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Enhancing our biocontrol preparedness for brown marmorated stink bug: Targeted survey of stink bug egg parasitoids

Avila G, Lima B, Chhagan A, Santos K, MacDonald F, Hunt S, Taylor T, Rowe C, Stannard K, Rogers P, Wallis R, Lopez P, Guo L

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The brown marmorated stink bug (BMSB), *Halyomorpha halys* Stål (Hemiptera: Pentatomidae), is one of the most invasive and economically damaging agricultural pests worldwide. Since its accidental spread from East Asia to North America and Europe, it has caused severe losses in fruit, nut, and vegetable production and disrupted international trade. The pest is still continuously spreading worldwide, and its presence was confirmed in Chile (South America) in 2017 and Argentina in early 2025. In New Zealand, BMSB has been repeatedly intercepted at the border and is listed as a major threat to the country's agricultural and horticultural industries.

Because BMSB are highly mobile, polyphagous, and difficult to control with insecticides, biological control has emerged globally as the most sustainable long-term management strategy. In its native range, the pest is naturally regulated by scelionid egg parasitoids, primarily *Trissolcus japonicus*, and in its adventive range, by both *T. japonicus* and *T. mitsukurii*. These two egg parasitoid species, since they have been established adventively, now play a major role in the suppression of BMSB. In contrast, native parasitoids in North America and Europe have shown limited ability to complete development in BMSB eggs, although they may still contribute to pest mortality through unsuccessful attacks that cause egg abortion or developmental arrest. These "hidden" non-reproductive effects can substantially increase total host mortality, though they often go unrecorded because aborted eggs appear unhatched. Therefore, understanding the diversity and potential impact of local parasitoids is critical for assessing both New Zealand's natural biocontrol readiness to suppress BMSB and the likely outcomes of future classical biological control introductions.

To address these needs, a three-year project (2022–25) was undertaken to characterise the community of native and adventive stink bug egg parasitoids in New Zealand and to evaluate their potential to interact with BMSB. The study formed part of New Zealand's pre-emptive biological control programme for BMSB, and its objectives were to a) establish a national baseline of abundance and diversity of egg parasitoids of stink bug species which may contribute to a future biocontrol programme against BMSB, and b) assess whether *T. mitsukurii,* a key parasitoid for BMSB, is already present.

Field surveys of egg parasitoids of stink bugs were conducted over three consecutive summers across five major regions in New Zealand: Auckland, Waikato, Bay of Plenty, Hawke's Bay, and Nelson/Marlborough. Sentinel egg masses of different resident stink bug species were deployed monthly between November and March at different sites within each region, complemented by the collection of naturally laid egg masses from the field. All recovered egg masses were maintained under controlled conditions to record parasitism and parasitoid emergence.

In addition to the field component, laboratory host testing was conducted in Italy and Switzerland in May–June 2025 to evaluate whether three native scelionid parasitoids recovered from field surveys (*Trissolcus oenone*, an undescribed *Trissolcus* species, and an undescribed *Telenomus* species) could parasitise BMSB eggs. Conventional no-choice oviposition assays were used to measure both reproductive parasitism (successful emergence) and non-reproductive effects (egg mortality without parasitoid emergence).

Across the three survey seasons, more than 120,000 sentinel eggs and over 5,000 naturally laid eggs were examined. Parasitism of sentinel eggs was relatively low, ranging from 3% to 9% across the three survey seasons, but when parasitism occurred, it was typically intense within each egg mass, with 65–96% of eggs parasitised and 58–82% emergence success. In contrast, naturally laid egg masses experienced much higher parasitism, between 41% and 65%, with similarly high emergence rates of 70–84%. Parasitism consistently peaked in January across all regions and years, reflecting seasonal host availability and favourable summer temperatures. Although the regional differences were not statistically significant, slightly higher rates were observed in Auckland and Waikato, suggesting that warmer northern conditions may enhance parasitoid activity.

