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Enhancing early detection and monitoring of *Halyomorpha halys* (Stål 1855) (Hemiptera: Pentatomidae): field evaluation of a novel wind-orienting, pheromone-baited tunnel trap

Rachael Horner[*,1], **Gerardo Roselli**[2,3,4], **Raffaele Sasso**[5], **Gianfranco Anfora**[2], **and Massimo Cristofaro**[4]

[1]The New Zealand Institute for Plant and Food Research Limited, Christchurch, New Zealand
[2]Center of Agriculture, Food and Environment (C3A), University of Trento, San Michele all'Adige, Italy
[3]Technology Transfer Centre, Fondazione Edmund Mach, San Michele all'Adige, Italy
[4]Biotechnology and Biological Control Agency (BBCA Onlus), Rome, Italy
[5]ENEA, Casaccia Research Center, SSPT-BIOAG-SOQUAS Laboratory, Rome, Italy

*Corresponding author. The New Zealand Institute for Plant and Food Research Limited, Private Bag 4704, Christchurch 8140, New Zealand (Email: rachael.horner@plantandfood.co.nz).

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The brown marmorated stink bug (*Halyomorpha halys* (Stål, 1855); Hemiptera: Pentatomidae), commonly known as BMSB, is a highly invasive plant-feeding insect pest that poses a serious threat to the agriculture, environment, and economy of Australia, New Zealand, and beyond. Effective technologies for BMSB detection and delimitation during an incursion are crucial to support eradication efforts including for assessing control measures' efficacy. This study evaluated a wind-orienting, live-catch, pheromone-baited tunnel trap, designed for resilience to diverse weather conditions, ease of storage and transport, and discreet deployment in various habitats. Our field trials conducted in Italy between 2020 and 2022 across several commercial kiwifruit orchards and vineyards tested the tunnel trap against traditional Pherocon sticky panels and CYMA TRAP PRO pyramid traps. Utilizing a generalized linear mixed model with a negative binomial distribution, we analyzed trap efficacy in capturing adult BMSB. The tunnel trap demonstrated superior performance in consistently attracting more adult BMSB than other trap types. The increased catch of the tunnel traps highlighted their promise as a crucial tool for the early detection and control of BMSB populations.

Keywords: biosecurity, surveillance, brown marmorated stink bug, trap, aggregation pheromone

Introduction

The brown marmorated stink bug *Halyomorpha halys* (Stål 1855) (Hemiptera: Pentatomidae), or BMSB, is a highly invasive insect species, originally from East Asia (Lee et al. 2013), that has spread throughout Europe and the United States (Leskey and Nielsen 2018) and continues to spread into new territories (Cianferoni et al. 2018, Temreshev et al. 2018, Güncan and Gümüş 2019). BMSB is highly polyphagous, with over 300 host plants (Kriticos et al. 2017), including many fruit and vegetable crops of economic importance (Leskey and Nielsen 2018). If BMSB were to establish in New Zealand, it would have significant production impacts on several important export crops, including kiwifruit (Lara et al. 2018, Chen et al. 2020a) worth NZ$2.608 billion (United Fresh 2023), apples (Nielsen and Hamilton 2009) worth NZ$1 billion (United Fresh 2023), and wine grapes (Basnet et al. 2015) worth NZ$1.95 billion (United Fresh 2023) and would probably have an impact on New Zealand's native ecosystems (Teulon et al. 2019). At the time of this study, there was no evidence of the establishment of BMSB in New Zealand, but routine surveillance continues to be conducted throughout the country, particularly around high-risk border entry points such as ports and transitional facilities. There have been regular interceptions of live adult BMSB at the border since 2014 (Ormsby 2018). Based on interception data, inanimate objects imported from the Northern Hemisphere during the BMSB overwintering period remain the highest risk for aggregations of adult BMSB to arrive in New Zealand (Burne 2019).

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With a flight capacity greater than 5 km in 24 h (Wiman et al. 2015), winged adult BMSB possess a significant propensity to invade new regions, surpassing the egg or nymph stage in their potential for range expansion. Adults also overwinter in inanimate objects and structures (Inkley 2012, Malek et al. 2018), which encourages unintended cross-border migration with human assistance. Overwintering adults are primed for survival through harsh conditions and upon arrival in warmer temperatures and longer photoperiods, they emerge from overwintering with a need to feed and undergo gametogenesis before mating can occur (Nielsen et al. 2017).

Accidental incursion of BMSB into the Southern Hemisphere is expected by overwintering adults, owing to their greater tolerance for a wider range of climates than eggs and nymphs and their greater adaptability to environmental changes than eggs and nymphs, which need quick access to food sources and appropriate microclimates on arrival (Leskey and Nielsen 2018). Any eggs or nymphs arriving would probably arrive in Southern Hemisphere winter. For this reason, the focus of surveillance and requirements for importers is on adult BMSB.

The early season is a difficult time to capture adult BMSB but still has high risk of incursion. The difficulties are due to altered feeding and mate-searching behavior patterns and varied responses to pheromone lures, which we still do not fully understand (Leskey and Nielsen 2018). Furthermore, BMSB activity is generally reduced early in the season compared with later periods due to lower temperatures that suppress movement, thereby reducing the likelihood of adults encountering pheromone plumes emitted from traps (Nielsen et al. 2011, Lee and Leskey 2015). In addition, adult abundance is typically lower early in the season because this period includes only the overwintering generation prior to reproduction, and substantial mortality occurs during diapause. Consequently, effective early detection with pheromone traps depends on modifying trap placement and design to account for both reduced activity and lower population density during this period.

