Subcommittee on National Plant Health Surveillance

National Surveillance Protocol

for

Brown marmorated stink bug (*Halyomorpha halys*)

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1 Scope / rationale

Brown marmorated stink bug (BMSB) is an invasive hemipteran that causes severe damage to many agriculturally significant crops and is also a nuisance pest that forms large aggregations. Establishment of this pest would negatively impact host plant production, market access and social amenity in Australia. This protocol has been developed for early detection, response and pest status surveillance.

2 Background

Genus: *Halyomorpha*

Species: *halys*

Previous/alternate names (CABI 2020)**:**

Pentatoma halys Stål, 1855,
Halyomorpha brevis
Halyomorpha mista
Halyomorpha remota
Poecilometis mistus Uhler, 1860,
Dalpada brevis Walker, 1867
Dalpada remota Walker

Common name: Brown marmorated stink bug

Brown marmorated stink bug (*Halyomorpha halys*) is an exotic plant pest not established in Australia. It is an arboreal insect in the family Pentatomidae, native to East Asia - China, the Korean peninsula, Taiwan and Japan (Xu *et al.* 2014). The pest has become extensively established across North America and Europe (Haye & Weber 2017) and in 2017 BMSB was reported from the southern hemisphere for the first time (Chile) (Faúndez and Rider 2017). It has been intercepted many times at the Australian border as a hitchhiking pest on goods and commodities, most commonly between September and April.

BMSB is a polyphagous species, with both the adult and nymph life stages causing extensive damage to the leaves, stems, fruits and buds of many agriculturally important field crops, fruit and ornamental trees (Haye *et al.* 2015a). The host range extends to hundreds of species and feeding damage will cause malformation of fruit and seed, reduced fruit set and premature fruit drop. Malformation reduces marketability of fruit, and wounds from feeding behaviour leave plants susceptible to secondary infections by pathogenic bacteria or fungi (Rice *et al.* 2014). BMSB is a difficult pest to manage across landscapes as it will move readily to different food sources as crop species ripen.

Overwintering aggregations of BMSB often form on the interior and exterior surfaces of houses and buildings, where they will damage the surface with excretions and produce an unpleasant odour when disturbed. This pest is also a known vector of witches' broom disease, a destructive phytoplasma disease of *Paulownia* spp. (CABI 2020) which are grown commercially in Australia.

Eradication of BMSB in other countries has not been successful although limited control has been established through the use of chemical pesticides (Kuhar & Kamminga 2017). Recent work has focussed on biological control agents including the parasitoid wasp *Trissolcus japonicus* (Haye *et al.* 2015b, Stahl *et al.* 2019). In the United States (U.S.), BMSB has become one of the worst pests in recent history with over $37 million damage in their apple growing regions alone, while losses amounting to an estimated EUR500 million were caused in the Italian fruit and nut industry in 2019 (Haye *et al.* 2015a, Leskey & Nielsen 2018).

BMSB represents a major biosecurity threat to Australian agriculture and a serious social amenity pest. Intercepts of BMSB occur regularly at the border and if the pest penetrates beyond the border, establishment is likely to occur rapidly.

3 Glossary

Table 1 - Definitions and abbreviations

Term/Abbreviation	Definition
BMSB	Brown marmorated stink bug
DAFF	Department of Agriculture, Fisheries and Forestry
DAWR	(former) Department of Agriculture and Water Resources
NSP	National Surveillance Protocol
SNPHS	Subcommittee for National Plant Health Surveillance
Polyphagous	Feeds on many different host plants
Gravitaxis	Directional movement of the pest, in response to gravity.
Phototaxis	Directional movement of the pest, in response to light.

4 Pest risk profile and pathway analysis

The likelihood of BMSB arrival in Australia is heavily influenced by the bugs' lifecycle and behaviour in the northern hemisphere, and their subsequent dispersal and spread in the country will be similarly influenced.

4.1 Entry pathways

Pathway and establishment analyses have been completed by the Commonwealth Department of Agriculture and SNPHS and documented in *Priority Pest Surveillance Requirements Brown Marmorated Stink Bug*[1]. Entry pathways were assessed based on information from the department's risk analysis (DAWR 2017) and more recent incidents at the border.

[1] Available on request through the *Subcommittee on National Plant Health Surveillance*

Live BMSB can potentially enter on goods at any time of year, but during spring to late summer BMSB in the northern hemisphere are active, feeding, flying and completing their lifecycle on host plants (Lee *et al.* 2013; Haye *et al.* 2014; Rice 2014). As a result, BMSB are not usually associated with structures or goods at this time as they are not looking for overwintering sites.

Through pest risk analyses, DAFF has identified that the overall likelihood of entry is high for BMSB during the months of September to April. This corresponds with decreasing temperatures in the northern hemisphere and a change in the behaviour of BMSB as it seeks out overwintering shelter sites. The risk to Australia is that these overwintering sites include vehicles and machinery, containers and goods going into containers. As BMSB expands its range in Europe and South America, the approach rate on this pathway is likely to increase. Import restrictions and phytosanitary controls are applied offshore (e.g. mandatory treatments of risk goods) and at the border to reduce the risk of BMSB entering Australia.

Less likely but still possible pathways include commercial vessels that house overwintering aggregations and bugs that have hitchhiked on baggage or goods from high-risk countries.

4.2 Establishment and spread

Establishment, as measured by multiple new generations of BMSB after arrival, is highly likely in the vicinity of ports and premises where containers are deconsolidated, particularly if there are local hosts available. Significantly for establishment and spread, in its native range ovarian development in BMSB is labile, commonly producing 1-2 generations per year although more have been suggested (reviewed in Lee *et al.* 2013). Haplotype analysis suggest all BMSB present in the U.S. and Canada have dispersed from a single founding event, highlighting the capability of this insect to spread (Wiman *et al.* 2015).