Four parasitoid and one hyperparasitoid species were recorded during the surveys: *Trissolcus oenone*, *T. basalis*, an undescribed *Trissolcus* sp., an undescribed *Telenomus* sp., and the hyperparasitoid *Acroclisoides* sp. Among these, *T. oenone* was dominant and widespread across all regions, followed by *T. basalis*, a species historically used as a classical biocontrol agent against the cosmopolitan pentatomid pest *Nezara viridula* Linnaeus. The observation of two undescribed scelionids is a breakthrough in this project, as they represent new records to science and for New Zealand, and may reflect previously uncollected endemic diversity. The adventive Asian parasitoid *T. mitsukurii*, which is present in Australia, was not detected in any samples, indicating that it has not yet naturally colonised New Zealand.

The laboratory component provided additional insights into the potential functional response of native parasitoids to BMSB. When exposed to BMSB eggs, *T. oenone*, *Telenomus* sp., and *Trissolcus* rarely produced viable offspring, with emergence rates below 0.5%. However, *T. oenone* and *Telenomus* sp. significantly increased egg mortality to 37% and 30%, respectively, compared with 20% in untreated controls, suggesting that parasitoid attack alone was sufficient to kill many eggs, even in the absence of development. These findings align with international evidence that parasitoid-induced egg abortion is a major, yet often overlooked, component of pest mortality. Comparable hidden mortality has been documented for native scelionids attacking BMSB eggs in North America and Europe and for non-target hosts exposed to *T. japonicus* in Europe.

Collectively, these results provide a detailed picture of the composition and function of the scelionid parasitoid community in New Zealand. The dominance of *T. oenone* and *T. basalis* across diverse habitats indicates well-established and ecologically versatile populations capable of exploiting a range of pentatomid hosts. The presence of previously undescribed species adds to New Zealand’s known biodiversity and highlights the need for continued taxonomic and molecular work to describe these new parasitoids to the species level. According to data gathered from naturally laid egg masses collected during the field surveys, parasitism rates in native hosts were high, suggesting that the local parasitoid guild is active and effective within the ecosystem. Although laboratory assays have shown that native species are unlikely to develop successfully within BMSB eggs, their capacity to cause substantial non-reproductive mortality indicates their potential to contribute indirectly to pest suppression should BMSB be established in New Zealand.

The implications of these findings are paramount for future development, planning, and implementation of a biological control programme against BMSB in New Zealand. They demonstrate that while New Zealand’s native parasitoids are unlikely to serve as primary control agents for BMSB, they could play a complementary role alongside an introduced specialist such as *T. japonicus*. This additive effect could enhance overall egg mortality, particularly if native species attack eggs not parasitised by the specialist or impose additional mortality through egg abortion.

The project also identified key methodological and knowledge gaps. Field surveys using sentinel eggs may underestimate natural parasitism because laboratory-reared eggs lack natural semiochemical cues. Molecular tools capable of detecting parasitoid DNA in unhatched eggs would enable more accurate quantification of hidden mortality and total impact. Additionally, semi-field or large-arena laboratory studies under more realistic environmental conditions (e.g. mesh cages with potted plants and hosts) are needed to better assess host acceptance and competitive interactions between native and exotic parasitoids.

In conclusion, this study provides the first nationwide baseline for stink bug egg parasitoids in New Zealand and a detailed assessment of their biocontrol potential against BMSB. Field surveys revealed a scelionid community dominated by *Trissolcus oenone*, while laboratory testing demonstrated that native species can significantly increase BMSB egg mortality, even without successful parasitism. These findings highlight that New Zealand already possesses a functionally active parasitoid guild that could complement future biological control efforts. Continued monitoring, molecular characterisation, and additional host-specificity testing (e.g. using mesh cage large arenas) will be essential to strengthen the country’s readiness for a possible BMSB incursion. Overall, the results provide robust evidence that agroecosystems in New Zealand are ecologically equipped to meaningfully contribute to integrated pest management should this globally significant pest arrive.

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Introduction

Halyomorpha halys Stål (Hemiptera: Pentatomidae), the brown marmorated stink bug (BMSB), is a highly invasive polyphagous pest native to China, Japan, and Korea (Lee et al. 2013). Recognised as one of the world's most serious insect biosecurity threats, BMSB has established in North America (USA, Canada), most of Europe including Russia, and more recently in Chile and Argentina (Leskey et al. 2012; Haye et al. 2015a; Gapon 2016; Faúndez & Rider 2017; Faúndez et al. 2024).