Pheromone trapping forms an important component of any surveillance and eradication program for any insect (Cohnstaedt et al. 2012). Additionally, effective trap design is necessary for pest monitoring and control as part of an integrated pest management (IPM) program (Morrison et al. 2015). A 2-part aggregation pheromone (Khrimian et al. 2014), combined with a synergist, forms the basis for pheromone lure surveillance for BMSB (Weber et al. 2014). Various trapping systems have been tested for IPM (Morrison et al. 2015, Rice et al. 2018), and surveillance of BMSB, with varied success (Acebes-Doria et al. 2018). The surveillance traps currently used in New Zealand are clear sticky panel traps (Vandervoet et al. 2019). These are low cost but may suffer from poor bug retention and loss of trap efficacy because of saturation by plant material or dust (Nixon et al. 2024). During an incursion or in the early establishment of BMSB, it will be vital to have effective tools for detection and delimitation to prevent spread.

Suckling et al. (2019a) developed an innovative trap, which, using a rudimentary prototype swiftly assembled from readily available materials, demonstrated a ~7-fold improvement in average trap catch over A4 sticky panel traps in a 14-d experiment. This aerodynamically designed trap is a live-catch, pheromone-baited cylinder trap with solid walls. It uses a wind vane to rotate on a string pivot. The upwind end is covered by a flat mesh panel and the downwind end is sealed by an entry-only mesh cone, admitting the attracted insects. The multimodal properties of the trap are what make it innovative. It combines visual cues (prominent black silhouette) with wide ranging olfactory stimuli (the presence of the aggregation pheromone and odors from trapped individuals, which are dispersed aerially in the environment because of the rotating trap design).

The tunnel trap has potential for both improved surveillance and delimitation of BMSB if an incursion were to occur, greatly increasing the likelihood of a successful eradication (Tobin et al. 2014). Additionally, a trap with increased sensitivity improves effective population monitoring and can support management options such as barrier trapping of BMSB in an IPM environment in commercial crops, as well as lure-and-kill, that is, mass trapping at low population densities (Suckling et al. 2019a).

An optimal surveillance trap for an insect that does not exhibit sensory overload (Baker and Roelofs 1981), such as BMSB should produce a high-integrity and high-concentration pheromone plume with a high air speed exiting the trap so that the plume tail is longer. The tunnel trap achieves this because the plume does not experience wind shear when the wind comes at a right angle to the plume (Chen et al. 2020b). Additionally, several important aspects must be considered to increase the likelihood that end-users (ie. government biosecurity departments and farmers) will use a particular monitoring trap. Firstly, it is imperative that the traps are not too costly, cumbersome, or difficult to put up. Furthermore, throughout the active growth period or biosecurity risk season, the trap should exhibit great efficiency, giving a precise indication of the presence or density of the population or the possible hazard to crops that are susceptible.

This paper reports the continued development and evaluation of a wind-oriented, live-capture tunnel trap for *H. halys*, with a focus on improving adult capture relative to existing commercially available traps. The specific objectives of the study were to: (i) evaluate whether a redesigned, flat-packed tunnel trap improves the capture of adult *H. halys* compared with standard sticky panel and pyramid traps (ii) test the consistency of trap performance across multiple agricultural environments and seasons where *H. halys* is established; and (iii) examine seasonal patterns in adult capture to inform the potential utility of the trap for early-season detection. Considerations relating to trap robustness, portability, and suitability for large-scale deployment are presented as design motivations and operational context rather than as experimental endpoints. Data on nymph capture were collected but are largely not reported here due to the focus on adult catch for surveillance by the flight-entry tunnel trap.

Materials and Methods

Tunnel Trap Description

The cylindrical trap body was made of a single sheet of 1-mm-thick black polypropylene and, although conceptually derived from the wind-oriented live-capture trap described by Suckling et al. (2019c), incorporated substantial structural modifications to enable standardized manufacture and replication. The original design was assembled from planter pots and mesh components joined by adhesive, whereas the trap used in this study was re-engineered as a flat-packed, 2-dimensional polypropylene sheet with integrated tabs and slots that could be assembled in situ into a cylindrical body,

Fig. 1. A 150-mm diameter, 300-mm long wind-orienting tunnel trap prototype for *Halyomorpha halys* constructed of 1-mm thick polypropylene, Corflute windvane and 2-mm plastic mesh with a hex bolt counterweight. The right image shows he entry only mesh-cone.

allowing consistent reproduction, compact transport, and scalable deployment. A wind vane, made of 3.3-mm wide Corflute, was slotted into the downwind end and the ends are closed off with 2-mm industrial-grade high-density polyethylene (HDPE) mesh made into the flat panel and entry-only mesh cone. The trap rotated around a string pivot, with the trap stabilized in the wind by a M20X40 hex head bolt-and-nut counterweight (Fig. 1). Several prototypes are described below. The final designs for the trap are provided in Supplementary Figs S1–S5.

