, lamda-cyhalothrin, cyflurthrin, and β-cyfluthrin, and other pesticides including acephate, methomyl, dinotefuran and endosulfan (Nielsen et al. 2008b, Krawczyk et al. 2011, Kuhar et al. 2012, Leskey et al. 2012b) were demonstrated to be effective against BMSB in laboratory trials. The same pyrethroid sprays showed efficacy in several field assays, along with the neonicotinoids: dinotefuran, clothianidin and thiamethoxam, endosulfan, and the carbamates methomyl and oxamyl (Kuhar and Kamminga 2017). Pyrethrum based sprays, in general, are broad spectrum and have short action periods and residual lives. Pyrethrum use can also cause secondary pest, namely aphid and scale, outbreaks in tree fruit crops (Rice et al. 2014).

Adult BMSB knockdown recovery or sub-lethal effects have been reported by numerous authors (Leskey et al. 2012b, Leskey et al. 2014, Peverieri et al. 2017, Bergh and Quinn 2018) associated with the use of many pyrethroid and neonicotinoid products. Employing secondary control options (e.g. physical removal of moribund insects combining chemical control with the use of entomopathogenic fungi) to ensure insect mortality may improve efforts to reduce BMSB abundance.

Of the pyrethroid products tested or recommended for BMSB control, bifenthrin (Nielsen et al. 2008b, Leskey et al. 2012b), fenpropathin and cypermethrin have been shown to be the most efficacious against BMSB adults. Eliciting control similar to that reported by insecticides belonging to the more toxic chemical groups including organophosphates, organochlorines and carbamates (Leskey et al. 2012b).

Table 10. Chemical, organic compounds and other agents reported to show efficacy against *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB).

Chemical group	Chemical name
Carbamates	Alanycarb, Carbaryl, Methomyl, Oxamyl, Thiocarb
Organophosphates	Acephate, Chlorpyrifos, Cyanophos, Diazinon, Dichlorvos, Dimethoate, Fenitrothion, Fenthion, Methidathion, Ometnoate, Phenthoate, Prothiophos
Organochlorines	DDT, Dieldrin, Endosulfan, Lindane
Pyrethroids	Bifenthrin, Cyfluthrin, β-Cyfluthrin, Cyhalothrin, Cypermethrin, Deltamethrin, Esfenvalerate, Etofenprox, Fenpropathrin, Fenvalerate, Gamma cyhalothrin, Lamba cyhalothrin, Permethrin, Silafluofen, Tralomethrin, Zeta cypermethrin
Neonicotenoids	Acetamiprid, Clothianidin, Dinotefuran, Imidacloprid, Thiacloprid, Thiamethoxam
Phenylpyrazoles	Fipronil
Combinations	Dichlorvos + Diazinon, Dichlorvos + Lindane, Fenvalerate + Fenitrothion, Fenvalerate + Malathion, Zeta-cypermethrin + bifenthrin, lamba cyhalothrin + chlorantraniliprole
Other agents	Kerosene
Organic sprays	Azadirachtin, Kaolin Clay

Source: Lee et al. 2013, Rice et al. 2014, Utah State University 2017 Stop BMSB 2017b.

Aigner et al. (2015) showed that the neonicoicotenoids; clothianidin, dinotefuran, imidacloprid and thiamethoxam, were highly toxic to BMSB following systemic uptake under laboratory and field conditions. Soil application of these products produced significantly less BMSB damage to treated pepper and tomato crops (Aigner et al. 2015). Soil drench or drip chemigation of dinotefuran was shown to control BMSB for up to two weeks in fruiting vegetables like pepper and tomato (Rice et al. 2014).

As with all pest management programmes chemical rotation (modes of action and products) is essential to avoid the development of pesticide resistance. This is especially important for BMSB as few chemicals are currently registered for the pest and many of the insecticides identified as effective against the pest are highly toxic and prohibited from use in certain countries.

Employing more integrative strategies that include cultural and pest behavioural aspects may lead to reduced spray applications. Targeting BMSB nymphs and overwintered adults that are more susceptible to chemical sprays has been shown to be efficacious (Nielsen et al. 2008b, Leskey et al. 2014, Kuhar and Kamminga 2017). Various attract and kill strategies that combine the use of pheromone stimuli and chemical methods have been explored for BMSB control particularly in apple and peach orchards in North America (see Section 2.7 Integrated Pest Management).

Insecticide applications have also been recommended for the home garden and external applications on the exterior of homes and possible entry points to deter stink bug invasion during the late autumn and winter (University of California Agriculture and Natural Resources 2017).

2.3 Cultural control

The use of pheromone-baited traps is the only established method used widely to monitor BMSB populations, however general cultural control methods (as described below) may help to reduce BMSB populations. Cultural control methods described here include the use of physical barriers, susceptible host removal/control and trap cropping.

a) Crop monitoring

Light traps

Blue and black (ultraviolet) light traps, although non-species specific, have been shown to be efficient at trapping BMSB throughout the growing season even when BMSB populations densities are low (Nielsen et al. 2013, Rice et al. 2017), and furthermore competing light sources do not negatively affect BMSB light (blue) trap catches.

Pheromone stimuli

Crop monitoring using pheromone-baited traps and visual inspection of vegetation near the pheromone stimuli is recommended (Morrison et al. 2016, Astorga 2018). Aggregation pheromones tend to bring insects into the general vicinity of deployed stimuli rather than directly to the source. BMSB pheromone lures can be deployed in ground or canopy/tree based pyramid traps, or with clear sticky traps (Stop BMSB 2017a). Insecticide strips (dichlorvos-impreganated kill strips (2,2-dichlorovinyl dimethyl phosphate or DDVP)) can be deployed inside the capture containers atop the pyramid traps as a secondary kill strategy. Pheromone traps can also be used as indicators of population thresholds that initiate spray applications (see Section 2.7 Integrated Pest Management (IPM)). Due to high toxicity and shorter lethal exposure time, some researchers have replaced the standard dichorvos kill strips used in BMSB baited pyramid traps with 15cm^2 strips of the long lasting insecticide net (LLIN) ZeroFly® (Kuhar et al. 2017, Stop BMSB 2017a).

b) Exclusion nets

Exclusion nets are used as preventative methods that rely on physical barriers to reduce the flow of insects into cropping situations.

Dobson et al (2016) recommended the use of light-coloured exclusion netting in organic capsicum (*Capsicum annum* 'Aristotle') growing systems: in areas with smaller BMSB populations, wider mesh (1/8-1/6 inch or 4.23-3.18mm openings) was recommended to allow sun penetration and natural enemy movement while smaller mesh (1/25 inch or 1.02mm openings) was recommended in areas with higher BMSB pressure. The use of dark-coloured mesh resulted in reduced marketable yield due to low light conditions and aphid outbreaks were reported with the light-coloured nets (Dobson et al. 2016). In spite of this use of the smallest mesh, net size resulted in "increased crop yield due to general insect exclusion and protection from sunscald" (Dobson et al. 2016: p. 191). The use of exclusion nets (pearl anti-hail photo selective net Tenax Iridium (mesh: 2.3 x 4.8mm) (AGRINTECH, Eboli, Italy) in semi field trials in Italy reduced BMSB damage by "45% in peaches compared with non-netted and untreated trees and 20% in apples compared with chemical control treatments" (Candian et al. 2018: p. 21), and furthermore did not negatively affect fruit quality.

Exclusion nets have the potential to reduce chemical applications whilst providing control of insect pests. However factors such as the potential for outbreaks of other pests such as scale and thrips, practicality, cost and potential reductions in crop quality and/or quantity need to be considered before integrating exclusion nets into crop protection programs.

c) Chemically treated nets or Long-Lasting Insecticide Nets (LLINs)

Long-lasting insecticidal nets (LLIN), designed for the control of insect disease vectors, contain UV stabilisers and chemical slow-release technologies which with recommended use and care, are said to extend the lifetime and insecticide effects of the product for several years (Vestergaard 2014). LLIN use against BMSB remains, for the moment, in the experimental phases where nets impregnated with deltamethrin (ZeroFly® previously known as D-Terrance (Vestergard-Fransden)) or α-cypermethrin (Storanet®, BASF, Ludwigshafen a.R., Germany, 0.1% g/m^3 α-cypermethrin) have shown efficacy against BMSB (Peverieri et al. 2017, Stop BMSB 2017a).