BMSB is a strong flyer and a highly mobile pest which can move from host to host during the growing season. They deliberately disperse in search of hosts or overwintering sites, or when habitats are disturbed. Flight tests have shown adult BMSB is capable of flying 2-5 km per day in search of preferred food sources, depending on both nutritional and overwintering status (Wiman *et al.* 2015). BMSB has spread rapidly aided by human movement throughout both Europe and North America (Haye *et al.* 2015a) and in climatically favourable locations in Australia spread is likely to be just as swift. Once established, BMSB can spread over land along highways and railways, through passive contamination of vehicles e.g. cars, tractor-trailers, trains, recreational vehicles and moving trucks.

Physiological constraints on establishment

BMSB adults overwinter and require a minimum photoperiod to break diapause. In a number of studies from populations around the world in different temperature regimes, the critical photoperiod has been measured between 13.5 to 14.5 hours (Watanabe 1980; Haye *et al.* 2014; Nielson *et al.* 2016). Below this range, overwintering BMSB adults will not emerge, and any active adults that arrive during months in which the photoperiod is below this range will most likely enter diapause.

Temperature also strongly influences development and the behaviour of adult BMSB. Adults will become inactive below 15°C and above 30°C they will seek shelter (Niva & Takeda, 2003; Li *et al.* 2007; Lee *et al.* 2014a).

Development will not complete below 15°C or above 35°C, and in this range, takes an average of 60 days (Nielson *et al.* 2008; Haye *et al.* 2014). Females require 1-2 weeks where the temperature does not exceed 30°C to feed and complete development after diapause and before oviposition.

Limits on distribution in Australia

The complexity of BMSB behavioural and developmental responses to multiple environmental effects has decreased the confidence of predicting establishment within Australia. Arid Australia is unsuitable for establishment due to high temperatures and a lack of host plants. Establishment in southern coastal Australia (south of Brisbane) is likely due to suitable climate, photoperiod and host plant availability.

On the summer solstice, the photoperiod in Brisbane is around 13.9 hours and it remains above 13.5 hours from mid-November to late January. Given the regularity of day time temperatures exceeding 30°C in these months, it is unlikely adult BMSB that arrive in Brisbane would be active long enough to emerge from diapause, complete maturity, mate and oviposit, unless they were transported south on commercial consignments soon after arrival. This assumption is supported by modelling predictions in Zhu *et al.* (2012). However, BMSB has been detected in regions around the world that experience a similar photoperiod as Brisbane e.g. Florida where summer solstice is 13.9 hours (Penca & Hodges 2018). Records of the pest in these areas suggests limited establishment and distribution but it is clear BMSB has a degree of intraspecific variation in response to environmental cues that limits accurate predictions of establishment potential.

5 Pest biology and ecology

Surveillance must consider the influence of BMSB lifecycle and behaviour in an Australian context.

5.1 Detection in the field

Populations of BMSB in the United States went undetected for five years due to misidentification of similar species (Rice *et al.* 2014). Australia has multiple species similar in appearance to BMSB and there are public guides available to help differentiate between these species, including the *Guide to the identification of brown marmorated stink bug, Halyomorpha halys, and other similar bugs* (DAWR 2015).

Eggs

White or pale green eggs are laid by females in clusters usually near the top of the canopy on the underside of leaves (**Figure 1**). Each egg is approximately 1.6 mm in diameter and barrel shaped. Egg clusters are laid in masses of approximately 28 eggs and females may lay multiple clusters.

Figure 1 – Eggs on underside of the leaf (left) and with early-stage instars (right) [Source*: Ian Grettenberger, from Rice* et al. *2014*]

Juveniles or nymphs

First and second instars remain clustered around the eggs as they feed on empty egg cases (**Figure 1**). Juveniles range from 2.4 mm to 12 mm in length and do not have fully developed wings. Young nymphs have a dark head with an orange abdomen and red with black stripes along the edge and down the centre of the body. Older nymphs are similar but often darker, with small lateral spines around the front edge of the body and a banding pattern on the legs and antennae beginning to appear (**Figure 2**). Second instars eventually disperse from the egg cases and begin feeding on host plants.

Figure 2 – (Left) to (right), first, second, fourth and fifth instars. The characteristic white leg bands are obvious in the fifth instar nymph. [Source: *Ian Grettenberger, from Rice* et al. *2014*]

Adults

Adults are 12 to 17 mm long and 7-10 mm in width. They have a distinctive shield shape and are variable in colour, often with a reddish tinge (**Figure 3**). The most distinguishing characteristic of the adults in the field is the alternating dark and white bands across the last two antennal segments, and legs that appear to have a single pale band on the tibiae - which can also often be seen in late instar nymphs (Hoebeck & Carter 2003).

Figure 3 – (left) Adult BMSB, male left, female right [*Source: W. Hershberger. USDA, stopbmsb.org*] (right) Adult with light banding on antenna and legs, distinctive shield shape and red tinge [*Source: David R. Lance, USDA APHIS PPQ, Bugwood.org*]

5.2 Identification

Generally, nymph and adult BMSB are able to be identified using morphological keys and descriptions (e.g. Hoebeke & Carter 2003). Eggs should be reared to confirm identification.

5.3 Lifecycle

The BMSB lifecycle consists of three stages – egg, nymph (5 instars) and adult. Development from egg to adult takes approximately 40 to 60 days, depending on temperature and photoperiod. Overwintering females emerge with undeveloped ovaries, becoming reproductively mature after a developmental delay and to coincide with photoperiods of greater than 14 hours (Watanabe 1980). Females that mature before the critical photoperiod cue may reproduce, while those emerging later will enter diapause (Leskey & Nielsen 2018). Maturity takes up to two weeks before mating occurs during which time adults feed. The female lays eggs on host plants, with egg development usually taking 5-6 days (Leskey *et al.* 2012a).

Mean development time at the optimal temperature (25-33°C) for juveniles is generally 30-40 days, though cooler temperatures slow down each instar stage dramatically (Nielson *et al.* 2008). Where conditions allow for more than one generation per season, adults mate and females oviposit within weeks of the last instar. Average longevity of a BMSB adult is 300 days, which includes the overwintering stage.

5.4 Habitat

When overwintering (before the daytime temperature reaches a minimum of 15°C), adults cluster in large numbers in shelters such as sheds, machinery, building cracks and trees (such as dead standing trees) and sometimes in leaf litter. At ports this can include containers.