Field Trap Prototyping and Assessment

Four experiments were conducted at locations in northern and central Italy in a variety of different habitats. All traps were evaluated for attraction and trapping of *H. halys*. All traps were baited with a high dose commercial lure (Trécé, Adair, OK, USA), which contained 20 mg of the 2-component aggregation pheromones (3S, 6S, 7R, and 10S)-10,11-epoxy-1-bisabolen-3-ol and (3R, 6S, 7R, and 10S)-10,11-epoxy-1-bisabolen-3-ol (Khrimian et al. 2014), plus 200 mg of the synergist methyl (E, E, Z)-2,4,6-decatrienoate (Weber et al. 2014). The lures were positioned on top of the sticky panels and pyramid traps, while in the wind-orienting traps the lure was hung ~20 cm from the flat-panel (upwind) end, inside the trap. Traps were hung from vegetation or orchard structures at approximately 1.5 m. Kirkpatrick et al. (2019) identified the plume reach of the BMSB pheromone to be <3 m from a standard loading lure on a sticky panel trap, but the maximum dispersive distance of adults at the border of an apple orchard (ie. maximum net distance most randomly dispersing insects displace from their point of origin) was found to be 70 m. Trap spacing was set at a minimum of 25 m for initial rapid prototyping, with 50 m trap spacing used in subsequent season-long trials to minimize plume overlap and behavioral interference.

Experiment 1

Eight replicates of each of 4 trap types were placed into blocked transects in the hedgerow located adjacent to 2 commercial vineyards with mixed grape varieties in Fondazione Edmund Mach, San Michele all'Adige (TN), Northern Italy (co-ordinates 46.189295, 11.137286). Traps were out for 2 mo, from 24 September 2020 to 11 November 2020. The 4 trap types were (i) 150-mm diameter prototype, (ii) 250-mm diameter prototype, (iii) ventilated 250-mm diameter prototype, and (iv) Pherocon sticky panels (Trécé, Adair, OK, USA). The 3 wind-orienting trap prototypes were all the same length, 600 mm, and had the same basic design, with 2 diameters tested. The ventilated trap had a network of holes at the downwind end to create a wider, but less concentrated plume. Traps were 25 m apart. Traps were checked and emptied every Monday, Wednesday, and Friday, for a total of 24 collections. The numbers of adults and nymphs inside each trap were counted. Vegetation beating of a 1.5-m radius was conducted (Vandervoet et al. 2019) and the numbers of bugs recorded separately. In the last 2 collections, no bugs were caught in any traps, so these data were excluded. For summary statistics and figures, counts were summed within week to give adults captured per trap per week.

Experiment 2

This experiment was conducted across several commercial kiwifruit orchards in the Lazio region of Central Italy. They were all in a small valley going from west to east, with the hills at the north and the Mediterranean Sea at the south-west. The first site was near the town of Campo Verde, the second near Cisterna di Latina, while the last 2 sites were close the town of Sermoneta (Table 1). Sites 1 and 2 were green-fleshed kiwifruit *Actinidia chinensis* var. *deliciosa* cultivars, with site 1 vines not yet at fruit production stage, and sites 3 and 4 were gold-fleshed kiwifruit *A. chinensis* var. *chinensis* cultivars. All sites selected were well managed and had a relatively low pest density compared with other kiwifruit orchards in the region. These sites were chosen to simulate, as far as possible, an early-establishment scenario in New Zealand because of low BMSB populations. The kiwifruit growers applied insecticides as part of their normal BMSB control practices. Ten replicates of 3 trap types were trialed: (i) the 150-mm diameter, 600-mm long tunnel trap as described above (used based on results of Experiment 1), (ii) the Pherocon sticky panels (Trécé, Adair, OK, USA), and (iii) the CYMA TRAP PRO pyramid trap (GEA, Settimo

Milanese, Italy) (Fig. 2). There was a maximum of 3 traps/2 ha and traps were placed at least 50 to 70 m apart along the orchard rows to prevent trap interference. Monitoring of the traps for BMSB occurred weekly and the traps were assessed for numbers of adult BMSB as well as nymph numbers. Foliage 1.5 m around each trap was monitored for adult bugs and nymphs that had not entered the trap. Traps at sites 1 and 2 were placed out from 17 August to 26 October 2021. Two sticky panel traps at Site 2 were removed prematurely on 14 September and 5 October, and traps at Sites 3 and 4 were deployed from 17 August to 14 September, all due to excessive fruit drop that threatened commercial production.

Experiment 3

Experiment 3 was conducted in commercial kiwifruit orchards from 10 May 2022 to 8 November 2022. We trialed 2 trap types to obtain season-long phenology data with the tunnel trap, including early in the BMSB flight season, across 4 sites (Table 1). Site 1 had continuous temporal coverage across all sampling periods so seasonal effects were interpreted primarily using data from this site (14 traps). Sites 2 to 4, which had more limited temporal coverage, were used mainly to inform comparisons of relative trap type performance across the season. The season was split up into 3 sampling periods: early (10 May to 15 June), mid (16 June to 25 August), and late (26 August to 8 November). Two trap types were trialed: 150-mm diameter, 600-mm long tunnel trap as described above, and the CYMA TRAP PRO pyramid trap (GEA, Settimo Milanese, Italy). There were 17 replicates of each trap, with one of each trap type per replicate. There was a maximum of 3 traps/2 ha and traps were placed at least 50 m apart along the orchard rows to prevent trap interference. Monitoring of the traps for BMSB occurred weekly and the traps were assessed for numbers of adult BMSB as well as nymph numbers. Foliage 1.5 m around each trap was monitored for adult bugs and nymphs that had not entered the trap.

Table 1. Details and locations of the Italian kiwifruit orchards used in field trials (2021 to 2022)

Year	Site number	Coordinates	Trial area (ha)	No. of traps (reps)
2021	1	41.5694, 12.7808	6	9 (3)
2021	2	41.5694, 12.8569	9	12 (4)
2021	3	41.5461, 12.9294	2	3 (1)
2021	4	41.5289, 12.9717	4	6 (2)
2022	1	41.5694, 12.7808	6	14 (7)
2022	2	41.5694, 12.8569	9	8 (4)
2022	3	41.6427, 12.8173	2	4 (2)
2022	4	41.5903, 12.8968	4	8 (4)

Sites 1 and 2 were used in the same orchards in both years, whereas sites 3 and 4 were located in different orchards in 2021 and 2022 within the same production region.