Kuhar et al. (2017) reported 90% mortality of BMSB nymphs after 8.27 seconds of exposure to the LLIN ZeroFly® (3.85mg deltamethrin/g fibre) and adult mortality of 40.8–83.6% (24 hours after exposure) in response to increasing exposure time (10 seconds to 10 minutes respectively). In this study all dead and moribund insects were included in a single assessment category (dead/mortality). Peverieri et al. (2017) reported similar BMSB mortality rates (40–100%) in response to longer exposure periods (5–60 minutes) to the LLIN Storanet®, along with substantial sub-lethal effects (insect paralysis) and knockdown recovery, especially in response to shorter exposure periods. Some treated adults "could fully resume their activity in the days following treatment, even after almost two weeks spent under paralysed conditions" (Paverieri et al. 2017: p. 146). Although there are fundamental differences between these laboratory-based studies (assessment period >7 days vs 24 hours) and assessment criteria (moribund versus dead), both studies found that BMSB mortality increased with longer exposure periods (Bergh and Quinn 2018).

In field situations achieving longer BMSB exposure or contact periods to/with LLIN products may limit their efficacy as crop protection tools. Bergh and Quinn (2018) observed that BMSB tended to remain on the insecticide-treated netting for significantly shorter periods (4.26 ± 3.04mins) than untreated netting (7.27 ± 6.74mins), which may result in low BMSB adult mortality and knockdown recovery. In an attempt to overcome this 'exposure factor', various attract and kill (AK) strategies have been explored combining the use of LLINs and BMSB pheromone stimuli, these include: the construction of 'ghost' traps and hanging netting from apple trees or orchard fences (Stop BMSB 2017a, Kuhar et al. 2017). 'Ghost' traps, constructed by draping LLIN over or around a garden stake, captured BMSB consistently in late spring through summer in the USA (Kuhar 2018) when compared to standard baited pyramid and clear sticky traps.

In US apple orchards use of LLINs (ZeroFly® (3.85mg deltamethrin/g fibre) in combination with BMSB pheromone stimuli has been assessed as a potential AK method. This involved the use of individual deploying pheromone stimuli (1 per netted square) and three 1m square sections of ZeroFly® LLIN into individual perimeter apple trees spaced every 50m around three experimental blocks. Pheromone lures and LLIN were deployed on the outer facing facade of each tree (Stop BMSB 2017a). These AK sites formed the basis of the crop management programme for these treated blocks (Stop BMSB 2017a). In the single-year trial this method “provided equivalent protection to standard grower programs” (Stop BMSB 2017a: p 24).

Further research into the efficacy of LLINs for the control of BMSB revealed that placing the netting vertically (baited with BMSB pheromone stimuli) in apple trees was more efficacious than setting the net horizontally (Stop BMSB 2017a) and furthermore on average more dead BMSB were collected from beneath LLIN treated trees than those treated with bifenthrin weekly (Stop BMSB 2017a).

LLINs have been demonstrated to be efficacious against BMSB in research trials which are ongoing. Factors such as secondary insecticidal effects (e.g. effects on non-target/beneficial insects including pollinators, insecticide resistance) cost, deployment methods (cover entire crop or use in attract and kill etc.), and social acceptability and impact need to be considered before integrating LLINs into crop protection programmes.

d) Host plant removal and overwintering population destruction

Reducing the availability of primary hosts or hosts attractive to BMSB near managed/cropped areas may reduce the likelihood of BMSB invasion. However, as BMSB is highly mobile, this may not be feasible or efficacious especially later in the growing season when larger BMSB populations are present. Removal of hosts that may serve as overwintering environments, such as standing dead trees (see Section 1.7.5 Overwintering), may help reduce early season movement into nearby crops and possible reductions in subsequent resident BMSB generations.

Destruction of overwintering populations could possibly have the same localised effect. Overwintering BMSB generations are more amenable to chemical control than subsequent generations (Nielsen et al. 2008b, Leskey et al. 2014, Kuhar & Kamminga 2017) so targeting this generation is appropriate. Applying chemicals to overwintering generations occurs outside of the summer growing season hence limitations placed on chemical use during this time may not apply out of season. Qin (1990 in Lee et al. 2013) suggested the use of artificial overwintering traps which could then be subjected to secondary control methods.

e) Trap cropping

Trap cropping involves planting a highly attractive host next to a cash-crop in an attempt to attract and arrest the pest insect long enough that secondary control methods can be applied.

Trap cropping to deter *Nezara viridula* (green vegetable bug, GVB syn. southern green stink bug) from entering cash crops has been documented by several authors (McPherson & Newsom 1984, Todd & Schumann 1988, Rea et al. 2002, Knight & Gurr 2006, Smith et al. 2009, Tillman 2014, Gordon et al. 2017) using early-flowering soybean, pea (*Pisum sativa*) with black or white mustard (*Sinapsus albus*), striped sunflowers (*Helianthus annus*) and sorghum

(*Sorgum bicolor*) to protect cash crops such as soybean (main crop), tomatoes (*Solanum lycopersicum*) and sweetcorn (*Zea mays*). Secondary control measures such as insecticide applications are essential for trap cropping to be effective, as this reduces the risk of population increases and movement of trapped insects into nearby cash crops (McPherson & Newsom 1984).

For BMSB a mixture of sorghum (*Sorghum bicolor* L.) and sunflower (*Helianthus* L.) has been demonstrated to be an effective trap crop (Pinero 2017). Chemical sprays, or for organic systems, physically collecting or vacuuming insects, can be used as secondary control methods to kill or reduce the incidence of invading BMSB (Pinero 2017).

Several factors including trap crop species, placement, magnitude and development need to be taken into account when considering the integration of trap crops into a crop management system. In order for trap cropping to be successful, the trap species needs to be more attractive than the cash crop when an insect pest is present. This requires synchronisation of trap crop maturity and insect presence, hence a firm knowledge of local insect pest phenology is essential.

2.4 Postharvest control

Postharvest application of chemical sprays in cropping areas may kill BMSB remaining in a cropping area. This may reduce the number of adults entering into overwintering and thereby potentially reducing summer populations. Destruction of suitable overwintering sites (where applicable) or the removal of susceptible host plants including overwintering hosts year round may aid in reductions in resident BMSB population numbers.

2.5 Biological control

Classical biological control, involving natural enemies from the native range of BMSB to augment the activity of existing natural enemies provides the most promising long-term solution for BMSB control (Leskey et al. 2012a). This has been explored in North America and New Zealand.

Invasive BMSB populations establish in new environments in the absence of their native natural enemies. The samurai wasp, *T. japonicus*, is a parasitic wasp that is reported to parasitise up to 80% of BMSB eggs in its native range (KVH 2017a) and is therefore the preferred agent for classical biological control in invaded regions.

Figure 22. *Trissolcus japonicus* adult (Source: Stop BMSB 2017a: p. 10).

The use of biopesticides that contain virulent strains of *Beauvaria bassiana* and *Metarhizium anisopliae* have been shown to be efficacious against BMSB under laboratory conditions, however further research and field experimentation is needed to evaluate field efficacy, seasonal suitability and to enhance the formulation of such products specifically for BMSB control.

2.6 Organic control

As with cultural control methods, at present there are no formal organic guidelines recommended for BMSB control, however adoption of general cultural management practices and utilising pheromone traps as monitoring tools or in attract and kill (using physical removal, vacuuming or flaming to reduce pest numbers) strategies could be integrated into organic growing systems.

Bergmann and Raupp (2014) showed that many ready to use organic insecticides were ineffective at controlling BMSB (<30% mortality adult and >60% nymph mortality); this included: insecticidal soap, neem oil (azadirachtin), essential oils and capsaicin. Neem oil alone has been shown to cause sub-lethal effects (and hence recovery) in treated BMSB (Cira et al. 2017). Some essential oils have been shown to repel insects, however further research is required to formulate slow-release formulations suitable for use in the field (KVH 2017a).

Morehead and Kuhar (2017) demonstrated that several pesticides approved for organic use showed efficacy against BMSB under laboratory conditions. Pesticides included in this study included; pyrethrins alone, neem oil (azadirachtin) alone, pyrethrins + neem oil, spinosad alone, potassium salts alone and the combination of spinosad + potassium salts (Morehead & Kuhar 2017). However, when these treatments were tested in the field, there was no difference between feeding injury detected in the treated and untreated plots (Morehead & Kuhar et al. 2017). The addition of pyrethrin (Azera®) increased the efficacy of neem oil by approximately 20–50% in laboratory based submersion and bean dip assays respectively (Morehead & Kuhar 2017). However, pyrethrum alone was more efficacious than when combined with neem oil. Interestingly neem oil has shown to cause up to 80% mortality to BMSB egg batches prior to hatch in laboratory assessments (Bergmann & Raupp 2014).

Spinosad has been demonstrated to elicit control against BMSB under laboratory conditions, however variable efficacy and life stage susceptibility have been reported. Bergmann and Raupp (2014) demonstrated that BMSB nymphs were more susceptible to spinosad and Lee et al. (2014b) reported significant adult mortality with the same product. Further investigation into the efficacy of spinosad against BMSB is required particularly in terms of targeted life stage control and field efficacy.