BMSB feeds on more than 300 plant species worldwide, causing severe damage to numerous economically important crops, including vegetables, fruit, and ornamentals (Lee et al. 2013; Rice et al. 2014; Bergmann et al. 2016; Leskey & Nielsen 2018). Both adults and nymphs feed by piercing plant tissues, leading to fruit deformation, internal damage, and abscission of flowers, buds, and fruit (Rice et al. 2014; Leskey & Nielsen 2018). For instance, in sweet corn, feeding results in aborted or discoloured kernels (Rice et al. 2014), whereas in kiwifruit, it can cause suberised internal tissues and fruit abortion (Lara et al. 2018). Owing to its broad host range, BMSB poses a significant economic threat to New Zealand's multi-billion-dollar fresh produce industry, including kiwifruit, apples, and summer fruit.

Although not yet present in New Zealand, frequent border interceptions indicate a high risk of introduction (Burne 2019). Therefore, a proactive strategy is essential to prevent establishment, safeguard export markets, and avoid reliance on chemical control. If BMSB were to establish and eradication proved unfeasible, long-term area-wide management would be required. Under both BMSB incursion and establishment scenarios, classical biological control represents a key strategy for achieving sustainable and cost-effective suppression.

In both its native and adventive ranges, BMSB is attacked by various natural enemies, including predators, dipteran parasitoids, and hymenopteran egg parasitoids (Haye et al. 2015b; Herlihy et al. 2016; Zhang et al. 2017; Pezzini et al. 2018; Chen et al. 2020). In Asia, eggs are parasitised mainly by species in the genera *Trissolcus*, *Telenomus*, *Anastatus*, *Ooencyrtus*, and *Acroclisoides* (Yang et al. 2009; Zhang et al. 2017). Among these, *Trissolcus japonicus* Ashmead (Hymenoptera: Scelionidae) and *T. mitsukurii* (Ashmead) (Hymenoptera: Scelionidae) are considered as the most promising natural enemies for classical biocontrol of BMSB (Hedstrom et al. 2017; Zhang et al. 2017; Bout et al. 2021; Moraglio et al. 2021).

Adventive populations of *T. japonicus* have been discovered in the USA, Canada, Switzerland, and Italy (Talamas et al. 2015; Milnes et al. 2016; Sabbatini-Peverieri et al. 2018; Abram et al. 2019; Stahl et al. 2019), prompting the initiation of classical biocontrol programmes in these regions. Rearing and redistribution are now underway in several US states, Canada, and Italy, where official releases began in 2020 (Sabbatini-Peverieri et al. 2020). Similarly, in Europe, adventive populations *T. mitsukurii* were reported for the first time in 2018 (Sabbatini et al. 2018), and since then research has been conducted to assess its role as a biocontrol agent of BMSB in its adventive range (Moraglio et al. 2020, 2021; Scaccini et al. 2020; Mele et al. 2025).

Native scelionid parasitoids in invaded regions typically exhibit low reproductive success on BMSB eggs, although they may contribute to background mortality through aborted or unsuccessful parasitism (Haye et al. 2015b; Abram et al. 2017). These "hidden" non-reproductive effects—egg mortality caused by parasitoid probing or oviposition without emergence—can add substantially to total host mortality and have important ecological implications (Abram et al. 2016; Kaser et al. 2018; Hepler et al. 2020). Therefore, understanding the diversity and functional potential of resident parasitoids before pest arrival is essential to evaluate their prospective contribution to natural regulation and to inform future classical biological control strategies.

New Zealand currently remains free of BMSB but is considered at very high risk of establishment due to frequent interceptions on imported goods, the country's favourable climate, and the abundance of suitable host plants (Burne 2019). In anticipation of BMSB's potential arrival, a pre-emptive classical biocontrol programme using *T. japonicus* was launched in New Zealand in December 2015 (Charles et al. 2019) through a Plant & Food Research (now part of the Bioeconomy Science Institute) and Better Border Biosecurity (B3) collaboration. This work supported the New Zealand Environmental Protection Authority's 2018 approval for the conditional release of *T. japonicus* should BMSB be detected (EPA 2018; Charles et al. 2019), providing a crucial tool for future BMSB management in New Zealand.