Experiment 4

This experiment focused on simplifying the mounting system for the tunnel trap and assessing whether a reduction in trap length affected capture efficiency. In previous experiments, traps were suspended from overhead structures (eg. tree branches or support wires) using a string, allowing free orientation into the wind. Where no suitable structure was available, traps were mounted using a “gallows” system, that being an overhead horizontal arm supported by a vertical post, which allows the trap to hang freely but requires additional hardware and installation time.

To simplify deployment, we developed and tested a single-post ground-mounted system, in which the trap is mounted directly on top of a vertical post and allowed to rotate freely around its vertical axis. Wind tunnel testing showed that the single-post system required a minimum wind speed of approximately 1 to 1.5 m/s to orient correctly into the wind, whereas a string-suspended trap oriented reliably at wind speeds below 0.3 m/s. Because fewer than 10% of adult *H. halys* initiate flight at wind speeds exceeding 0.75 m/s (Lee and Leskey 2015), correct orientation at low wind speeds is critical for effective trap performance in surveillance contexts.

To improve low-speed orientation, we aimed to reduce the aerodynamic resistance of the trap by halving its length and reducing the counterweight required for stabilization. However, wind tunnel testing demonstrated that removal of the counterweight, even with the shorter trap, prevented correct orientation, as the surface area of the trap body itself acted as a wind vane, causing the trap to align perpendicular to the wind. Despite this limitation, reducing trap length remained desirable for cost, portability, and concealment, and we therefore tested whether trap length alone influenced capture efficiency under field conditions.

Fig. 2. The 3 *Halyomorpha halys* trap types assessed for use in monitoring populations in commercial Italian kiwifruit orchards. Left to right: Pyramid trap, tunnel trap, sticky panel trap.

Field trials were conducted at Fondazione Edmund Mach, San Michele all'Adige (TN), northern Italy, between 2 and 16 September 2022. Two trap lengths were tested: 600 mm (standard design) and 300 mm (reduced-length design), both with a diameter of 150 mm. All traps shared the same basic design and lure configuration; the only differences were trap length and counterweight mass, with the 300-mm trap fitted with a proportionally reduced counterweight. All traps were deployed using string suspension from existing vegetation, rather than the single-post system, to ensure traps were orienting at low wind speeds.

Traps were arranged in five blocked transects along a sloping forest margin adjacent to vineyards of mixed grape varieties, with a minimum spacing of 25 m between traps. Traps were checked and emptied every Monday, Wednesday, and Friday for a total of 7 collection events. At each check, the number of adults and nymphs inside each trap was recorded, along with the number of adults present on the exterior of the trap.

Statistical Methods

All analyses were conducted in R version 4.3.1 (R Core Team 2024). General statistical methods were similar across all 4 experiments. Where appropriate, model structure differed slightly among experiments to reflect differences in experimental design (eg. variable deployment duration). To assess how well distinct types of traps caught adult insects on different dates, blocks and sites, we used a generalized linear mixed model (GLMM) with a negative binomial distribution. This method routinely yielded a more accurate model fit than a Poisson distribution, since it took into account the count nature of our data and addressed observed overdispersion. The model is given as $\mathrm{Count}_{\mathrm{adults}} \sim \mathrm{NegativeBinomial}(..,,)$ where μ represents the mean count of adults captured, and θ represents the dispersion parameter of the negative binomial distribution. To evaluate the effect of trap type on adult catch, this was treated as a fixed factor. Random intercepts were incorporated for block, date and site, to take within-group correlation and temporal variability into consideration. In Experiment 3, for comparisons of relative trap effectiveness, models were fitted using data from all sites. Seasonal effects were evaluated primarily using data from site 1 only, which had continuous temporal coverage across all sampling periods. The glmmTMB package in R was used for the analysis (Brooks et al. 2017). It provided strong modelling capacities for ecological count data, including the ability to handle zero-inflation and overdispersion. The Akaike information criterion (AIC), the Bayesian information criterion (BIC), and log-likelihood values were used to assess the model fit. By looking at the dispersion parameter supplied by the negative binomial model, overdispersion was evaluated. Following the fitting and validation of the model, *post hoc* comparisons were performed using the "emmeans" package (Lenth 2023) with Tukey-adjusted pairwise comparisons to identify significant differences between the trap types.

Results

Experiment 1

Significant differences in adult catch between the various types of traps were shown by the model. The comparisons, adjusted for multiple testing via Tukey's method, revealed no significant differences in mean weekly adult catch between the 3 tunnel trap prototypes (150-mm, 250-mm, and vented 250-mm diameter traps), which indicated similar degrees of effectiveness among these traps (all $P > 0.59$) (Fig. 3).