2.7 Integrated Pest Management (IPM)

Current IPM practices trialled or being developed for BMSB control include various attract and kill (AK) strategies and the use of trap thresholds to inform management decisions. AK methods use aggregation pheromone stimuli followed by the application of secondary control methods. Many of these strategies involve controlling BMSB at the crop edges in an attempt to prevent the pest from invading the interior of the crop.

These methods are largely being developed for US tree crops where weekly spray applications have been implemented in attempts to control BMSB.

a) Pheromone stimuli + weekly border sprays

Morrison et al. (2018) described an AK method that achieved equal or better BMSB control than the grower standard. This method involved baiting individual apple trees spaced at 50m intervals with pheromone stimuli (20 high does BMSB lures (42mg per lure, total of 840mg/tree) and a single MDT lure (66mg)), termed AK sites, and spraying these on a weekly basis. Lures were placed in the outer facing façade of each AK tree and replaced every four weeks. Trees within five metres on either side of the AK were also sprayed.

Baited black pyramid traps were also deployed and checked weekly. When a threshold of 10 adults per trap was exceeded, this initiated two alternate row middle (ARM) sprays in the interior of the crop (one spray each week for two consecutive weeks, applied to alternate drive rows) (Morrison et al. 2018). ARM sprays have been employed by growers to maximise the use of chemical sprays applied to crops. This strategy involves spraying one half of every tree within a block by applying spray to alternating rows over a two-week period, ensuring that within this period a single tree receives a total of two sprays; one to each half of the tree. After completing ARM spraying, trap thresholds were reset and AK site spraying resumed.

This AK method achieved BMSB control, (indicated by fruit injury levels) equal or superior to that achieved in the grower standard treatment. This trend also held true under increased (up to three times more BMSB than the previous year) pest pressure. ARM sprays were triggered a total of seven times across AK blocks compared with 16 times in the grower standard blocks over the two-year trial, indicating that AK was reducing the invasion of BMSB into the interior of the orchard blocks. Although spray application frequency remained high, this AK method achieved a 97% reduction in spray area (Morrison et al. 2018). A major limiting factor of this method was the cost of pheromone lures which accounted for 88% of the total cost of AK treatment, this resulted in the cost of AK treatment being up to seven times more expensive than the grower standard (Morrison et al. 2018). The 16–30% greater revenue conferred by lower crop damage did not offset the overall costs of AK (Morrison et al. 2018). With cheaper and wider BMSB pheromone lure production and marketing, it is hoped that AK will become more economically viable.

It is feasible that the AK strategy could be adapted to other cropping situations, however "optimisation of deployments methods, amount of pheromone, distance between AK sites and economic viability need to be considered to improve the efficacy of AK compared with conventional management" (Morrison et al. 2018).

b) Pheromone-baited trap action thresholds

Other AK strategies involving the use of pheromone trap thresholds to inform crop management decisions have been investigated as viable BMSB control options.

Short et al. (2017) investigated cumulative BMSB trap capture thresholds of 1, 10 or 20 BMSB adults which initiated two ARM (two consecutive sprays across two consecutive weeks, applied to alternate drive rows, as described above) sprays. After each spray trap thresholds were reset.

Trap threshold of 1 or 10 insects significantly reduced BMSB injury in comparison to a 20-insect threshold and the untreated control (Short et al. 2017). The 10-insect threshold also achieved a 40% reduction in spray applications in comparison to the lower threshold (Short et al. 2017, Stop BMSB 2017a).

c) Crop perimeter restructuring (CPR)

Crop perimeter restructuring or CPR has been trialled in peach and apple orchards in the US. CPR involved the application of a single early-season full-block spray when a cumulative threshold of 10 insects (across six monitoring traps) was reached. This threshold was then reset and weekly full border (+ the first full crop row) spraying until harvest was initiated when the 10-insect threshold was exceeded again. This method resulted in "similar injury (11.02%) at harvest relative to the grower standard management (10.88%)" (Stop BMSB 2017a: p. 26) in apples. This method reduced spray applications by 40–75% (Nielsen et al. 2019) and ultimately costs to growers while being more natural enemy friendly as well (Stop BMSB 2017a, Nielsen et al. 2019).

d) Use of LLINs in IPM strategies

Long-lasting insecticide nets could potentially further reduce spray applications when used in combination with some of the IPM strategies described above. Preliminary studies based on the use of LLIN have indicated efficacy against BMSB (Peverieri et al. 2017, Stop BMSB 2017a). The combination of utilising pheromone stimuli and LLINs in border-focused AK strategies has been shown to provide equivalent protection to that of the grower standard in experimental apple blocks in the US (Stop BMSB 2017a).

Research relating to LLIN use as a control tool against BMSB is still in the preliminary stages and further research is required to optimise its efficiency against BMSB. The opportunity LLINs present in terms of reduced spray application and therefore residues means they should not be discounted as potential future BMSB control tools.

Table 12a. Current and potential monitoring and chemical control methods for pre and postharvest management of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB).

	Method	Expected outcomes(s)	Likely impact on BMSB populations	Used elsewhere	Key limitation(s)	Ease of on orchard implementation	Technical difficulty of research	Relative development costs	Developmental time <3yrs, 4-6yrs, >7yrs
Monitoring	Visual surveying	Detection of BMSB host plants and overwintering BMSB populations	Low-medium	No	BMSB has an extremely wide host range.	Easy	Easy	Low	Short
	BMSB pheromone baited traps (pyramid or clear sticky traps, with/out 2° kill strips)	Detection of BMSB	Low-Medium	United States, Chile	Aggregation pheromone only brings insects into the general vicinity of the lure. Ongoing lure replacements.	Easy	Easy	Medium	Short
	Black light traps	Detection of BMSB	Low-medium	No, experimental at present	Light trap cost and on-orchard implementation	Medium	Easy	Medium	Short
	Trap crop monitoring	Detection of BMSB	Low-medium	No, experimental at present	Cost of implementation, maintenance, monitoring. Land area required.	Medium	Medium	Medium	Short-medium
Chemical	Fumigation of import/export goods from high risk countries	Mortality of 'hitchhiking' BMSB populations	Medium	NZ, Japan, US, Italy, China	Live BMSB detected in goods post border	n/a	Medium	Medium	Medium
	Foliar sprays (contact) pre and post-harvest	Knock-down mortality	Variable	Italy, US	Many are highly toxic, sub-lethal effects, chemical residues, potential IPM disruption	Easy	Easy	Low	Short
	Soil drench (neonicotinoids)	Knock-down mortality	Low-medium	No, experimental at present	Toxicity to other soil organisms, social acceptability	Easy	Easy-medium	Low	Short
	Application of chemical sprays on or around man-made structures	Exclusion of BMSB from residential homes, gardens and other manmade structures	Low-medium	US	Sub-lethal effects, social acceptability	Easy	Easy	Low	Short
	Long-lasting insecticide nets (LLINs)	Knock-down activity and exclusion of BMSB from commercial crops	Variable (efficacy may depend on net deployment strategy)	No, experimental at present	Cost, sub-lethal effects, potential negative impacts on fruit quality if used to cover crops coupled with potential 2° pest problems	Medium-hard (dependant on deployment strategy)	Medium	Medium-high	Medium-long

Table 12b. Current and potential cultural, biological and postharvest methods for pre and postharvest management of *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB).

	Method	Expected outcomes(s)	Likely impact on BMSB populations	Used elsewhere	Key limitation(s)	Ease of on orchard implementation	Technical difficulty of research	Relative development costs	Developmental time <3yrs, 4-6yrs, >7yrs
Cultural	Exclusion nets	Exclusion of BMSB from commercial crops	Low (populations only excluded not reduced)	Italy	Cost, deployment of nets (infrastructure etc.), secondary pest outbreaks,	Medium-hard	Medium-hard	Medium-high	Short-medium
	Alternate host plant removal	Reduction in attractive host plant abundance	Low-medium	No	BMSB has a wide host range, scout training for host plants and O/W environments, scouting time and success	Easy-medium	Easy-medium	Low-medium	Short
	Overwintering (O/W) population destruction	Reduction in resident/local O/W BMSB population	Low-medium	No	Scout training for host plants and O/W environments, scouting time and success	Easy-medium	Easy-medium	Low	short
	Trap cropping	Reduction in BMSB abundance, BMSB interception and potential exclusion from commercial crops	Low	No, experimental at present	Planting and maintaining trap crop, spray timing and monitoring	Medium	Medium	Medium	Short-medium
Biological	Biopesticides	Reduction in BMSB abundance	Medium	No, experimental at present	Product availability, field efficacy	Easy-on completion of research	Medium	Medium-high	Medium-long
	Classical biological control	Long-term BMSB control	Medium-high	Asia (BMSB and *T. japonicus* native range), US and Switzerland (adventive populations detected), approved for limited use in NZ	Compatibility with chemical control methods and other crop protection/management strategies	Easy	Easy to medium (already approved for limited release in NZ due to prior research and EPA approval)	Medium-high	Short-medium

3 PEST MANAGEMENT IN KIWIFRUIT

Kiwifruit is highest grossing export horticultural crop in New Zealand (The New Zealand Institute for Plant & Food Research Ltd. 2017) with exports in 2017 valued at NZ$1.664b (fob). New Zealand produced kiwifruit is exported to over 50 countries around the globe with Asia being the largest receiving market.