During the active life stage (spring – early autumn), the highly polyphagous and preferentially arboreal BMSB are frequently found on a large range of trees as well as vegetables, legumes and other plants (Lee *et al.* 2013).

5.5 Vectoring capacity

BMSB is a known vector of witches' broom disease, a destructive phytoplasma disease of *Paulownia* spp. (Yu & Zhang 2009).

5.6 Movement

Adult BMSB are excellent flyers and will rapidly move away when disturbed. Nymphs do not fly, and they demonstrate negative gravitaxis and positive phototaxis – that is they are most often travelling upwards to feed during the day. Nymphs have a strong dispersive capability and will walk up to 40m (Kirkpatrick *et al.* 2019). Traps that allow nymphs to climb from the substrate are more successful than hanging traps (Acebes-Doria *et al.* 2016) and visual surveillance should include canopy areas of tall trees.

6 Host range and part of host affected

BMSB is an extremely polyphagous bug and moves from early fruiting plants to late fruiting plants across the warmer months. True hosts, those that support oviposition and nymphal development, may be limited, hosts on which BMSB feed belong to dozens of families (Leskey & Nielsen 2018). Of particular note is the true host, *Ailanthus altissima* or Tree of Heaven, a widespread weed found along the east coast and across southern and south western areas of Australia (Centre for Invasive Species Solutions 2020).

Fruit trees including peaches, nectarines and apples, vegetables such as beans, capsicum and eggplant, and crops including sorghum, cotton, sweetcorn and soybeans are particularly susceptible. The feeding behaviour of BMSB on grapes adversely affects the quality of wine (Mohekar *et al.* 2017). Ornamentals including woody and herbaceous plants in nurseries, urban landscapes, natural and residential areas have also been extensively damaged in the U.S. (Leskey *et al.* 2012a). Australian native *Acacia* species are also hosts (Lee *et al*. 2013). A comprehensive list of ongoing host impacts in the U.S. can be found at https://www.stopbmsb.org/where-is-bmsb/.

Appendix one contains a comprehensive list of known host species.

7 Pest damage

Apples often exhibit pitting and discolouration symptoms, and peaches frequently display a characteristic distortion referred to as 'cat-facing'. https://www.stopbmsb.org/managing-bmsb/management-by-crop/ has comprehensive images of damage on a wide variety of crops.

Damage from feeding behaviour can vary (**Figure 4**) and may appear as:

- scarring on fruit

- faded and sunken areas on the surface of fruit
- deformed fruits, shrivelled seeds or pods
- pale spongy areas on the surface of fruits
- internal tissue damage visible as discoloured, rotting or corking flesh

Figure 4 – (left to right) BMSB damage on tomato (with secondary bacterial infection), apple and corn [*Source: Tomato: Doug Inkley, National Wildlife Federation, Apple: Tracy Leskey, USDA, Corn: Galen Dively, University of Maryland*]

8 Surveillance methodology

This protocol considers two types of targets for surveillance: feeding or dispersing insects and overwintering aggregations. Trapping remains the most efficient early detection tool as individual BMSB that escape from containers, imported machinery and equipment may be difficult to detect visually. In large numbers, BMSB may aggregate in shelter on arrival until day length and temperature are suitable for feeding and flight behaviour. General surveillance and community engagement would be useful in detecting aggregating bugs during the period as they shelter.

8.1 Survey locations

Feeding and dispersing BMSB

As the photoperiod and temperature increases and dispersal and feeding are more likely, surveillance should extend to areas around first point of entry and Approved Arrangement facilities where they have moved in search of mates and host plants. Techniques include trapping and visual surveillance which can be supported with host sweeping or beating. Feeding BMSB will be attracted to fruiting host plants and the following survey locations around first point of entry facilities/Approved Arrangements can include:

- Community gardens, botanic gardens and residential areas where host plants are abundant
- Nurseries
- Bushland with native or introduced fruiting host species
- Host trees lining streets

Overwintering aggregations

As the lifecycle and behaviour of BMSB is correlated with seasonal effects, surveillance should be similarly directed. BMSB present in Australia during the cooler months of April to October are likely to continue to shelter to overwinter and are most likely to be picked up during inspections. During delimiting or pest status monitoring of introduced populations, overwintering sites such as sheltered dry areas of both human-made structures and dead trees in residential areas can be targeted.

8.2 Surveillance methods

Overall early detection surveillance is a high priority around ports including Approved Arrangement sites, other sites where containers are moved to and natural areas in the vicinity with hosts that may support incursions as they disperse. If flying BMSB have been detected and not isolated, early detection surveillance would extend around port areas and depending on seasonal effects, surveillance design would need to consider the flying capability of adults and dispersal capability of nymphs to plan trapping and visual surveys.

8.2.1 Feeding and dispersing BMSB

During the period of September to April, early detection surveillance should focus on feeding and dispersing insects, and as the weather and day length increases all life stages should be included in surveillance activities.

Feeding nymphs and adults may aggregate towards the top of the canopy of trees or on the underside of plants and bushes or drop to the ground if disturbed, therefore beating sheets may be placed below trees during visual examination. **Visual surveys** and **sweep net or beating tray surveys** for feeding and overwintering BMSB should include:

- Woody plants as BMSB is primarily an arboreal species, including weeds such as Tree of Heaven.
- If there are multiple fruiting hosts, trees should be prioritised given the arboreal nature of BMSB, and trees with abundant or mature fruit should be preferentially chosen over immature fruiting trees.
- Preferential fruiting crops include those with fleshy or pod like fruit, such as apples, pears, berry crops and summer fruit or vegetables such as tomatoes, capsicums, sweetcorn and eggplant. All plant parts should be visually examined as BMSB may be on stems and leaves as well as fruit. Acacias with immature pods are also known hosts (G. Norton pers. comm.).
- Egg masses and nymphs which can be found on the underside of leaves.
- Foliage or structures within 5 m of lure traps as BMSB may be attracted to the lure but not enter the trap (Ingels *et al.* 2015).

Sweep nets should be used to detect and collect suspect nymphs or adults from large trees and beating trays should be used to detect and collect suspect nymphs or adults from low branches or short plants. On hot days, bugs may be sheltering in foliage close to trunks and it is recommended to conduct surveillance in the early morning when it is cooler as the bugs will be less mobile and less likely to escape.