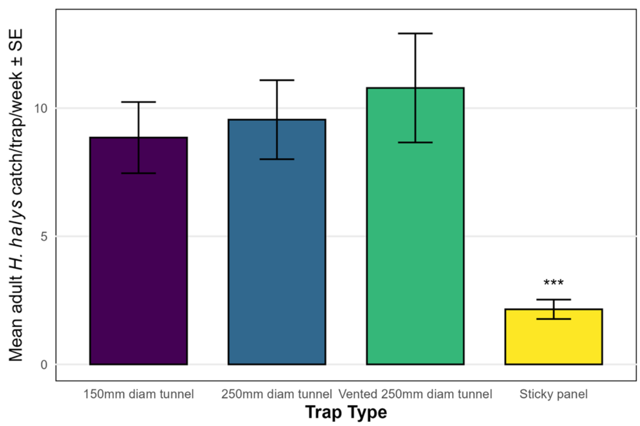

Fig. 3. Mean (±SE) catch per trap per week of adult *Halyomorpha halys*, brown marmorated stink bug (BMSB), adults in 4 trap prototypes ($n = 8$) operated at the forest-vineyard margin in San Michele all'Adige, Italy, for 2 mo from September to November 2020. ***Denotes significant difference at $P < 0.001$.

On the log scale, the estimated difference between sticky panel traps and tunnel traps was -1.37 ± 0.18 ($z = -7.58$, $P < 0.001$), corresponding to substantially lower expected weekly catches for sticky panels. Estimated mean weekly adult catch per trap was 3.7, 4.0, and 4.5 adults for the 150-mm, 250-mm, and vented 250-mm tunnel trap prototypes, respectively, compared with 0.9 adults for sticky panel traps.

Substantial variability in catch was associated with week (variance = 4.12) and block (variance = 0.17). Over 22 collection periods for 32 traps, on 117/176 occasions, sticky panel traps caught zero adults. This contrasted to 68/176, 60/176, and 52/176 occasions for the 150-mm, 250-mm, and vented 250-mm prototypes, respectively.

Experiment 2

All 3 trap types were successful at catching adult BMSB at all 4 sites (Fig. 4). Adult captures are reported as numbers of adults per trap per week. Trap type had a significant effect on adult captures. On the log scale, tunnel traps captured significantly more adults than pyramid traps (estimate = -1.66 ± 0.20, $z = -8.48$, $P < 0.001$) and sticky panel traps (estimate = -2.45 ± 0.23, $z = -10.91$, $P < 0.001$). Pyramid traps also captured significantly more adults than sticky panel traps ($z = 3.61$, $P < 0.001$). Estimated marginal means (EMMs) on the log scale were highest for tunnel traps (3.17, 95% confidence interval [CI]: 2.66 to 3.69), followed by pyramid traps (1.52, 95% CI: 1.00 to 2.03) and sticky panel traps (0.72, 95% CI: 0.21 to 1.24). Weekly adult captures varied over the sampling period; however, tunnel traps consistently captured more adults than sticky panel traps across most weeks. The maximum number of adult bugs caught by a single trap in a single week was 230 for the tunnel trap, 29 for the pyramid trap and 12 for the sticky panel trap.

Numbers of BMSB nymphs captured in pyramid traps were significantly greater than those in tunnel traps and sticky traps at all 4 orchards (estimate = 1.88 ± 0.37, $z = 5.12$, $P < 0.001$) (Fig. 5). There was no significant difference in nymph catch between sticky panel and tunnel traps. At site 2, where the