Should BMSB invade and establish in New Zealand, challenges the national kiwifruit industry are likely to face include (as adapted from KVH 2017a: p. 2):

- Reduced fruit yields and quality
- Market access issues possibly resulting from
    i. exceeding minimum residues levels (MRLs) for some export markets in the face of the need to apply insecticides to control BMSB. This will depend on the spray timing, the chemical used and application rates
    ii. border closure in countries where BMSB is not present e.g. Australia
- Insecticide applications may disrupt existing integrated pest management (IPM) programmes and cause secondary pest outbreaks
- Increased packing and quality assurance (QA) costs to prevent storage rot
- Increased operational costs from insecticide use, netting and labour.

BMSB invasion and establishment in New Zealand would certainly disrupt current kiwifruit management programmes, reduce commercial crop yields and possibly impede access to global export markets. Control options suitable for use or adaptation in the current kiwifruit management systems in New Zealand are highlighted in this section and include chemical, cultural and biological strategies.

3.1 Chemical control

Current BMSB control programmes, particularly in North America, are based on weekly foliar chemical applications. Many products shown to be efficacious against BMSB are highly toxic, belonging to chemical groups either prohibited from use in New Zealand and/or the current Zespri® Crop Protection Programme (CPP). Use of such products would likely result in impeded access to export markets because of chemical residues surpassing current export minimum residue limits (MRLs).

Three products including two pyrethroids, namely bifenthrin and cypermethrin, and a neonicotinoid, dinotefuran, have been deemed to be “the most suitable chemical candidates for use against BMSB in NZ” (KVH 2017a: p. 6). Of these, bifenthrin is the only product permitted under the current CPP and is used for passionvine hopper (*Scolypopa australis*, PVH), cicadas (Hemiptera: Cicadoidea) and scale insect control at various kiwifruit growth stages, along with other pyrethrum-based products (see Table 13).

During the postharvest and crop dormancy periods bifenthrin is applied to conventional kiwifruit blocks to control PVH and cicada eggs. Appropriately timed applications of bifenthrin during these periods may have some efficacy against BMSB adults entering and exiting the overwintering phase (respectively) and ultimately the abundance of resident BMSB populations. Bifenthrin applications during these cropping phases should not have any adverse effects on

MRLs as the fruit have already been removed. This may also allow some flexibility in chemical applications rates as those included in the current CPP may not be effective against BMSB.

Targeting overwintering adults during crop dormancy is recommended as this life stage has been demonstrated to be more susceptible to chemical sprays than subsequent generations (Nielsen et al. 2008a, Leskey et al. 2014, Kuhar & Kamminga 2017). The presence of overwintering adults will need to be determined via visual inspection of suitable overwintering sites including: kiwifruit trunks and leaders, particularly those with loose bark, spray guards, and weed, or alternate host plants including Cryptomeria shelterbelts. Man-made structures may also require inspection including sheds, barns and fruit bins. It is unlikely that overwintering adults will be present in the canopy during this time due to the lack of suitable shelter (vegetation etc.).

Insecticides permitted for application in kiwifruit during the bud phase, (bifenthrin (plus Engulf®), spirotetramat, thiacloprid, PyGanic®, ZEtaPY and Pylon®) may also help reduce BMSB, however this would require further information. The bud phase corresponds to when BMSB are exiting the overwintering stage and eggs or early-stage nymphs are present. These life stages are more vulnerable to insecticides and so the bud phase is likely to be an important time to reduce first generation populations.

During the fruit set and monitoring period, chemical usage is limited by the risk of residues. These two crop phases represent crucial control periods as BMSB are increasing in abundance in response to warmer temperatures and the presence of kiwifruit flowers and fruit.

It is recommended that the efficacy of all chemical products permitted under the kiwifruit CPP (including other pyrethrums, spinosad, mineral oil, thiacloprid and spirotetromat) reported as efficacious against BMSB be tested at current field rates (with appropriate adjuvants etc.) against either BMSB itself (overseas or in quarantine) or a suitable proxy to yield baseline information regarding effectiveness on BMSB life stages likely to be present during the applicable crop growth periods. Chemical application rates (including the use of adjuvants) specific to BMSB in kiwifruit orchards may need to be considered and developed to identify if these will fit or interfere with current practices and export MRLs. Exceeding chemical MRLs for specific export markets will depend on the product sprayed, the application time and rate and will need to assessed on a case by case basis.

KVH and Zespri® have indicated the use permethrin (270g ai/ha) or bifenthrin (224g ai/ha) in the event of a BMSB detection and subsequent eradication. In the event of invasion and prevention of establishment these chemicals would be “included in intensive spray programmes with all vegetation, shelter belts, buildings and structures in the immediate area to be sprayed” (KVH 2017b). Permethrin is listed as prohibited in the CPP (KVH 2017b). These application rates will exceed current MRLs and affected orchard blocks will not be harvested (KVH 2017b). Intensive residue testing of surrounding orchards will be required to ensure confidence in meeting MRLs (KVH 2017b).

The use of long-lasting insecticide nets (LLINs) has the potential to reduce spray applications and residues; they may also have applications on the domestic market to exclude BMSB from residences. Research into their use for BMSB control is ongoing. Factors such as secondary insecticidal effects (e.g. effects on non-target/beneficial insects including pollinators, insecticide resistance) cost, and social acceptability and impact need to be considered before integrating LLINs into any crop protection programme. The two LLIN products shown to have efficacy against BMSB include the deltamethrin impregnated net ZeroFly® and the cypermethrin impregnated net Storanet®. Cypermethrin is prohibited under the CPP and deltamethrin is not registered for use in kiwifruit, hence these products may not be eligible for adaption.

The efficacy of Movento® 100SC or mineral oil have not been evaluated against BMSB. The current timing of Movento 100SC or mineral oil applications in kiwifruit would coincide with the presence of overwintering adults and possibly later into the bud phase when first-generation eggs and early nymphs may be present. Both products are most efficacious against immature insect life stages, and it is possible that a spring application of Movento 100SC (plus penetrant plus spreader) and/or mineral oil would impact against these life stages. Overwintering BMSB adults are more amenable to contact chemical sprays than subsequent generations, hence application of these products during this crop stage could potentially be efficacious against post-overwintering adults present in the crop. Studies to evaluate the efficacy of these current winter/spring treatments against appropriate BMSB life stages, particularly nymphs and overwintering adults, is warranted.

Table 13. Insecticides in the Zespri listed in the Zespri® Crop Protection Programme that have, or may have, activity against *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) and the BMSB life stage present when each insecticide is permitted for use is also listed, as are the key knowledge gaps and limitations. Insecticides marked with an asterisk (*) would not be suitable for use in organic orchards.

Crop period	Active ingredients/ insecticides permitted	BMSB life stage(s) present	Knowledge gaps and limitations
Dormancy	*Bifenthrin (plus Engulf®)	Overwintering adults (possibly on vine trunks, spray protectors, crops shelters, gullies, ornamental and weed hosts)	Moderate-high efficacy against BMSB adults Possible phase-out
	Mineral oil		Unknown efficacy Possible phase-out
Bud phase	*Bifenthrin (plus Engulf®)	Adults, eggs and nymphs (overwintering adults and F1 generation may be present late in this crop phase and into flowering)	Moderate-high efficacy against BMSB adults and nymphs Possible phase-out
	*Thiacloprid		Unknown efficacy Possible phase-out
	*Spirotetramat		Unknown efficacy
	Mineral oil		Unknown efficacy Possible phase-out
Fruit set to monitoring	Spinosad	Adults, eggs and nymphs (Multiple generations, if BMSB is multivoltine in New Zealand)	Moderate efficacy after application, no efficacy after 7 days
	Mineral oil		Unknown efficacy Possible phase-out
	Pyrethrum		Moderate-high efficacy against BMSB adults and nymphs
Monitoring	Pyrethrum	Adults, eggs and nymphs (Multiple generations, if BMSB is multivoltine in New Zealand), late in the season adults preparing for overwintering	Moderate-high efficacy for specific products against BMSB adults and nymphs Possible phase-out
	Mineral oil (also suitable for organic growers)		Unknown efficacy Possible phase-out
Postharvest	*Bifenthrin	Overwintering adults	Moderate-high efficacy against BMSB adults

3.2 Cultural control

In the absence of tailored cultural control techniques, general cultural control methods such as the removal of susceptible non-host plants may help reduce resident BMSB populations. Crop monitoring/trapping strategies and the use of exclusion nets offer season long BMSB control benefits.