Lure based trapping can be used for adults and nymphs. There are a range of suitable BMSB traps which are used with a lure, some have not been tested in low population densities for early detection, although may be effective for response or monitoring surveillance. For early detection, a highly sensitive trapping network is likely to be costly and should be used to support visual surveillance.

Traps are most likely to attract BMSB adults when they are dispersing to find food, and not stationary in aggregations. However, when set all season long, trapping could determine the timing of emergence from overwintering, movement onto foraging sites, relative numbers of adults and nymphs, and when adults return to begin diapause (Weber *et al.* 2014, Leskey *et al.* 2015). Trapping would continue to be useful in measuring spread in the case of ongoing detections. Commonly distances of 50-100m between traps have been effective in studies with high populations, though host plant presence can be influential (Kirkpatrick *et al*. 2019).

Plants that BMSB preferentially visit such as sunflower and sorghum – can be planted or baited with BMSB lures and traps to act as a sentinel surveillance site.

Traps

Tall black pyramid traps (**Figure 5**) are placed on the ground. A clear collection jar with insecticide-impregnated netting inside should be placed on the top. The jar and the entrance funnels need to be cleared often, and non-target animals including flying insects such as wasps and climbing animals including frogs and snails have been observed in the jars (Acebes-Doria *et al.* 2018). Both adult and nymph BMSB are caught in these traps, and they demonstrate consistent high trapping rates in studies throughout the United States including in low population densities. However, pyramid traps are large and cumbersome in the field, can be time-consuming to install and are more costly particularly compared to sticky traps.

Cross-vane panel traps (**Figure 6**) are similar to pyramid traps but hung in host trees, not in contact with the foliage so they capture flying BMSB. Panel traps also require a collection jar and insecticide. As they are placed higher than pyramid traps, they may be less susceptible to vandalism and can be used for multi-species surveillance where other species are commonly trapped by panel traps e.g. *Monochamus* beetles (Chase *et al.* 2018; M. Mebalds pers comm.).

Sticky traps (yellow or clear) are less expensive than pyramid traps and easy to install. They should be placed among foliage in trees that are fruiting or attached to tree trunks or wooden stakes, at least 1.5m off the ground to allow the adults and nymphs to crawl up into the trap (**Figure 5**). Yellow sticky traps attract the most by-catch compared to clear sticky traps, and they are susceptible to predation from birds. As such they should be checked more frequently than pyramid traps. Although sticky traps often capture less BMSB than pyramid traps, their capture rate is still consistent with population levels, and at very low densities they have demonstrated success as a monitoring tool (Acebes-Doria *et al.* 2018).

RESCUE!© traps (**Figure 6**)have reportedly been shown to be more attractive than sticky traps in outbreaks in Georgia (G. Norton pers. comm). While available commercially these traps are a more expensive option than sticky traps and have not yet been tested in low populations for early detection.

An additional trap type was reported by Suckling *et al*. (2019). A **live capture trap** (**Figure 7**) consists of two flower pots with the bottoms removed, taped together, and a removable mesh cone placed inside. The trap also has a cardboard wind vane that positions the trap to maximise release of the aggregation lure. Trials of this trap in high population areas had higher capture rates than sticky traps, but it has not yet been trialled in early detection surveillance.

Some jurisdictions in Australia require the use of cages around the sticky traps to reduce by-catch and the efficacy of catching BMSB with the cages in place should be tested.

Figure 5 – (left) Standard black wooden pyramid trap with clear plastic collecting jar (right) Double-side clear sticky trap [*Source: Acebes-Doria et al. 2018*]

Figure 6 – (left) Cross-vane panel trap with collection jar [*Source: Chase* et al. *2018*]. (right) RESCUE!© Trap in Georgia [*Source: G. Norton*]

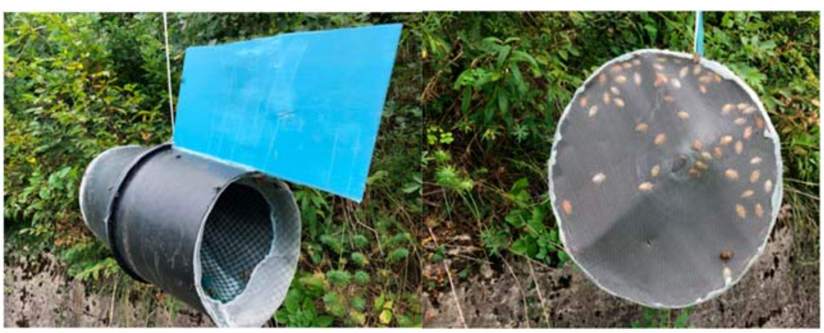

Figure 7 - Live capture trap with cardboard windvane. An explanatory video of this trap is available with the paper [*Source: Suckling et al. 2019*].

Lures

BMSB produces an aggregation pheromone that is available for commercial use as a lure and has proven effective in trapping all nymph stages as well as adults, even in low population numbers (Leskey *et al.* 2015). The addition of a synergist (methyl (E,E,Z)-2,4,6-decatrienoate or MDT) has improved trapping numbers significantly (Leskey *et al.* 2012b Weber *et al.* 2017). This protocol recommends the use of BMSB lure produced by Trécé Inc. (Adair, OK, USA). AgBio Inc. also produce a lure for BMSB traps, however this lure has proven to be less successful in field studies (Acebes-Doria *et al.* 2018).

Acebes-Doria *et al.* (2018) compared loading rates of lures (low, 5 mg of the *H. halys* aggregation pheromone and 50 mg of MDT, or high, 20 mg of the *H. halys* aggregation pheromone and 200 mg of MDT) and found higher capture rates with the higher loads but relative capture numbers were still correlated with population densities. Significantly for early detection surveillance, low load rates were still successful at very low population levels. Lures in all trap types should be replaced every 4-6 weeks.

Overall trap placement distance and lure load rates have not yet been optimised for early detection surveillance (see Section 10: Research and development).