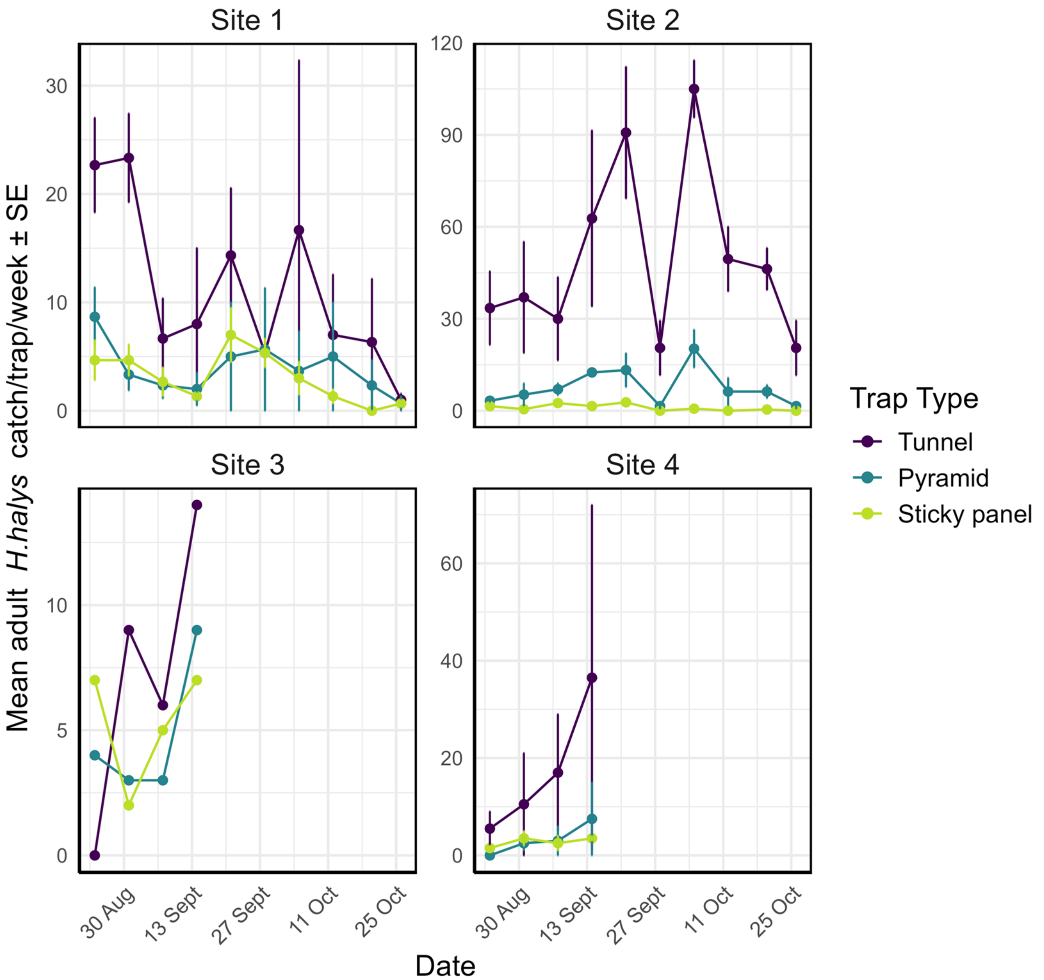

Fig. 4. Brown marmorated stink bug, *Halyomorpha halys* (BMSB), adult captures in tunnel ($n = 17$), pyramid ($n = 17$), and sticky panel traps ($n = 17$) across 4 Italian kiwifruit orchards per week. Traps were out in site 1 and site 2 orchards for 10 wks, while traps in site 3 and site 4 were out for 4 wks in 2021.

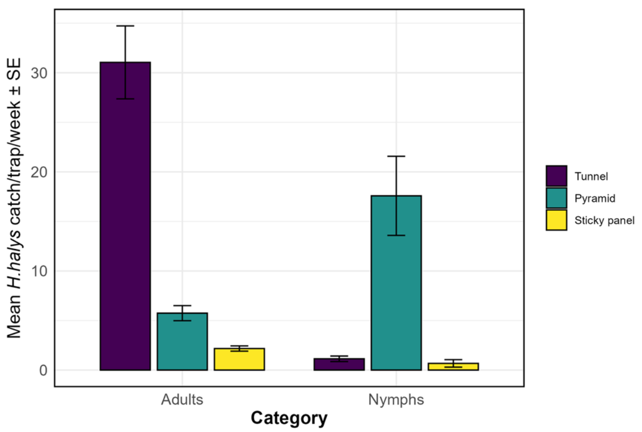

Fig. 5. Brown marmorated stink bug, *Halyomorpha halys* (BMSB), adult and nymph captures per trap in tunnel, pyramid, and sticky panel traps across 4 Italian kiwifruit orchards. Traps were out in site 1 and site 2 orchards for 10 wks, while traps in site 3 and site 4 were out for 4 wks in 2021.

BMSB population densities were the highest, a much greater number of adult bugs were found in the 1.5-m radius surrounding the tunnel trap than in the areas surrounding the sticky panel or pyramid traps (Table 2). A similar pattern was observed at site 1, although overall numbers were lower. Across the 4 wks that beating was carried out across the 4 replicates within site 2, the tunnel trap had a mean number of bugs in a 1.5-m vicinity of 6.8 bugs per trap per week, while the pyramid trap had 2.6 bugs per trap per week and the sticky panel trap had 4.9 bugs per trap per week. Nymphs were recorded infrequently in tunnel traps but were detected during foliage sampling around all trap types.

Table 2. Mean numbers of adult and nymph brown marmorated stink bug, *Halyomorpha halys*, found in a 1.5-m vicinity around traps in 2 Italian kiwifruit orchards per trap per week in 2021

	Site 1		Site 2	
	Adults	Nymphs	Adults	Nymphs
Pyramid	0.06	1.63	2.63	2.88
Sticky	0.81	6.9	4.88	7.9
Tunnel	1.06	7.9	6.78	13.85

Experiment 3

At site 1, which had continuous temporal coverage across all sampling periods, trap type had a strong effect on adult *H. halys* captures. Tunnel traps captured significantly more adults per trap per week than pyramid traps in all parts of the season. In the early season, tunnel traps captured a mean of 6.5 adults