As part of an ongoing pre-emptive classical biocontrol approach, a 3-year project was initiated to enhance New Zealand's biological control preparedness for BMSB by conducting a targeted multi-region survey to examine New Zealand's stink bug egg parasitoid fauna. This was achieved with the following objectives:

a. Assess the abundance and diversity of resident stink bug parasitoid populations, some of which may contribute to a future biocontrol programme against BMSB.
b. Assess the biocontrol potential against BMSB of native egg parasitoids identified.
c. Assess the presence/absence of *T. mitsukurii*, an egg parasitoid introduced in Australia in 1962 against the green vegetable bug, *Nezara viridula* (Clarke 1990; Caron et al. 2021), and known to be an effective parasitoid of BMSB.

This integrated field–laboratory approach represents the first comprehensive evaluation of New Zealand's pentatomid egg parasitoid community and its relevance to biocontrol preparedness for the potential arrival of BMSB.

Materials and methods

Assessment of abundance and diversity of egg parasitoids of New Zealand stink bugs

Experimental sites

The abundance and diversity of egg parasitoids of New Zealand stink bugs were evaluated during a three-year systematic parasitoid survey by assessing parasitism on laboratory-reared ‘sentinel’ egg masses and wild egg masses in selected survey sites within five regions. The selected regions were Auckland, Waikato, Bay of Plenty, Hawkes Bay, and Nelson/Marlborough.

Source of insects

Laboratory cultures of New Zealand stink bug species, namely, *Monteithiella humeralis, Glaucias amyoti, Cuspicona simplex, Cermatulus nasalis nasalis,* and *Oechalia schellenbergii*, were established from field collections of nymphs and adult pentatomid species. The source of *Nezara viridula* was an established colony available at Mt Albert Research Centre (Bioeconomy Science Institute). The stink bug colonies used to generate sentinel egg masses (see section 2.1.3. below) were maintained in nylon mesh cages (60 × 60 × 60 cm) and reared continuously on a diet, as described in Charles et al. (2019). Each cage was provided with water in wet cotton wool and a folded piece of wax paper as a substrate for oviposition. Cages with *N. viridula* were kept under a 25 ± 1°C 16:8 h [L:D] photoperiod, and all others were kept under a 20 ± 1°C 16:8 h [L:D] photoperiod.

Individual egg masses of pentatomid species for field deployment (i.e. sentinel egg masses) were collected from the rearing cages daily and examined microscopically. Any egg masses that were 3 days old (designated by developed egg-breakers), or with any eggs that had been cannibalised, were discarded. All collected egg masses were stored in an incubator at 10 ± 1°C, relative humidity (RH) of 60 ± 10%, and a 16:8 [L:D] photoperiod in preparation for field deployment. Only egg masses that were cool stored for a maximum of 20 days were used for field deployment.

Egg parasitoid surveys by deployment of sentinel eggs

Egg parasitoid surveys were conducted during mid-spring to late-summer in 2022–23, 2023–24 and 2024–25 by exposing laboratory-reared ‘sentinel’ egg masses of different stink bug species (see 2.1.2 for details) at different times from November to March in selected experimental sites within each region (see Appendix).

A couple of days before deployment, egg masses were mounted onto double-sided sticky tape on a 22.5 × 70 mm^2 cardboard strip, taking care to maintain their natural orientation. The remaining exposed portion of the sticky tape was covered with fine white sand (White ‘‘Scenic Sand’’ Activa products) to allow unimpeded access to parasitoids. The number of eggs in each egg mass, egg mass age, pentatomid species, and deployment site were recorded on the cardboard strip (Figure 1), and the strips were then placed over a tray and stored in an incubator in preparation for field deployment, as per the conditions in the previous section.

In Season 1 (2022–23), sentinel egg masses were deployed and exposed to wild parasitoids once a month, from 15 November to 30 March in six different sampling sites within each region. Within each site, sampling sites were classified into two different types of environments, where half of the sampling sites were classified as “Native” (mostly native vegetation present, e.g. reserves) and the other half as “Modified” (mostly a modified environment, e.g. crops) (see Appendix). Sites were selected based on existing knowledge of the presence of stink bug populations. Sentinel egg masses were deployed on fine days, and rainy days were avoided. During each deployment, no fewer than 10 strips with sentinel egg masses were deployed at each site. At each site, sentinel egg masses were attached to a yellow corflute-made shelter and placed in a netting bag for protection against rain and predators, which was then attached to a branch of randomly selected trees (Figure 1).