8.2.2 Overwintering aggregations

BMSB that arrive into cold weather will most likely continue to overwinter on the containers or vehicles they arrived on unless they are disturbed. Early detection surveillance for one or two bugs that may seek shelter in industrial or residential areas is likely to be inefficient and not yield satisfying results. However in the case of an incursion, overwintering aggregations can be obvious to find as they congregate in high numbers, and overwintering sites can serve as fixed positions from which to monitor, capture and kill new populations before they disperse into host areas.

Visual surveys for BMSB should look in dry areas under eaves and gutters or other sheltered areas of human-made structures and sheltered areas on the surface of machinery e.g. cars, tractors, forklifts. In natural areas, aggregations tend to form concealed, in standing dead trees. The outer bark may need to be lifted to find aggregations, and they preferentially choose dry standing trees over those that have fallen (Lee *et al*. 2014b). Aggregating adults can be collected via sweep netting, or if near the time of dispersal, can be attracted with lured traps.

8.3 Survey timing and frequency

This protocol provides general advice for the timing of surveys for overwintering and feeding and dispersing insects. As the behaviour of BMSB is extremely sensitive to changes in temperature and day length, programs must assess changes in these conditions at a local level, to develop an appropriately timed surveillance response.

Overwintering aggregations

BMSB hitchhikers could arrive in Australia at any time but as BMSB adults begin searching for overwintering sites in the northern hemisphere in September and October, arrivals in Australia can be expected to increase as they enter cargo and ships for overwintering. However, in these months in Australia, day length does not reach 13 hours, and day time temperatures are variable. As such, surveillance at this time will most likely only detect adults sheltering in buildings and vehicles close to the port.

Feeding and dispersing

Day lengths of 13.5 -14 hours, required to initiate sexual activity and promote egg-laying (Niva & Takeda 2003), are reached in late October through to March/April, depending on latitude. Therefore, early detection surveillance in these months should increase in frequency and focus on all life stages; late summer early detection surveillance can include looking for eggs and nymphs.

Response or pest status surveillance will need to consider BMSB's lifecycle in relation to seasonal influences in Australia and adjust surveillance timing and methods if the introduced population begins to align its behaviour with local conditions (**Table 2**).

Table 2 – Behavioural ecology of BMSB in northern hemisphere ports of origin and potential behaviour on incursion in Australia. Both temperature and photoperiod have strong impacts on the timing of emergence and reproductive maturity, as such, latitude is a large predictor of behaviour and surveillance targets.

Month	BMSB behaviour		Surveillance target
	Northern hemisphere	Southern hemisphere (Australia and Chile)	
January	Diapause	Feeding and mating, oviposition	Feeding and dispersing adults, eggs and nymphs
February	Diapause	Searching for overwintering sites	Feeding and dispersing adults, eggs and nymphs
March	Diapause	Searching for overwintering sites	Feeding and dispersing adults, eggs and nymphs
April	Beginning of emergence	Diapause	Feeding and dispersing adults, beginning overwintering aggregations
May	Dispersal, initially to trees and fruiting plants	Diapause	Overwintering aggregations
June	Feeding and mating, oviposition	Diapause	Overwintering aggregations
July	Feeding and mating, oviposition	Diapause	Overwintering aggregations
August	Feeding and mating, oviposition	Diapause	Overwintering aggregations
September	Searching for overwintering sites	High likelihood of arrivals/emergence of overwintering insects	Overwintering aggregations, feeding and dispersing adults
October	Searching for overwintering sites	Dispersal, initially to trees and fruiting plants	Feeding and dispersing adults
November	Diapause	Feeding and mating, oviposition	Feeding and dispersing adults, eggs
December	Diapause	Feeding and mating, oviposition	Feeding and dispersing adults, eggs

8.4 Sample handling

By law everyone must comply with biosecurity legislation when moving any suspect exotic plant pest sample, including when sending samples for identification.

In developing a surveillance program, all participants must be clear about their obligations regarding what to do if suspect samples need to be moved.

If movement obligations are not understood, contact the Emergency Plant Pest hotline on 1800 084 881, to obtain instructions to collect and move samples safely.

General diagnostic laboratory contact, preparation and sample submission information is provided below in Table 3.

All laboratories should be contacted before sample submission to determine if they have suitable diagnostic capability for the pest (including the life stage being sampled) and have appropriate accreditation to receive biosecurity material. In some cases, specimens may need to be collected as live samples for diagnostic reasons and the laboratory must meet jurisdictional requirements to handle live specimens.

Table 3 – State and territory diagnostic contacts for submission of suspect plant pest samples.

Jurisdiction	Contact details
Queensland	13 25 23 Submitters will be advised what to do with samples through this service.
Western Australia	08 9368 3080 Photos of samples can also be submitted through MyPestGuide app or website Preparation and submission: https://www.agric.wa.gov.au/livestock-biosecurity/sending-specimens-identification
South Australia	(08) 8429 2249 Preparation: https://pir.sa.gov.au/__data/assets/pdf_file/0020/236234/Packaging_Brochure_low.pdf Submission: https://pir.sa.gov.au/research/services/crop_diagnostics/insect_diagnostic_service
New South Wales	1800 680 244 biosecurity@dpi.nsw.gov.au Preparation and submission: https://www.dpi.nsw.gov.au/about-us/services/laboratory-services/plant-health/collecting-and-submitting-plant-or-insect-samples
Northern Territory	(08) 8999 2118 Submission: https://nt.gov.au/industry/agriculture/food-crops-plants-and-quarantine/plant-diseases-and-pests/plant-pathology-and-entomology-contacts
Victoria	(03) 9032 7515 Submission: https://agriculture.vic.gov.au/support-and-resources/services/diagnostic-services
Tasmania	(03) 6165 3777 plantdiagnosticservices@nre.tas.gov.au Preparation and submission: https://nre.tas.gov.au/biosecurity-tasmania/plant-biosecurity/plant-diagnostic-services

Given the similarity of a number of Australian species of stink bugs and the difficulty of taxonomic identification in the field, all stink bug nymphs and adults caught that resemble BSMB should be submitted to an entomologist for identification. Good photographs showing distinguishing features can also be used to triage suspect samples – head shape, underside of body, colour of shield and an indication of scale within the photo is necessary to identify the sample.