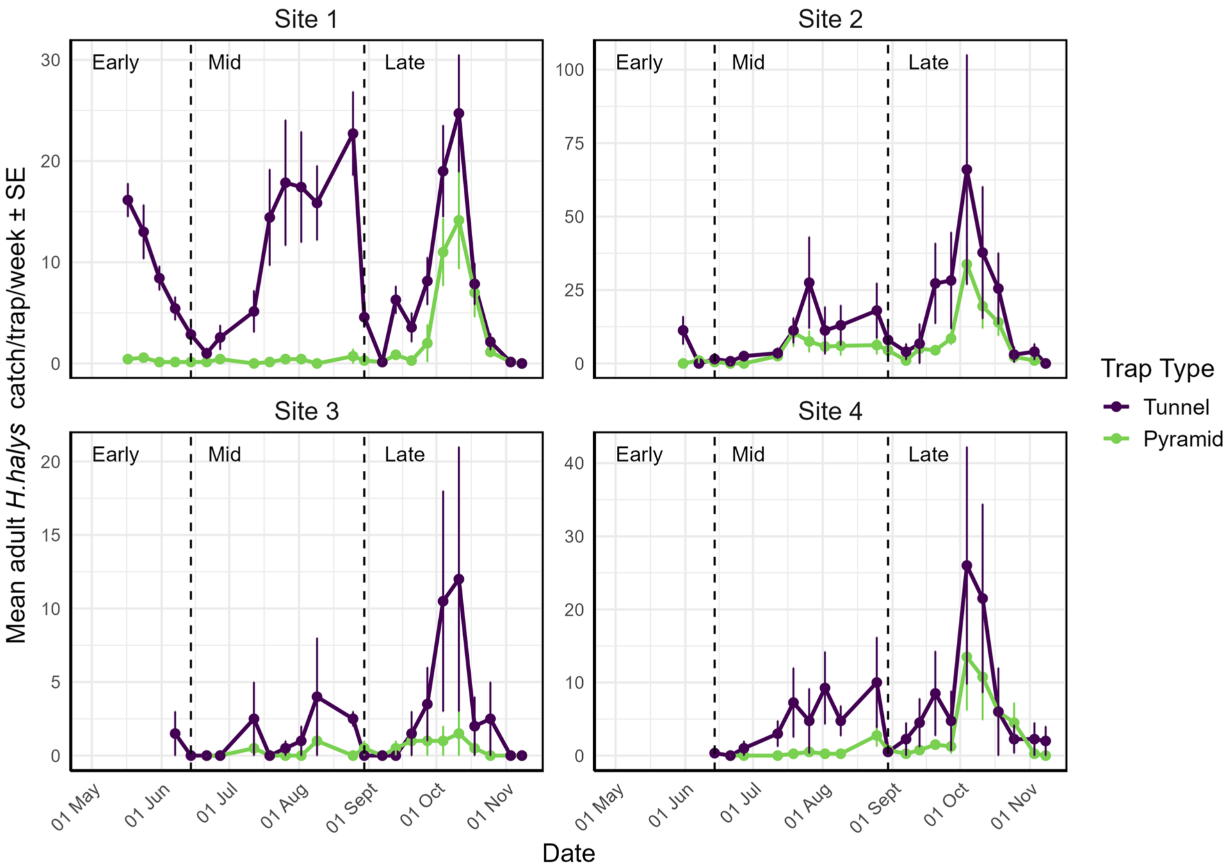

Fig. 6. Brown marmorated stink bug, *Halyomorpha halys* (BMSB), adult captures in pyramid ($n = 17$), and tunnel traps ($n = 17$) across 4 Italian kiwifruit orchards. In site 1, traps were placed out from 10 May to 8 November 2022, and were placed out from 24 May in site 2, 31 May in site 3, and 7 June in site 4. Vertical dashed lines indicate early, mid and late season demarcations. The season was split up into 3 sampling periods: early (10 May to 15 June), mid (16 June to 25 August), and late (26 August to 8 November).

per trap per week (95% CI: 4.0 to 10.5), compared with 0.8 adults per trap per week (95% CI: 0.4 to 1.4) in pyramid traps. Similar patterns were observed in the mid-season (7.9 vs. 0.9 adults per trap per week) and late season (15.6 vs. 1.9 adults per trap per week). Within-season contrasts confirmed that tunnel traps outperformed pyramid traps in the early, mid, and late seasons (all $z = -7.71$, $P < 0.0001$). Adult captures at site 1 increased later in the season, with significantly higher weekly catches in the late season compared with the early season, whereas captures did not differ significantly between early and mid-season (Fig. 6).

When data from all 4 sites were pooled, trap type remained a significant predictor of adult *H. halys* captures. Across all sites and sampling dates, tunnel traps captured significantly more adults per trap per week than pyramid traps (GLMM, negative binomial; $z = -2.60$, $P = 0.009$). EMMs indicated that tunnel traps captured a mean of 4.98 adults per trap per week (95% CI: 2.41 to 10.31), compared with 1.65 adults per trap per week (95% CI: 0.79 to 3.44) in pyramid traps, confirming higher overall capture effectiveness of tunnel traps across the study region (Fig. 6). The observed increase in captures later in the season likely reflects increasing adult availability and/or seasonal changes in responsiveness to aggregation pheromone during late-season dispersal, rather than changes in intrinsic trap performance. Importantly, tunnel traps remained consistently more effective than pyramid traps throughout the season at both site 1 and across all sites.

Experiment 4

Trap length did not significantly affect adult *H. halys* captures (estimate = 0.24 ± 0.18 SE, $z = 1.31$, $P = 0.19$). Short traps captured more adults (mean ± SE: 5.3 ± 1.2; $n = 105$) than long traps (4.1 ± 1.5; $n = 105$), but the difference was not statistically significant (estimate = 0.24 ± 0.18 on the log scale). The model accounted for spatial and temporal variation with random intercepts for block and date. The estimated variance for block was 0.10 (SD = 0.32), and for date was 0.13 (SD = 0.36), indicating that variability in captures was present across locations and sampling dates.

Discussion

Our research indicates that the tunnel trap is a highly effective tool for surveillance and delimitation of BMSB in the event of an incursion. In comparison to pyramid traps and sticky panel traps, the tunnel trap consistently captured more adult bugs, offering superior results. Although these trials were conducted in regions where *H. halys* is well established, the comparative design allowed a robust assessment of relative trap performance; however, absolute capture rates should not be extrapolated directly to early incursion conditions. In this study, "early detection" is interpreted as improving the probability of detecting low-density adult populations during surveillance or incursion responses, rather than replicating pre-establishment conditions in the field. In a surveillance context, tunnel traps would be most appropriately deployed at high-risk entry points such as ports, transitional facilities, freight hubs, and peri-urban host vegetation, to maximize detection probability. These traps, aimed at better surveillance, are currently under trial in high-risk sites near ports and transitional facilities in Australia and New Zealand.