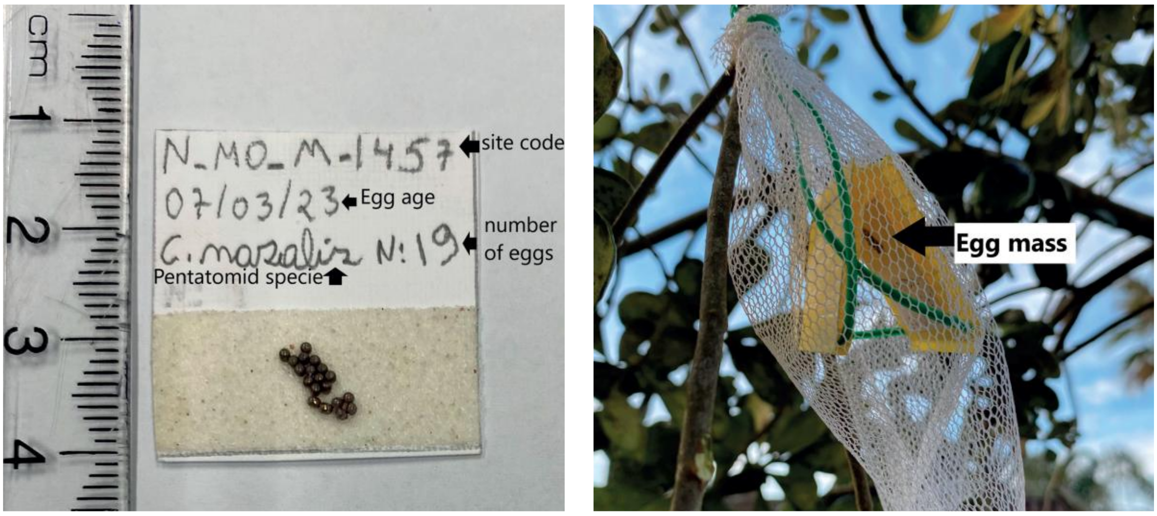

Figure 1. Sentinel egg mass set on card before field deployment (left) and sentinel egg mass set on card fixed to a corflute cover within a mesh bag for protection after deployment in the field (right)

Branches carrying sentinel egg masses were marked with colour-flagging tape attached to the branch of the tree carrying the egg mass. Sentinel egg masses were retrieved after 5–7 days (depending on weather and temperature) and brought back to the laboratory for rearing. Retrieved egg masses were individually maintained in small Petri dishes (60 mm × 15 mm) and stored in a controlled-temperature (CT) room set at 23 ± 1°C, 60 ± 10% RH, and a 16:8 [L:D] photoperiod for a maximum of 30 days until all parasitoids had emerged. All emerged parasitoids were identified, counted, sexed, and frozen for morphological identification. Before freezing, selected female parasitoids from the field-collected species were used to establish parasitoid colonies for further laboratory work. Unhatched eggs were counted and dissected under a stereomicroscope to assess parasitism. After dissection, unhatched eggs were labelled as either unemerged parasitoid (i.e. pharate adults observed), unemerged pentatomid nymph (i.e. undeveloped nymph observed), or unviable eggs (i.e. undetermined content). Information on emerged parasitoids was used to determine parasitism rates (i.e. total number of egg masses from which at least one emerged parasitoid was recorded—successful parasitism) and emergence rates (i.e. number of emerged parasitoids recorded from parasitised eggs).

The same procedure for deployments and parasitism assessments was conducted during Seasons 2 (2023–24) and 3 (2024–25). However, in Season 2, four of the six sampling sites within each region were “Modified” and the other two were “Native”. This change in type sampling sites was implemented because higher parasitism was detected in “Modified” sites during Season 1. Such a change in methodology was agreed upon by all project partners prior to implementation. In addition, in Season 3, only two sampling sites were used for deployment of sentinel eggs, which were selected based on parasitism rates found in previous years (i.e. high parasitism sites selected). This additional modification in sampling methodology in Season 3 was due to a change in project priorities (i.e. conducting host-testing work against BMSB with native parasitoids found during the first two seasons) and was agreed with project partners before implementation.