Currently, pheromone stimuli are the most efficacious and widely available BMSB attractants. It is likely that pheromone stimuli will be used widely in New Zealand should the BMSB establish here. The use of vibrational stimuli is experimental at present but may be suitable as an alternative or supplementary method of BMSB aggregation, however this will depend on application technologies. Along with traditional trapping methods using clear sticky traps or pyramid traps (with or without secondary chemical controls), pheromone lures could also be used as attractants in various attract and kill (AK) strategies. AK has been demonstrated to reduce spray applications and BMSB injury in apples and peaches in North America and could potentially be adapted for use in kiwifruit. AK strategies specific to kiwifruit need to be developed before implementation here in New Zealand, particularly the use and establishment of trap catch action thresholds and investigations into the effects of applying border sprays (e.g. spray drift and residues).

Trap cropping may not be feasible for kiwifruit dependant on the availability of land and the crops identified as potential traps. Maintenance of such crops warrants increased workloads and monitoring to identify when BMSB is present in order to employ secondary control options. Adoption of trap cropping may be location dependant within an orchard as these could potentially impede day to day activities and limit block access.

The removal of alternate or susceptible BMSB hosts within or near kiwifruit orchards may not be feasible due to the wide host range of BMSB and, given the proximity of some orchards to gully or naturalised areas, this would be impossible. However focusing removal efforts on overwintering hosts (standing dead trees) and environments (loose kiwifruit trunk bark, spray guards, man-made structures, fruit bins etc.) near or within an orchard may reduce resident BMSB populations and prevent early-season movement of the pest into kiwifruit.

Cryptomeria is a principal shelter-belt species in many kiwifruit orchards and is a known BMSB host. It is advised that these shelter belts be monitored for the presence of BMSB, however, due to the height and sheer magnitude of these shelter belts, this may not be feasible. Pheromone lures could be deployed within shelter belts to aggregate insects lower in the trees and then secondary controls applied to these areas (sticky or collection traps, chemical sprays, physical collection, deployment of long-lasting insecticide net pieces).

Crop netting has been erected by some kiwifruit growers to reduce fruit damage caused by hail. Some blocks are fully covered (including side netting) while others only have netted ceilings (over the top of the crop). These nets, particularly fully netted blocks, have the potential to exclude invading BMSB adults and provide a degree protection from feeding damage, however, negative effects (on fruit dry matter, pollination, secondary pest outbreaks) associated with the use of these nets may outweigh the benefit of their use.

3.3 Biological control

The Environmental Protection Authority has approved the importation and limited release in New Zealand of the samurai wasp, *Trissolcus japonicus*. Further approval warranting the widespread release of *T. japonicus* is recommended should BMSB establish here. This would support more integrated crop management and likely reduce the need for chemical sprays within commercial crops such as kiwifruit.

The use of biopesticides against BMSB remains for the moment experimental, however they do offer a softer control option compared to traditional contact chemical sprays. Further research into strains of *Beauvaria bassiana* and *Metarhizium anisopliae* that have shown virulence against BMSB, particularly field efficacy and formulation, would need to be completed before the products could be used here in New Zealand.

3.4 Organic control

Spinosad has shown efficacy against BMSB, however, there are conflicting reports in regard to efficacy and susceptibility of BMSB life stages, so this warrants further testing. Spinosad is applied to kiwifruit during the fruit set phase when overwintered adults and first-generation eggs and nymphs might be present. These life stages (overwintered adults and nymphs) have been shown to more susceptible to contact sprays, hence spinosad may have some efficacy against BMSB present in the crop then.

Azadirachtin, or neem oil, has been shown to be shown to elicit efficient control (>80%) under laboratory conditions when applied to BMSB egg rafts. Several neem products have been registered for use in New Zealand but not specifically for kiwifruit (KVH 2017a) and furthermore MRLs either do not exist for the product or markets have chosen the default MRL of 0.01mg/kg (KVH 2017a). Hence investigating true MRLs for neem and the applications of this product in kiwifruit may provide organic growers with another tool for the control of BMSB.

3.5 Summary

In summary BMSB is a serious threat to kiwifruit here in New Zealand. Current BMSB control programmes consist largely of weekly insecticide applications; this is unfeasible in kiwifruit due to existing MRL standards. At present bifenthrin offers the main chemical solution for kiwifruit growers and further research into the efficacy of other chemicals (other pyrethrums, spirotetromat, mineral oil, thiacloprid, spinosad and neem) permitted under the current CPP is recommended. There is a need for the development of new chemical products including softer options like biopesticides for BMSB control however processes involved with product testing and registration are lengthy and costly.

It is clear that pheromone lures will play a large role in early eradication attempts, population monitoring and various control strategies in New Zealand. IPM management plans specific to kiwifruit could potentially be developed utilising combinations of pheromone lures, secondary controls and various deployment strategies. Further research is required, however offshore research may provide the basis of these strategies. Additional lures such as those based on vibration or plant volatiles may also prove effective, however further research is required.

Due to the lack of prescribed cultural control techniques specific to BMSB, general practices such as the removal of alternate host plants and overwintering population destruction may reduce BMSB abundance. It is likely that reductions in resident overwintering adult populations may then lead to lower early-season crop invasion. Exclusion nets are currently being used by some kiwifruit growers and it would be worthwhile investigating ways to overcome the limitations associated with their use before the arrival of BMSB.

Research gaps identified in this review include the:

- efficacy of insecticide sprays (including adjuvants etc.) permitted under the current kiwifruit CPP against BMSB,
- knowledge of chemical application rates applied for BMSB control overseas and how these compare to those applied in New Zealand kiwifruit,
- address the limitations associated with exclusion nets and ways to overcome these,
- the use, availability and acceptance of long-lasting insecticide net (LLIN) technologies,
- alternative lures and kill strategies that could be used in an IPM programme,
- development of IPM strategies including attract and kill, border spraying and action thresholds specific for kiwifruit.

BMSB is proving difficult to control overseas and this can be expected of the pest here in New Zealand. Customising and adapting current and developing BMSB chemical, cultural and biological control strategies specifically for the New Zealand kiwifruit industry is foreseeably the only way forward. Further research to address knowledge gaps is required and may provide information or techniques for the control of the pest in New Zealand kiwifruit.

Table 14a. Potential management plan for *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in kiwifruit (based on methods currently available) during the crop dormancy and bud growth phases. Techniques marked with an asterisk (*) would not be suitable for use in organic orchards.

Period	Method	Active Ingredient	Product name (available in Zealand)	Allowed in CPP	Adverse impact risk	Comments
Dormancy	Visual monitoring of on and off-orchard alternative and overwintering hosts and environments for BMSB, application of secondary control method	*Bifenthrin Physical removal	Talstar® 100EC plus Engulf® Venom®	Yes	High	Targeting overwintering adult populations
	Removal of alternate and overwintering hosts	Physical removal *Herbicide		Yes	Low	Utilise appropriate herbicide as permitted under the kiwifruit CPP that is suitable for prescribed host species
Bud Phase	Deploy BMSB pheromone-baited traps (with or without secondary chemical controls included) to monitor or reduce the movement of overwintering adults into kiwifruit blocks	3:5:1 ratio of (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol to (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol, and methyl (2E,4E,6Z)-decatrienoate (MDT)	Not available commercially in New Zealand		Low	Deploy traps in the crop and around the perimeter, traps in gullies may also prevent movement into the crop
	Application of permitted chemical controls	*Bifenthrin	Talstar® 100EC or Venom®	Yes	Moderate	These chemicals are already included in the current kiwifruit CPP and may have some efficacy against overwintering/ed BMSB adults, eggs and early nymph instars present later in this crop phase
		*Spirotetramat	Movento 100SC or Groventine			
		*Thiacloprid	Alpasso, Calyoso, Commend, Topstar			
		Mineral oil	D-C Tron plus Organic, Enspray 99, Eccel Organic Oil			

Table 14b. Potential management plan for *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in kiwifruit (based on methods currently available) during the flowering and fruit set to monitoring crop phases. Techniques marked with an asterisk (*) would not be suitable for use in organic orchards.