- Eggs can be left on leaves and the leaves placed in ethanol vials or kept protected on leaf material until they are able to be reared in controlled conditions. Eggs to be reared should not be exposed to temperatures below 15°C or above 35°C.
- BMSB nymphs and adults may damage easily and multiple adults in each vial should be avoided.
- 70% ethanol is suitable for most sampling techniques, 95% ethanol is recommended for any samples requiring molecular analysis.

9 Record keeping

Surveillance data captured for use in the plant health surveillance system in Australia should be collected using the Pest Record Specification. This biosecurity specific data standard is endorsed for use by the Sub-committee on National Plant Health Surveillance and Plant Health Committee and is maintained by the Commonwealth. Surveillance planning should include the development of a program data standard, based on the Pest Record Specification, and utilising any relevant pest-specific data protocols. Information on using the Pest Record Specification and Data Protocols is available on the Plant Surveillance Network Australasia-Pacific (PSNAP) website.

A pest specific data protocol for Brown Marmorated Stink Bug has been developed and is available on the PSNAP website.

When undertaking surveillance, the data fields to be collected must be considered for individual pests and surveillance methods and the data protocol describes the mandatory, required and optional data fields. A number of data fields have specific controlled vocabulary from which they must be filled. Controlled vocabulary lists are included in the data protocol and tabled below, based on the methods and technology described in this protocol.

Table 4 – Controlled vocabulary lists for brown marmorated stink bug

scientificName	inspectionMethod	hostMaterial	non-hostMaterial	lureType	trapType	protocolID
Halyomorpha halys	Trapping Visual surveillance Sweep netting Beating tray	Plantae Host lists provided in Appendix one	Container Machinery Vehicles Premises	BMSB lure	Tall black pyramid trap Yellow sticky trap Clear sticky trap Cross-vane panel trap	Brown marmorated stink bug

10 Research and Development

Effective trapping of BMSB has been established in a number of field studies in the United States, and as a detection tool, trapping is able to attract insects even in a low population density (Leskey *et al.* 2015). Lures used are a combination of the BMSB aggregation pheromone and a synergist, methyl (2E,4E,6Z)-decatrienoate (MDT), which is more effective than the aggregation component alone.

For early detection surveillance in Australia, the trapping network is required to be extremely sensitive to detect populations at very low numbers. It has been shown that increasing doses and loading rates of both pheromone and synergist has subsequently increased the capture rate of BMSB but will also significantly increase the cost of the trapping network. Leskey *et al.* (2015) suggest that there may be an optimal ratio of MDT and pheromone that will increase the sensitivity of the lure while minimising the cost-benefit ratio. Therefore, the question new research would ask is:

What is the optimal ratio of BMSB aggregation pheromone and synergist to maximise sensitivity, and synergistic response to low population captures? It will require:

- A definition of ‘low-population’ as it refers to detection thresholds and arrival numbers
- To consider changes in attraction of different life-stages (nymphs or adults)
- Account for adjustments in lure concentration across seasonal fluctuations in behaviour (aggregating or dispersing adults)

Refer to Leskey *et al.* (2015), Weber *et al.* (2017) and Acebes-Doria *et al.* (2018) for comparisons of lure efficiencies.

Due to its status as a nuisance pest, citizen science reporting may be utilised extensively in the case of an incursion and effective capture and implementation of this data should be researched. Areas for consideration would include:

- Quality and reliability of data capture across varying population levels
- Cost benefit to early detection or incursion response in citizen data capture
- Current extent of reporting tools and community engagement methods in capturing data

10.1 Triggers for protocol review

- Significant changes in effective surveillance methodologies (significant changes in trap or lure designs or composition).
- If establishment occurs in more export ports of the southern hemisphere, this may require an increase in surveillance effort as the BMSB behaviour in the port of origin is aligned with their potential behaviour in Australia.

11 Contact and further information

Plant Health Australia 2017

Contingency Plan for Brown Marmorated Stink Bug (*Halyomorpha halys*). Available from: http://www.planthealthaustralia.com.au/wp-content/uploads/2018/09/Brown-marmorated-stink-bug-CP.pdf.

Gertraud Norton

Department of Agriculture, Fisheries and Forestry

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13 Appendix one Known brown marmorated stink bug host plants

Host species	Common name	Reference
Abelia × grandiflora	Glossy abelia	a, d
Abelmoschus esculentus	Okra	a
Acer × freemanii	Freeman maple	a
Acer × tegmentosum	Manchurian snakebark maple	a, d
Acer buergerianum	Trident maple	a
Acer campestre	Hedge maple	a, d
Acer circinatum	Vine maple	a
Acer griseum	Paperbark maple	a
Acer japonicum	Amur (Japanese downy) maple	a
Acer macrophyllum	Bigleaf maple	a
Acer negundo	Box elder	a
Acer palmatum	Japanese maple	a
Acer pensylvanicum	Striped maple	a
Acer platanoides	Norway maple	a
Acer pseudoplatanus	na	d
Acer rubrum	Red maple	a
Acer saccharinum	Silver maple	a, d
Acer saccharum	Sugar maple	a
Actinidia deliciosa	Kiwifruit	c
Aesculus × carnea	Red horse-chestnut	a
Aesculus glabra	Ohio buckeye	a
Ailanthus altissima	Tree of heaven	a, c
Akebia sp.	Chocolate vine	c
Amaranthus caudatus	Love-lies-bleeding (amaranth)	a
Amelanchier laevis (syn. × grandiflora)	Allegheny (apple) serviceberry	a
Antirrhinum majus	Garden snapdragon	a
Arctium minus	Lesser burdock	a, c, d
Armoracia rusticana	Horseradish	a
Artemisia argyi	Argyi wormwood	c
Asimina triloba	American pawpaw	a
Asparagus officinalis	Asparagus	c
Baptisia australis	Blue wild indigo	a
Basella rubra	Ceylon spinach	c, d
Beta vulgaris	Beet	c, d
Beta vulgaris ssp. cicla	Swiss chard	a
Betula sp.	Birch	c, d
Betula nigra	River birch	a
Betula papyrifera	Paper birch	a
Betula pendula	European white birch	a
Brassia sp.	Orchid	c
Brassica juncea	Wild mustard	a
Brassica napus	Canola	c