Egg parasitoid surveys by collection of wild eggs

Wild pentatomid egg masses were collected from sampling sites in each region during deployment and retrieval of sentinel egg masses during Seasons 2 and 3. The undersides of leaves in randomly selected trees were carefully inspected, and 40–80 leaves per tree were inspected for wild pentatomid egg masses.

Leaves with egg masses were taken back to the laboratory and individually maintained in small Petri dishes (60 mm × 15 mm) stored in a CT room set at 23 ± 1°C, 60 ± 10% RH, and a 16:8 [L:D] photoperiod until all parasitoids and/or pentatomid nymphs had emerged. Handling of emerged insects and determination of parasitism and emergence rates were conducted as described in Section 2.1.3.

Data analysis

A generalised linear model (GLM) with binomial distribution (with logit function) was used to investigate differences in parasitism rates and emergence rates among months, regions, and survey seasons by deployment of sentinel egg masses of stink bugs.

Model fit was assessed using Pearson chi-square and deviance statistics. Evidence of overdispersion was detected (Pearson $\chi^2/df > 1$), indicating greater variability than expected under the binomial assumption. To account for this, the model was refitted with the scale parameter estimated using the Pearson chi-square statistic, which adjusts the standard errors accordingly and provides a robust inference.

Region, experimental months, survey seasons, and their interactions were used as fixed effects. Binary variables (yes or no) of parasitism were fitted to the GLM model in each season separately. Regions where no parasitism was recorded were excluded from the analysis. Where overall tests of parasitoid species were statistically significant, pair-wise comparisons of the fitted means were conducted. Fitted means for each species, along with the respective 95% confidence intervals, were calculated and back-transformed onto the original scale. The same procedure was used for data analysis of parasitism rates by collection of wild egg masses.

All computations and graphics were performed using IBM SPSS Statistics version 28.0.1.

Host-specificity testing of native egg parasitoids of New Zealand pentatomids against the brown marmorated stink bug

Source of insects

Colonies of *T. oenone*, an unknown *Trissolcus* sp., *Telenomus* sp. and three native egg parasitoids recovered during field surveys were established from parasitised pentatomid egg masses retrieved during field surveys in Seasons 1 and 2. These colonies were maintained at Mount Albert Research Centre (Bioeconomy Science Institute), and were reared for approximately 10 generations in the lab before being used in host testing experiments. Parasitoid colonies were maintained in a CT room at 23°C (16:8 h [L:D] photoperiod) on the eggs of either *G. amyoti*, *M. humeralis*, or *C. nasalis nasalis*. Fresh (<24 h old) or stored host eggs (i.e. stored at 10 ± 1°C for up to 2 weeks) were used to maintain the colonies. Following exposure, female parasitoids were removed after 1–3 days and the resulting progeny usually started to emerge after 11–14 days, with males emerging first.

For each parasitoid species, parasitised egg masses of *M. humeralis* and *C. nasalis nasalis* were shipped to quarantine facilities at Council for Agricultural Research and Economics (CREA), Florence, Italy and CAB International (CABI), Delémont, Switzerland for experimentation with BMSB. This was conducted after obtaining all relevant import permissions from the corresponding regulatory agencies from Italy and Switzerland, as well as the corresponding Māori approval from iwi representatives from Auckland, Bay of Plenty, and Nelson.

In preparation for parasitoid shipments, parasitised egg masses were housed in 37-mL screw-cap plastic vials (Figure 2a) placed within vented Sistema® plastic boxes (13 × 13 × 7 cm) (Figure 2b). Each vial was provisioned with a ~10-µL drop of honey as a carbohydrate source. Four parasitoid consignments were sent to CREA (30 April, 7 May, 9 May and 14 May 2025) and three to CABI (14 May, 20 May, and 30 May 2025). Each shipment consisted of 10 vials containing egg masses parasitised in New Zealand, with parasitoids developing inside. The vials were dispatched after 3–5 days of exposure to host eggs, ensuring that individuals emerged and reached maturity within an appropriate time window (4–7 days approx.) for the experimental assays upon arrival. This strategy minimised the risk of adult ageing during transit and maximised the availability of healthy mated females for testing.