Period	Method	Active Ingredient	Product name (available in Zealand)	Allowed in CPP	Adverse impact risk	Comments
Flowering	Continued BMSB pheromone (with or without secondary *chemical controls included) monitoring/control	3:5:1 ratio of (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol to (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol, and methyl (2E,4E,6Z)-decatrienoate (MDT)	Not available commercially in New Zealand		Low	Refresh lures and *chemical controls as per label instructions
Fruit-set to monitoring	Continued BMSB pheromone (with or without secondary *chemical controls included) monitoring/control	3:5:1 ratio of (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol to (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol, and methyl (2E,4E,6Z)-decatrienoate (MDT)	Not available commercially in New Zealand		Low	Refresh lures and *chemical controls as per label instructions
	Application of permitted chemical controls	Spinosad	Success Naturalyte, Entrust Naturalyte	Yes	Moderate	These chemicals are already included in the current kiwifruit CPP and may have some efficacy against BMSB present during this crop phase
		Mineral oil	D-C Tron plus Organic, Enspray 99, Eccel Organic Oil			
		Pyrethrum	Pyganic®, ZETaPY, Pylon®			
	Deployment of effective attract and kill strategies to prevent BMSB Invasion				Moderate	Strategies specific for kiwifruit have not been developed or researched

Table 14c. Potential management plan for *Halyomorpha halys* (Stål, 1855) (brown marmorated stink bug, BMSB) in kiwifruit (based on methods currently available) during the monitoring and postharvest crop phases. Techniques marked with an asterisk (*) would not be suitable for use in organic orchards.

Period	Method	Active Ingredient	Product name (available in Zealand)	Allowed in CPP	Adverse impact risk	Comments
Monitoring	Continued BMSB pheromone (with or without secondary *chemical controls) monitoring/control	3:5:1 ratio of (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol to (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol, and methyl (2E,4E,6Z)-decatrienoate (MDT)	Not available commercially in New Zealand		Low	Refresh lures and *chemical controls as per label instructions
	Maintenance of attract and kill strategies to prevent BMSB Invasion, continued secondary control applications				Moderate	Strategies specific for kiwifruit have not been developed or researched
	Application of permitted chemical controls	Pyrethrum	Pyganic®, ZETaPY, Pylon®	Yes	Moderate	These chemicals are already included in the current kiwifruit CPP and may have some efficacy against BMSB present during this crop phase
		Mineral oil	D-C Tron plus Organic, Enspray 99, Eccel Organic Oil			
Postharvest	Continued BMSB pheromone (with or without secondary *chemical controls included) monitoring/control	3:5:1 ratio of (3*S*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol to (3*R*,6*S*,7*R*,10*S*)-10,11-epoxy-1-bisabolen-3-ol, and methyl (2E,4E,6Z)-decatrienoate (MDT)	Not available commercially in New Zealand		Low	Refresh lures and *chemical controls as per label instructions
	Maintenance of suitable attract and kill strategies to prevent BMSB invasion, continued secondary control applications			Yes	Moderate	Strategies specific for kiwifruit have not been developed or researched
	Application of permitted chemical controls	Bifenthrin	Talstar® 100EC plus Engulf®	Yes		This chemical is included in the current kiwifruit CPP and has efficacy against BMSB present
	Removal of alternate and overwintering hosts	Physical removal *Herbicide		Yes	Low	Utilise appropriate herbicide as permitted under the kiwifruit CPP that is suitable for prescribed host species

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APPENDIX I – HOST CLASSIFICATION OF *HALYOMORPHA HALYS* (STÅL, 1855) SECONDARY PLANT HOSTS

Family	Botanical name (common name)	Host classification	Reference
Aceraceae	*Acer buergerianum* (trident maple)	Ornamental	Stop BMSB 2018
	Acer campestre (field or hedge maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer circinatum (vine maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer fremanii (Freman maple)	Ornamental	Stop BMSB 2018
	Acer griseum (paperback maple)	Ornamental	Stop BMSB 2018
	Acer japonicum (full-moon maple)	Ornamental, wild host	CABI 2017 & 2019, Stop BMSB 2018
	Acer macrophyllum (broadleaf maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer negundo (box elder)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer palmatum (Japanese maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer pensylvanicum (striped maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer platanoides (Norway maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer rubrum (red maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer saccharinum (silver maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Acer saccharum (sugar maple)	Ornamental, wild host	CABI 2017 & 2019, Stop BMSB 2018
	Acer spp. (maple)	Ornamental	Lee et al. 2013
	Acer tegmentosum (East Asia stripe maple)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Actinidiacdeae	*Actinidia deliciosa* (syn. *A. chinensis* var. *deliciosa)* (Chinese gooseberry, kiwifruit)	Horticultural crop	Lee et al. 2013
Adoxaceae	*Sambucus recemosa* (red elderberry)	Ornamental	Lee et al. 2013
Amaranthaceae	*Beta vulgaris* (beet)	Horticultural crop	Lee et al. 2013
	Beta vulgaris ssp. *cicla* (Swiss chard)	Horticultural crop	Stop BMSB 2018
	Celosia argentea (celosia)	Ornamental	CABI 2017 & 2019
	Celosia spp. (cock's comb)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Anacardiaceae	*Pistacia chinensis* (Chinese pistache)	Ornamental	Stop BMSB 2018
	Rhus typhinastaghorn (staghorn sumac)	Ornamental/wild host	Stop BMSB 2018, Lee et al. 2013
Family	Botanical name (common name)	Host classification	Reference
Annonaceae	*Asimina triloba* (pawpaw-apple)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
Asparagaceae	*Asparagus officinalis* L. (asparagus)	Horticultural crop	EPPO 2013, Lee et al. 2013

Family	Botanical name (common name)	Host classification	Reference
Asteraceae	*Arctium minus* (common burdock, lesser burdock)	Wild	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
	Artemisia argyi (Argyi wormwood)	Ornamental, medicinal	Lee et al. 2013
	Chrysanthemum morifolium (Chrysanthemum)	Ornamental	Lee et al. 2013
	Helianthus spp. (sunflower)	Horticultural crop, ornamental	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
Balsaminaceae	*Impatiens balsaminia* (rose balsam)	Ornamental	Lee et al. 2013
Basellaceae	*Basella alba* (syn. *B. rubra*) (malabar spinach)	Ornamental	CABI 2017 & 2019, Lee et al. 2013
Berberidaceae	*Mahonia aquifolium* (Oregon grape)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
Betulaceae	*Betula nigra* (river birch)	Ornamental, wild	CABI 2017 & 2019, Stop BMSB 2018
	Betula papyrifera (paper birch)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Betula pendula (common silver birch)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Betulaceaealnus (Alder)	Ornamental, wild	Lee et al. 2013
	Carpinus betulus (hornbean)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Corylus colurna (filbert hazelnut)	Horticultural crop	Stop BMSB 2018
	Corylus spp. (hazelnut)	Horticultural crop	CABI 2017 & 2019
Boraginaceae	*Symphytum* spp. (comfrey)	Ornamental	Stop BMSB 2018
Brassicaceae	*Armoracia rusticana* (horseradish)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018
	Brassica juncea (wild mustard)	Horticultural crop	Stop BMSB 2018
	Brassica napus (rape)	Horticultural crop	Lee et al. 2013
	Brassica oleracea (cabbage, cauliflower, collard greens)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018
Canabaceae	*Cannabis sativa* (hemp)	Agricultural	Stop BMSB 2018
	Humulus lupulus (syn. *H. scandens*) (hop)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
Caprifoliaceae	*Abelia grandiflora* (glossy abelia)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Heptacodium miconioides (seven sons flower)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Family	Botanical name (common name)	Host classification	Reference
Caprifoliaceae	*Lonicera* spp. (honeysuckle)	Wild host/weed	CABI 2017 & 2019, Stop BMSB 2018
	Lonicera tatarica (tatarian honeysuckle)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Viburnum burkwoodii (viburnum)	Ornamental	Stop BMSB 2018
	Viburnum dilatatum (viburnum)	Ornamental	Stop BMSB 2018
	Viburnum prunifolium (viburnum)	Ornamental	Stop BMSB 2018
	Viburnum spp. (viburnum)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018