Host species	Common name	Reference
Brassica oleracea	Cabbage, collards	a
Buddleja sp.	Butterflybush	a, d
Buddleja davidii	Butterflybush	d
Camellia oleifera	Oil-seed camellia	c
Camellia sinensis	Chinese tea	c, d
Cannabis sativa	Hemp	a
Capsicum annuum	Cayenne pepper	a, c, d
Caragana arborescens	Siberian peashrub	a, d
Carpinus betulus	European hornbeam	a
Carya ovata	Shagbark hickory	a, d
Carya illinoinensis	Pecan	a
Catalpa sp.	Catalpa	a, c
Cayratia japonica	Bushkiller	c
Celastrus orbiculatus	Oriental bittersweet	a, d
Celosia sp.	Cock’s comb	a
Celosia argentea	Feather cockscomb	b, d
Celtis occidentalis	Common hackberry	a
Celtis koraiensis	Korean hackberry	a
Cephalanthus occidentalis	Common buttonbush	a
Cercidiphyllum japonicum	Katsura tree	a, b
Cercis canadensis	Eastern redbud	a
Cercis canadensis var. texensis	Texas redbud	a, d
Cercis occidentalis	Hackberry	d
Chaenomeles speciosa	Japanese flowering quince	c
Chamaecyparis obtusa	Hinoki cypress	c
Chenopodium berlandieri	Pitseed goosefoot	a
Chionanthus retusus	Chinese fringe tree	a
Chionanthus virginicus	White fringe tree	a
Cinnamomum camphora	Camphor tree	c
Citrus sp.	Orange, mandarin, yuzu	c, d
Cladrastis kentukea (syn. lutea)	Kentucky (American) yellowwood	a
Cleome sp.	Cleome	d
Clerodendrum trichotomum	Harlequin glorybower	c
Cornus × Stellar series	Dogwood	a
Cornus florida	Flowering dogwood	a
Cornus kousa	Kousa dogwood	a, d
Cornus macrophylla	(Large-leaf) dogwood	a
Cornus officinalis	Asiatic (Japanese cornel) dogwood	a
Cornus racemosa	Gray dogwood	a
Cornus sericea	Redosier dogwood	a, d
Corylus colurna	Filbert, hazelnut	a
Crataegus laevigata	Smooth (English) hawthorn	a
Crataegus monogyna	Oneseed hawthorn	a
Crataegus pinnatifida	Chinese hawthorn	c
Crataegus viridis	Green hawthorn	a

Host species	Common name	Reference
Cucumis sativus	Garden cucumber	a, c
Cucurbita pepo	Field pumpkin (summer squash)	a
Cupressus sp.	Cypress	d
Decaisnea fargesii	na	d
Dendranthema morifolium	Chrysanthemum	c
Diospyros sp.	Persimmon	c, d
Diospyros kaki	Japanese persimmon	a, d
Elaeagnus angustifolia	Russian olive	a, d
Elaeagnus umbellata	Autumn olive	a
Eriobotrya japonica	Loquat	c
Euonymus alatus	Winged euonymus	d
Euonymus japonicus	Japanese spindle	c
Evodia sp.	na	b
Ficus carica	Edible fig	a, c, d
Firmiana platanifolia	Chinese parasol tree	c
Forsythia suspensa	Weeping forsythia	a
Fraxinus americana	White (American) ash	a, d
Fraxinus chinensis	Chinese ash	c
Fraxinus pennsylvanica	Green ash	a
Ginkgo biloba	Maidenhair tree (ginkgo)	a
Gleditsia triacanthos var. inermis	Thornless common honeylocust	a, b
Glycine max	Soybean	a, c, d
Gossypium hirsutum	Upland cotton	c, d
Halesia tetraptera	Mountain (carolina) silverbell	a, b
Hamamelis japonica	Invasive witchhazel	a
Hamamelis virginiana	American witchhazel	a
Helianthus annuus	Sunflower	a, c, d
Heptacodium miconioides	Seven sons flower	a
Hibiscus moscheutos	Crimsoneyed rosemallow	a
Hibiscus rosa-sinensis	Chinese hibiscus	c, d
Hibiscus syriacus	Rose of sharon (hibiscus)	a
Humulus lupulus	Common hop	a
Humulus scandens (japonicus)	Japanese hops	c
Ilex aquifolium	English holly	a
Ilex opaca	American holly	d
Ilex verticillata	Winterberry holly	d
Impatiens balsamina	Rose balsam	c
Juglans nigra	Black walnut	a, d
Juniperus virginiana	Eastern red cedar	a
Koelreuteria paniculata	Goldenrain tree	a, d
Lagerstroemia indica	Crape myrtle	a
Larix kaempferi (syn. leptolepis)	Japanese larch	a
Ligustrum japonicum	Japanese or wax-leaf privet	a
Ligustrum sinense	Chinese privet	a
Liquidambar styraciflua	Sweetgum	a