Access to experimental BMSB colonies to supply experimental egg masses was provided by the CREA, Florence, Italy and CABI, Delémont, Switzerland.

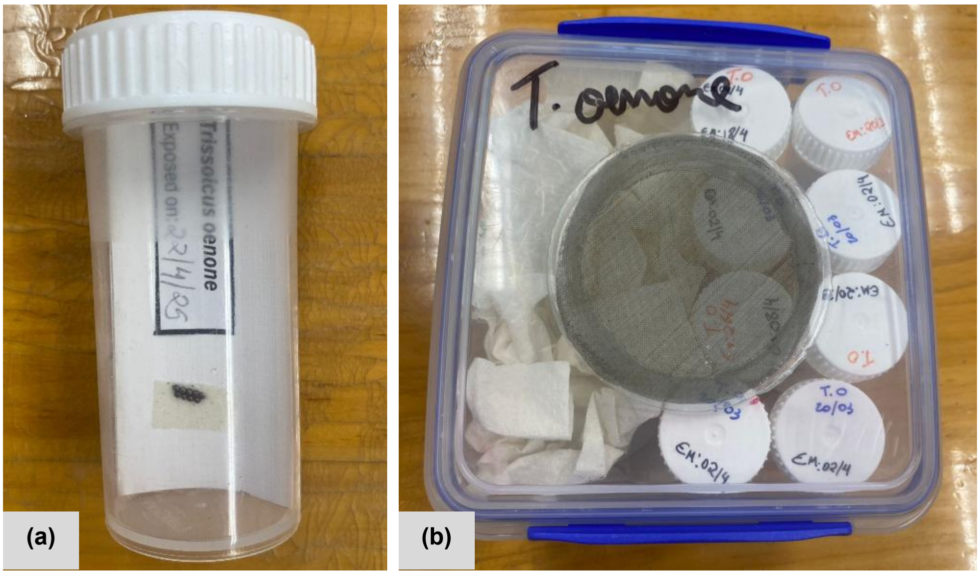

Figure 2. (a) Individual vial containing parasitoids developing within a host egg mass (e.g. *M. humeralis, C. nasalis*), and (b) plastic transport container holding vials of parasitised host eggs used for shipment of parasitoids from New Zealand to CREA, Italy and CABI, Switzerland.

No-choice oviposition tests

No-choice oviposition tests were performed with BMSB eggs to assess whether this invasive stink bug species could be a physiological host for *T. oenone*, *Trissolcus* sp., and *Telenomus* sp., and if so, to determine their biocontrol potential by assessing parasitism rates. All experimental work was conducted in quarantine facilities at CREA and CABI-Switzerland.

For each parasitoid species, each no-choice oviposition replicate consisted of a fresh (<24 h old) BMSB egg mass which was placed into a small Petri dish (60 mm × 15 mm) (the oviposition arena), before introducing a single naïve female (5–7 days old) parasitoid. Each Petri dish was labelled with the egg age, date tested, replicate number, and parasitoid species tested (Figure 3). No-choice tests were carried out in a quarantine CT room set at 23 ±1°C and a 16:8 [L:D] photoperiod. After 24 h, the female parasitoid was removed from the oviposition arena, and all BMSB egg masses exposed to parasitism were reared under the same CT room conditions until all parasitoids and/or pentatomid nymphs had emerged. Negative controls were conducted, but without the introduction of parasitoids. Additional no-choice oviposition experiments using frozen eggs were conducted, using the same methodology described above, to assess the ability of parasitoids to develop on unviable BMSB eggs. A total of 22 and 30 replicates per treatment were conducted at CREA and CABI, respectively.