Family	Botanical name (common name)	Host classification	Reference
	Waigela hortensis (Japanese weigela)	Ornamental	Lee et al. 2013
Celastraceae	*Euonymus japonicus* (Japanese spindle)	Ornamental	Lee et al. 2013
Cercidiphyllaceae	*Cercidiphyllum japonicum* (katsura)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Chenopodiaceae	*Chenopodium berlandieri* (pitseed goosefoot)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
Chenopodiaceae	*Chenopodium* spp. (goosefoot)	Wild host	CABI 2017 & 2019
Cornaceae	*Cornus florida* (flowering dogwood)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Cornus kousa (kousa dogwood)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Cornus macrophylla (large leaf dogwood)	Ornamental	Stop BMSB 2018
	Cornus officinalis (Asiatic dogwood)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Cornus racemosa (grey dogwood)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Cornus sericea (redosier dogwood)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Cornus spp. (dogwood)	Wild host	CABI 2017 & 2019
Cucurbitaceae	*Cucumis sativus* (cucumber)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
	Cucurbita pepo (marrow, pumpkin)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018
Cupressaceae	*Chamaecyparis obtusa* (Japanese cypress)	Ornamental	Lee et al. 2013
	Cryptomeria spp. (Japanese red-cedar)	Wild, ornamental	EPPO 2013
	Cupressus spp. (cypress)	Wild, ornamental	EPPO 2013
	Juniperus virginiana (eastern red cedar)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Metasequoia glyptostroboides (dawn redwood)	Ornamental	Stop BMSB 2018
	Platycladus orientalis (oriental arborvitae)	Ornamental	Lee et al. 2018
Ebenaceae	*Diospyros kaki* (persimmon)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
Elaeagnaceae	*Elaeagnus angustifolia* (Russian olive)	Wild host, ornamental	CABI 2017 & 2019, Stop BMSB 2018
Family	Botanical name (common name)	Host classification	Reference
Elaeagnaceae	*Elaeagnus umbellata* (autumn olive)	Wild host	CABI 2017 & 2019
Ericaceae	*Vaccinium corymbosum* (blueberry)	Horticultural crop, ornamental	CABI 2017 & 2019, Stop BMSB 2018
Euphorbiaceae	*Veronica fordii* (tung tree)	Horticultural crop, ornamental	Lee et al. 2013
Fabaceae	*Albizia julibrissin* (sensitive plants)	Ornamental	CABI 2017 & 2019
	Astragalus sinicus (milk-vetch)	Ornamental, medicinal	Lee et al. 2013
	Baptisia australis (blue wild indigo)	Ornamental	Stop BMSB 2018
	Caragana arborescens (Sinerian pea-tree)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Cercis canadensis (eastern redbud)	Wild host, ornamental	CABI 2017 & 2019, Stop BMSB 2018

Family	Botanical name (common name)	Host classification	Reference
	Cercis canadensis ssp. *Texensis (*Texas redbud)	Ornamental	Stop BMSB 2018
	Cladrastis kentukea (syn. *C. lutea*) (American yellowwood)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Gleditsia triacanthos (honey locust)	Wild, invasive	CABI 2017 & 2019
	Gleditsia triacanthos ssp. *Inermis* (thornless common honeylocust)	Ornamental	Stop BMSB 2018
	Pueraria montana var. *lobata* (kudzu)	Ornamental	Lee et al. 2013
	Robinia pseudoacacia (black locust)	Wild host	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
	Sophora japonica (Japanese pagoda tree)	Ornamental	Stop BMSB 2018, Lee et al. 2013
	Trifolium spp. (clover)	Agricultural crop, weed, wild	Lee et al. 2013
	Vigna angularis (adzuki bean)	Horticultural crop, weed	Lee et al. 2013
	Vigna sesquipedalis (Chinese long bean)	Horticultural crop	Lee et al. 2013
	Vigna unguiculata (Cowpea)	Horticultural crop	Lee et al. 2013
	Wisteria sinensis (Chinese wisteria)	Ornamental	Lee et al. 2013
Fagaceae	*Chastanea* spp. (chestnut)	Horticultural crop, ornamental	Lee et al. 2013
	Quercus alba (white oak)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Quercus coccinea (scarlett oak)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Quercus robur (common oak)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Quercus rubra (northern red oak)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Ginkgoaceae	*Ginkgo biloba* (Ginko)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Hamamelidaceae	*Hamamelis japonica* (invasive witch-hazel)	Wild host	Stop BMSB 2018
Family	Botanical name (common name)	Host classification	Reference
Hamamelidaceae	*Hamamelis virginiana* (Virginian witch-hazel)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Liquidambar styraciflua (sweetgum)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Hippocastanaceae	*Aesculus carnea* (red horse chestnut)	Ornamental	Stop BMSB 2018
	Aesculus glabra (Texas buckeye)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Juglandaceae	*Carya illinoinensis* (pecan)	Horticultural crop, ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Carya ovata (shagbark hickory)	Wild	CABI 2017 & 2019, Stop BMSB 2018
	Juglans nigra (black walnut)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
Lamiaceae	*Clerodendrum trichotomum* (harlequin gloryblower)		Lee et al. 2013
	Vitex negundo (Chinese chaste tree)	Ornamental, medicinal	Lee et al. 2013
Lardizabalaceae	*Akebia* spp. (chocolate vine)	Ornamental	
Lauraceae	*Cinnamomum camphora* (camphor tree)	Agricultural crop	Lee et al. 2013

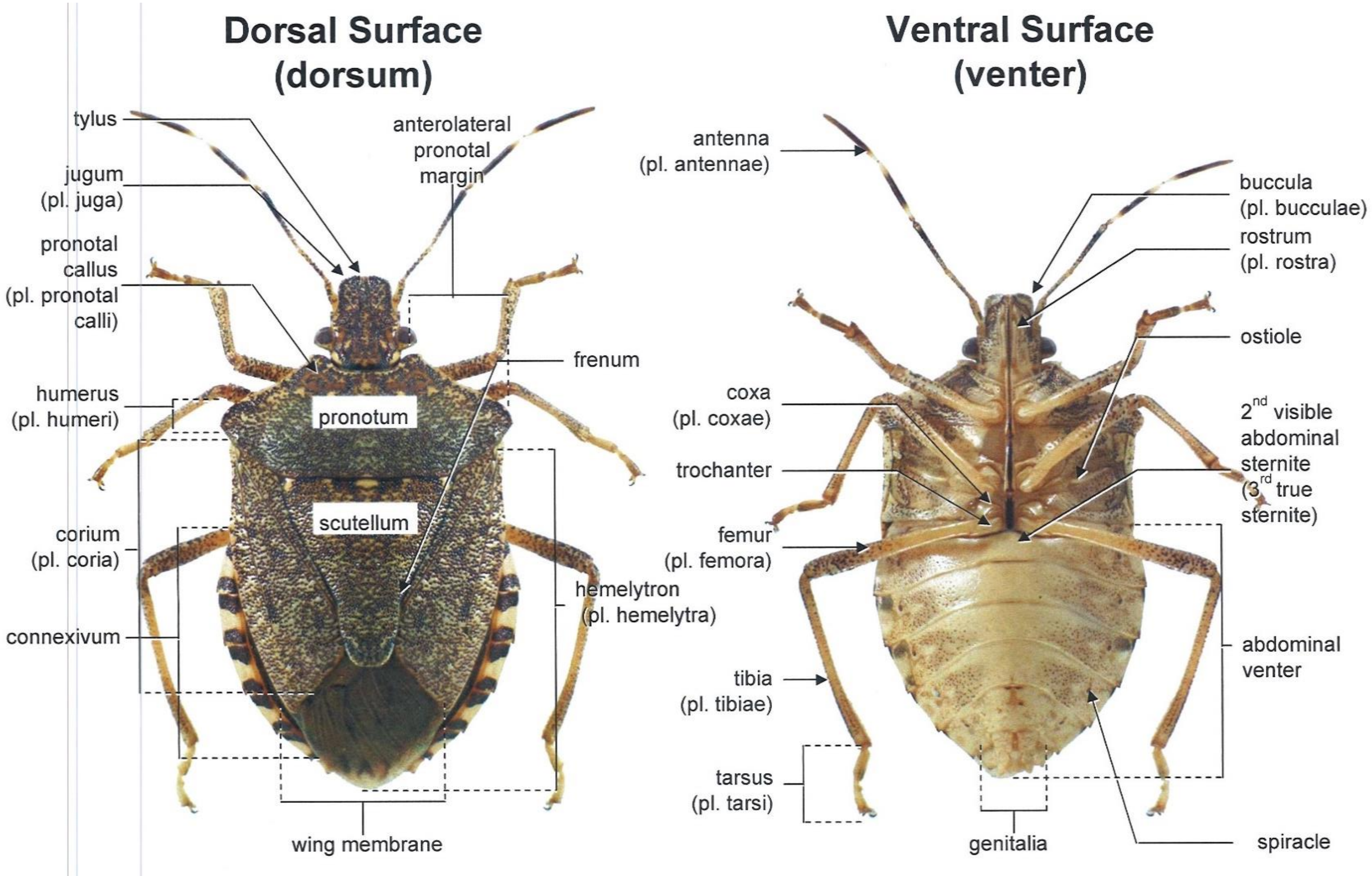
Family	Botanical name (common name)	Host classification	Reference
	Sassafras albidum (common sassafras)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
Lythraceae	*Lagerstroemia indica* (Indian crepe myrtle)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Lythrum salicaria (purple loosestrife)	Wild host, ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Punica granatum (pomegranate)	Horticultural crop	Lee et al. 2013
Magnoliaceae	*Liriodendron tulipifera* (tulip tree)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Magnolia grandiflora (Southern magnolia)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Malvaceae	*Abelmoschus esculentus* (okra)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018
	Firmiana platanifolia (Chinese parasol tree)	Ornamental	Lee et al. 2013
	Gossypium hirsutum (upland cotton)	Horticultural crop	Lee et al. 2013
	Hibiscus moscheutos (crimson eyed-mallow)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Hibiscus rosa-sinensis (China rose)	Ornamental	CABI 2017 & 2019, Lee et al. 2019
	Hibiscus syriacus (hibiscus)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Moraceae	*Ficus carica* (common fig)	Horticultural crop, ornamental	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
	Morus spp. (mulberry tree)	Other	CABI 2017 & 2019, Lee et al. 2013
Oleaceae	*Chionanthus retusus* (Chinese fringetree)	Ornamental	Stop BMSB 2018
Family	Botanical name (common name)	Host classification	Reference
Oleaceae	*Chionanthus virginicus* (white fringetree)	Ornamental	Stop BMSB 2018
	Forsythia suspensa (weeping forsythia)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Fraxinus americana (white ash)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Fraxinus chinensis (Chinese ash)	Ornamental	Lee et al. 2013
	Fraxinus pennsylvanica (downy ash)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Ligustrum japonicum (Japanese privet)	Wild host/weed, ornamental	Stop BMSB 2018
	Ligustrum sinense (Chinese privet)	Wild host/weed, ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Olea oleaster (wild olive)	ornamental	Lee et al. 2013
	Syringa pekinensis (Pekong tree lilac)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Syringa spp. (lilac)	Ornamental	Lee et al. 2013
Orchidaceae	*Brassia* spp. (orchid)	Ornamental	Lee et al. 2013
	Phalaenopsis spp. (moth orchid)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Phytolaccaceae	*Phytolacca americana* (American pokeweed)	Wild	Stop BMSB 2018
Pinaceae	*Larix kaempferi* (syn. *L. leptolepis*) (Japanese larch)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018