Host species	Common name	Reference
Liriodendron tulipifera	Tulip tree	a
Lonicera sp.	Honeysuckle	a
Lonicera tatarica	Tatarian honeysuckle	a, d
Lycium barbarum	Wolfberry	c
Lythrum salicaria	Purple loosestrife	a
Magnolia stellata	Star magnolia	a
Magnolia grandiflora	Southern magnolia	a, d
Mahonia aquifolium	Holly leaved barberry (oregon grape)	a
Malus × zumi	Crab apple	a
Malus baccata	Siberian crab apple	a, d
Malus domestica	Apple	a, c
Malus pumila (syn. domestica)	Paradise apple	a
Malus sargentii	Sargent’s crab apple	a
Manihot esculenta	Tapioca	c
Metasequoia glyptostroboides	Dawn redwood	a
Mimosa sp.	Sensitive plant (mimosa)	a
Morus sp.	Mulberry	c, d
Morus alba	White mulberry	a
Musineon divaricatum	Leafy wild parsley	a
Nicotiana alata	Jasmine tobacco	c
Nyssa sylvatica	Blackgum (tupelo)	a, b
Olea oleaster	Wild olive	c
Oxydendrum sp.	na	b
Panicum miliaceum	Common millet	c
Parrotia sp.	na	b
Paulownia tomentosa	Princess tree (paulownia)	a, c, d
Phalaenopsis sp.	Orchid, moth	a
Phaseolus sp.	Bean	a, c, d
Phaseolus lunatus	Lima bean	c, d
Phaseolus vulgaris	Kidney bean	c, d
Photinia (syn. Aronia) sp.	Chokeberry	a
Phytolacca americana	American pokeweed	a
Pistacia chinensis	Chinese pistache	a
Pisum sativum	Pea	c, d
Platanus occidentalis	American sycamore	a, d
Platycladus orientalis	Oriental arborvitae	c
Polygonum perfoliatum	Mile-a-minute weed	c
Populus tomentosa	Chinese white poplar	c
Prunus sp.	Cherry, plum	c
Prunus × incam	Flowering cherry	a
Prunus armeniaca	Apricot	a, c
Prunus avium	Sweet cherry	a
Prunus cerasifera	Cherry plum	a
Prunus domestica	Plum	d
Prunus grayana	Japanese bird cherry	c, d

Host species	Common name	Reference
Prunus incisa	Fuji cherry	a
Prunus laurocerasus	Cherry laurel	a
Prunus mume	Green plum	c
Prunus persica	Peach	a, c
Prunus pseudocerasus	Cambridge cherry	c, d
Prunus serotina	Black cherry	a, d
Prunus serrulata	Japanese flowering cherry	a
Prunus subhirtella	Winter-flowering (Higan) cherry	a
Pseudocydonia sinensis	Chinese-quince	a, b
Pueraria montana var. lobata	Kudzu	c
Punica granatum	Pomegranate	c
Pyracantha sp.	Firethorn	a, d
Pyracantha coccinea	Firethorn	d
Pyrus sp.	Pear	a, c
Pyrus calleryana	Callery (Bradford) pear	a
Pyrus fauriei	Korean sun pear	a, d
Pyrus pyrifolia	Chinese (Asian) pear	a
Quercus alba	White oak	a
Quercus coccinea	Scarlet oak	a
Quercus robur	English oak	a
Quercus rubra	Northern red oak	a
Rhamnus sp.	Buckthorn	d
Rhamnus cathartica	Common buckthorn	a
Rhodotypos scandens	Jetbead	d
Rhus sp.	Sumac	d
Rhus typhina	Staghorn sumac	c
Robinia pseudoacacia	Black locust	a, c
Rosa canina	Dog (native) rose	a
Rosa multiflora	Mulitflora rose	a
Rosa rugosa	Rugosa rose	a
Rubus sp.	Raspberry, blackberry	a, c
Rubus phoenicolasius	Wine raspberry (wineberry)	a, d
Salix sp.	Willow	a, d
Sambucus sp.	Elder	d
Sambucus racemosa	Red elderberry	c
Sassafras albidum	Sassafras	a
Secale cereale	Cereal rye	a
Setaria italica	Pearl millet	c
Sicyos angulatus	Bur cucumber	d
Solanum lycopersicum	Tomato	a, c, d
Solanum melongena	Eggplant	a, c
Solanum nigrum	Black nightshade	c
Sophora japonica	Japanese pagoda tree	a
Sophora japonica L. forma pendula	Weeping scholar tree	c
Sorbus sp.	Mountain ash	d

Host species	Common name	Reference
Sorbus airia	Winterbeam	a
Sorbus americana	American mountain ash	a
Sorghum bicolor	Sorghum	c
Spiraea sp.	Spirea	a, d
Stewartia koreana	Korean stewartia	a, d
Stewartia pseudocamellia	Japanese stewartia	a
Styrax japonicus	Japanese snowbell	a, b
Symphytum sp.	Comfrey	a, d
Syringa sp.	Lilac	c, d
Syringa pekinensis	Peking (Chinese) tree lilac	a
Taxus cuspidata	Japanese yew	c
Tetradium daniellii (syn. Euodia hupehensis)	Bee-bee tree (Korean euodia)	a
Tilia sp.	Basswood	d
Tilia americana	American basswood	a
Tilia cordata	Little leaf linden	a
Tilia tomentosa	Silver linden	a
Triticum aestivum	Wheat	c, d
Tropaeolum majus	Nasturtium	d
Tsuga canadensis	Eastern hemlock	a
Ulmus sp.	Elm	d
Ulmus americana	American elm	a
Ulmus parvifolia	Chinese elm	a
Ulmus pumila	Elm	c
Ulmus procera (syn. minor)	English (smooth leaf) elm	a
Vaccinium corymbosum	Highbush blueberry	a
Vibernum sp.	Viburnum	c, d
Viburnum × burkwoodii	Viburnum	a, d
Viburnum dilatatum	Linden arrowwood	a
Viburnum opulus var. americanum	Highbush cranberry	d
Viburnum prunifolium	Viburnum (blackhaw)	a
Viburnum setigerum	Tea viburnum	d
Vigna angularis	Azuki bean	c, d
Vigna sesquipedalis	Chinese long bean	c
Vigna unguiculata	Cowpea	c
Vitex negundo	Chinese chaste tree	c
Vitis riparia	Riverbank wild grape	a, d
Vitis vinifera	Wine grape	a, c
Weigela hortensis	Japanese weigela	c
Wisteria sinensis	Chinese wisteria	c
Zea mays	Corn (field and sweet corn)	a, c, d
Zelkova sp.	Japanese zelkova	c
Ziziphus jujube	Jujube	c
na	Chestnut	c
na	Pine	c
na	Arrowroot	c

Host species	Common name	Reference
na	Wax myrtle	c
na	Acacia	c
na	Alder	c
na	Cedar	c
na	Chinese milk vetch	c
na	Clover	c
na	Common mallow	c
na	Hairy vetch	c
na	Hollyhock	c
na	Strawberry	c
na	Tung	c

a Bergmann *et al.* (2015). **b** Bergmann *et al.* (2016). **c** Lee *et al.* (2013). **d** USDA-APHIS-PPQ (2010). **na** not available/ not provided.