Although the tunnel traps captured significantly more adult bugs, some insects were still discovered on or near the trap. The tunnel traps had the highest number of adults and nymphs in the vicinity that were not entering the trap. However, when considering that the tunnel traps caught more bugs overall, they were probably drawing more bugs into the area by having a larger plume reach. To date, the only empirical assessment of the active space of a *H. halys* aggregation pheromone trap was conducted by Kirkpatrick et al. (2019), who estimated plume reach to be less than 3 m using a standard lure and a sticky panel trap. Whether plume structure or reach differs under alternative trap designs or lure dosages remains unknown, though we suspect the unidirectional plume is likely to increase the effective sample area of the trap. We have previously modelled the dispersion of pheromones from the tunnel trap and found that it produces a more concentrated plume that travels further, without susceptibility to plume degradation caused by cross-winds, unlike the sticky panel trap (Chen et al. 2020b). This creates a less diffuse signal for insects to follow, increasing their chances of reaching the source. Repeating the experimental approach of Kirkpatrick et al. (2019) using the tunnel trap, and across a range of lure doses, would be valuable for quantifying differences in plume reach and active space among trap designs. The idea of exploiting plume structure is broadly applicable and could lead to improved catches of various lures and insects. This has been demonstrated historically in Lepidoptera (Lewis and Macaulay 1976, Angerilli and McLean 1984), but not in other insect groups.

The aggregation pheromones present in the lure attract BMSB to the area but not necessarily to the trap itself. Morrison et al. (2016) noted that these pheromones trigger an "attract and arrest" response in BMSB, causing bugs to typically congregate within 2.5 m of the stimulus. In situations where accurate population numbers are required, or for surveillance purposes, visual inspections and beating of vegetation around the trap may still be necessary, regardless of the efficacy of the trap. Recent studies conducted in Italy have demonstrated that female vibrational signals significantly increase both male and female attraction to the point source and have a powerful loitering effect on searching males, suggesting that this behavior could be used to enhance pheromone traps (Mazzoni et al. 2017, Caorsi et al. 2021, Zapponi et al. 2023). However, surveillance traps for biosecurity are often in public areas, and theft and vandalism are major issues for traps with electronic componentry and/or solar panels and batteries.

The pyramid trap outperformed the tunnel traps in capturing nymphs. This pattern is consistent with the limited mobility of nymphal stages, which are incapable of flight and move primarily by crawling. Nymphs can readily crawl up the sloped surfaces of pyramid traps and enter the collection chamber, whereas access to tunnel traps requires nymphs to traverse the suspension string, a narrow and infrequently used pathway from the canopy. Additionally, *H. halys* nymphs have a natural tendency to climb up (not down) vertical surfaces, showing negative gravitaxis in behavioral trials (Chambers et al. 2020), further limiting their likelihood of entering tunnel traps. Interestingly, a substantial numbers of nymphs were detected in the vicinity of pyramid traps, a further example of "arresting behavior," further solidifying the necessity for beating, regardless of trap type.

From a biosecurity perspective, the tunnel trap's bias towards adult capture is appropriate, as postborder incursions of *H. halys* are dominated by overwintering adults, reflecting the species' overwintering behavior in imported goods, rather than eggs or nymphs. Consequently, surveillance strategies prioritizing adult detection remain fit for purpose, even if trap designs differ in their ability to sample immature stages. Nevertheless, the complementary strengths of pyramid and tunnel traps suggest that their combined use, either spatially or temporally, may enhance detection and removal across life stages and improve mapping of pest distribution within landscapes in both a surveillance and IPM setting. Such an approach could also contribute to limiting pest dispersal or establishing trap-based barriers. Incorporating kill strips or insecticide-impregnated netting may further extend this strategy to a "lure-and-kill" approach targeting both adults and nymphs, although the efficacy of these methods requires further evaluation (Suckling et al. 2019b).

Tunnel traps have shown higher efficacy than pyramid traps in capturing adult BMSB early in the season. However, inference about very early-season trap performance is limited by the timing of trap deployment. Traps deployed from May onwards captured a proportion of post-overwintering adults (Francati et al. 2021), but earlier deployment would be required to fully assess trap performance immediately following emergence.

This study used a high-load lure to maximize trap catches and enable robust comparison of trap performance under field conditions; however, implications for operational use must consider cost and scalability. Standard commercially available BMSB lures are widely used for routine monitoring, and field studies have shown that although higher-dose lures increase absolute catch, trap performance using low- and high-load lures is strongly correlated across sites and seasons (Acebes-Doria et al. 2018). Consequently, standard lures are likely sufficient for routine monitoring, whereas higher lure loadings are most appropriate for targeted early detection or delimitation during biosecurity surveillance. The tunnel trap design tested here is fully compatible with standard lures, allowing flexible deployment across both surveillance and IPM programs, although further work is needed to evaluate performance at lower loading rates.

We have shown that the use of a wind-orienting tunnel trap provides superior catch of adult *H. halys* compared to current methods. The tunnel trap could be a highly effective tool for surveillance and delimitation of BMSB in the event of an incursion into New Zealand or in other territories working to prevent establishment of this pest. The tunnel trap could be used not only for surveillance trapping, but also for pest monitoring in an IPM setting. The trap strikes a balance between operational efficiency and efficacy, which helps to build integrated pest control strategies that aim to reduce the danger posed by BMSB while promoting sustainable agricultural practices.

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Author Contributions

Rachael Horner (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Validation [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), Gerardo Roselli (Data curation [equal], Investigation [equal], Methodology [equal], Writing—review & editing [equal]), Raffaele Sasso (Data curation [equal], Investigation [equal], Methodology [equal], Writing—review & editing [equal]), Gianfranco Anfora (Methodology [equal], Writing—review & editing [equal]), and Massimo Cristofaro (Data curation [equal], Investigation [equal], Methodology [equal], Writing—review & editing [equal])

Supplementary Material

Supplementary material is available at *Journal of Economic Entomology* online.

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Conflicts of Interest

None declared.

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