Family	Botanical name (common name)	Host classification	Reference
	Tsuga canadensis (eastern hemlock)	Wild	CABI 2017 & 2019, Stop BMSB 2018
Platanaceae	*Platanus occidentalis* (American sycamore)	Ornamental	Stop BMSB 2018
Poaceae	*Panicum miliaceum* (common millet)	Horticultural/agricultural crop	Lee et al. 2013
	Secale cereale (cereal rye)	Horticultural crop	Stop BMSB 2018
	Setaria italica (pearl millet)	Horticultural/agricultural crop	Lee et al. 2013
	Sorghum bicolour (sorghum)	Agricultural host	Lee et al. 2013
	Triticum aestivum (wheat)	Agricultural crop	Lee et al. 2013
Polygonaceae	*Polygonum perfoliatum* (mile-a-minute weed)	Ornamental, wild, medicinal	Lee et al. 2013
Rhamnaceae	*Rhamnus cathartica* (buckthorn)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Ziziphus jujuba (jujube)	Ornamental, horticultural crop	Lee et al. 2013
Rosaceae	*Amelanchier laevis* (syn. *A. grandiflora*) (Allegheny serviceberry)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Chaenomeles speciosa (quince)	Ornamental	Lee et al. 2013
	Crataegus laevigata (smooth hawthorn)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Family	Botanical name (common name)	Host classification	Reference
Rosaceae	*Crataegus monogyna* (one-seed hawthorn)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Crataegus viridis (green hawthorn)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Eriobotrya japonica (loquat)	Ornamental	Lee et al. 2013
	Fragaria ananassa (strawberry)	Horticultural crop	Lee et al. 2013
	Photinia spp. (syn. *Aronia* spp.) (chokeberry)	Horticultural crop	Lee et al. 2013
	Prunus grayana (Japanese bird cherry)	Wild	Stop BMSB 2018
	Prunus mume (Japanese apricot tree)	Ornamental	Lee et al. 2013
	Prunus pseudocerasus (Chinese sour cherry)	Other	CABI 2017 & 2019
	Pseudocydonia sinensis (Chinese quince)	Horticultural crop, ornamental	Lee et al. 2013
	Pyracantha spp. (firethorn)	Ornamental	Stop BMSB 2018
	Pyrus calleryana (bradford pear)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Pyrus communis (European pear)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Pyrus pyrifolia (Oriental pear tree)	Other	CABI 2017 & 2019
	Rosa canina (dog rose)	Horticultural crop/ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Rosa multiflora (multiflora rose)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Rosa rugosa (rugosa rose)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Rubus fruticosus (blackberry)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018

Family	Botanical name (common name)	Host classification	Reference
	Rubus idaeus (raspberry)	Horticultural crop, ornamental, weed	CABI 2017 & 2019
	Rubus phoenicolasius (wine raspberry)	Horticultural crop, ornamental, weed	CABI 2017 & 2019
	Rubus spp. *(raspberry, blackberry)*	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018
	Sorbus americana (American mountain ash)	Horticultural crop, ornamental, weed	Stop BMSB 2018
	Sorbus aria (whitebeam)	Wild	CABI 2017 & 2019, Stop BMSB 2018
	Spiraea spp. (spiraea)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Cephalanthus occidentalis (common buttonbush)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Rubiaceae	*Citrus* spp. (lemons, limes, mandarins, oranges)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Rutaceae	*Tetradium daniellii* (syn. *Euodia hupehensis*) (Korean euodia)	Horticultural crop, ornamental	CABI 2017 & 2019, Lee et al. 2013
Family	Botanical name (common name)	Host classification	Reference
Rutaceae	*Celastrus orbiculatus* (Asiatic bittersweet)	Ornamental	Stop BMSB 2018
Salacia	*Populus tomentosa* (Chinese white poplar)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Saliaceae	*Salix* spp. (willow)	Ornamental	Lee et al. 2013
Saliaceae	*Koelreuteria paniculata* (goldenrain tree)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
Sapindaceae	*Antirrhinum majus* (snapdragon)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Scrophulariaceae	*Buddleia davidii* (butterfly bush)	Ornamental, wild	CABI 2017 & 2019, Stop BMSB 2018
	Buddleia spp. (butterflybush)	Ornamental	Stop BMSB 2018
	Lycium babarum (boxthorn)	Ornamental, wild	EPPO 2013, Stop BMSB 2018
Solanaceae	*Nicotiana alata* (jasmine tobacco)	Weed	Lee et al. 2013
	Solanum lycopersicum (tomato)	Ornamental	Lee et al. 2013
	Solanum melongena (eggplant)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
	Solanum nigrum (black nightshade)	Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018, Lee et al. 2013
	Halesia tetraptera (mountain silverbell)	Wild host/weed	CABI 2017 & 2019, Lee et al. 2013
Styracaceae	*Styrax japonicus* (japonica)	Ornamental	Stop BMSB 2018
	Taxus cuspidata (Japanese yew)	Ornamental	CABI 2017 & 2019
Taxaceae	*Camellia oleifera* (oil seed camellia)	Ornamental	Lee et al. 2013
Theaceae	*Camellia sinensis* (Chinese tea)	Ornamental	Lee et al. 2013
	Stewartia koreana (Korean stewartia)	Horticultural crop	Lee et al. 2013
	Stewartia pseudocamellia (Japanese stewartia)	Ornamental	Stop BMSB 2018
	Tilia americana (basswood)	Ornamental	Stop BMSB 2018

Family	Botanical name (common name)	Host classification	Reference
Tiliaceae	*Tilia cordata* (small-leaf lime)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Tilia tomentosa (silver lime)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Celtis koraiensis (Korean hackberry)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Ulmaceae	*Celtis occidentalis* (hackberry)	Ornamental	Stop BMSB 2018
	Celtis spp. (nettle tree)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
	Ulmus americana (American elm)	Ornamental/wild host	CABI 2017 & 2019
	Ulmus parvifolia (Chinese elm)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Ulmus procera (syn. *U. minor*) (English elm)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
Family	Botanical name (common name)	Host classification	Reference
	Ulmus pumila (elm)	Ornamental	CABI 2017 & 2019, Stop BMSB 2018
	Zelkova spp. (Japanese zelkova)	Ornamental	Lee et al. 2013
	Cayratia japonica (bushkiller)	Ornamental	Lee et al. 2013
Vitaceae	*Vitis riparia* (riverbank grape)	Ornamental, medicinal	Lee et al. 2013
Vitaceae	*Vitis vinifera* (grapevine)	Wild host	CABI 2017 & 2019, Stop BMSB 2018
		Horticultural crop	CABI 2017 & 2019, Stop BMSB 2018

APPENDIX II – *HALYOMORPHA HALYS* (STÅL, 1855) MORPHOLOGY



Note that the second visible abdominal sternite is referred to here and in other keys as "abdominal sternite 2" although it is actually the third true sternite. The true sternite one is hidden beneath the metasternum.

(Source: Paiero et al. 2013: p. 4) Please note that permission would be required from the journal if this content was to be used outside of this review.

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