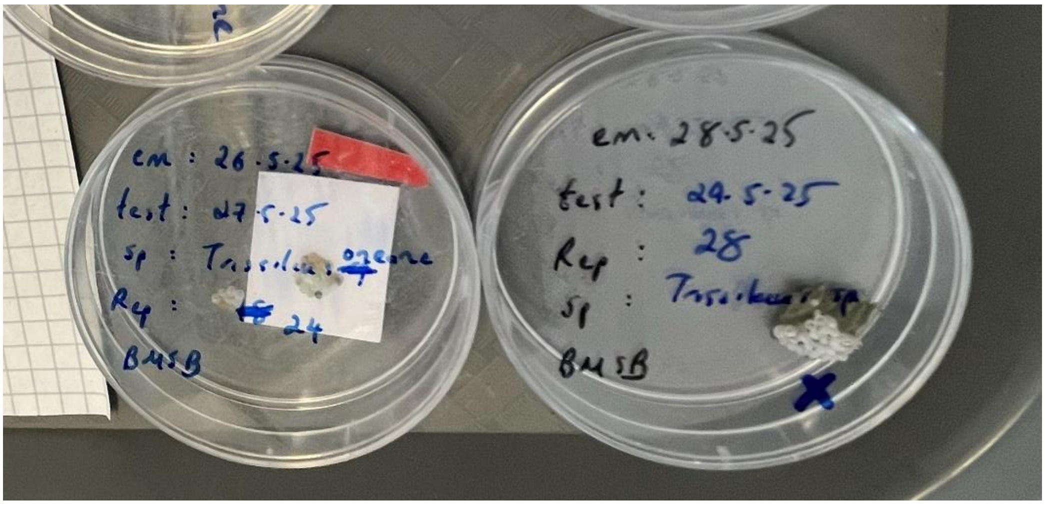

Figure 3. Petri dishes with experimental BMSB egg masses parasitised.

Data analysis

All data analyses were performed with pooled data from replicates conducted at CREA and CABI because no effects were found in oviposition tests performed in quarantine laboratories in these two locations.

Parasitism rates (total number of egg masses from which at least one parasitoid developed—successful parasitism), as well as emergence rates per successfully BMSB parasitised egg mass, were analysed using separate logistic regression models (with a logit link function) for each outcome.

Model fit was assessed using the Pearson chi-square and deviance statistics. Evidence of overdispersion was detected (Pearson $\chi^2/df > 1$), indicating greater variability than expected under the binomial assumption. To account for this, the model was refitted with the scale parameter estimated using the Pearson chi-square statistic, which adjusts the standard errors accordingly and provides robust inference.

Where overall tests of parasitoid species were statistically significant, pair-wise comparisons of the fitted means were conducted. Fitted means for each species along with the respective 95% confidence intervals were calculated and back-transformed onto the original scale. Similarly, to assess potential mortality of BMSB eggs as a result of parasitism, proportions of emerged nymphs from undeveloped parasitised BMSB egg masses and negative control masses were analysed using logistic regression models.

All computations and graphics were performed using IBM SPSS Statistics, Version 28.0.1.

Results

Assessment of abundance and diversity of egg parasitoids of New Zealand stink bugs

1.1.1 Egg parasitoid surveys by deployment of sentinel eggs of stink bugs

Seasonal parasitism of sentinel egg masses

In total, 52,057 sentinel stink bug eggs from 1,757 egg masses (Season 1), 56,828 eggs from 2,133 masses (Season 2), and 15,139 eggs from 600 masses (Season 3) were deployed and exposed to parasitism across all survey regions. Sentinel eggs retrieved from the field (51,331 in Season 1, 56,669 in Season 2, and 15,137 in Season 3) confirmed parasitism during all survey months and seasons (Table 1).

Table 1. Number of egg masses deployed, parasitoids recovered, and parasitoids that emerged from sentinel stink bug egg masses deployed in the five different survey regions during the survey seasons.

Season	Region	No. of egg masses deployed	No. of egg masses recovered	No. of eggs recovered	No. of parasitoids recovered	No. of emerged parasitoids
1	Auckland	338	338	10090	255	210
	Bay of Plenty	317	317	9468	0	0
	Hawke’s Bay	345	345	9994	235	232
	Nelson	371	371	10880	231	197
	Waikato	386	386	10899	36	36
2	Auckland	432	432	11058	564	500
	Bay of Plenty	428	428	10989	383	344
	Hawke’s Bay	426	426	11864	409	297
	Nelson	427	427	11728	653	527
	Waikato	420	420	11030	429	388
3	Auckland	120	120	3059	190	183
	Bay of Plenty	120	120	2965	32	30
	Hawke’s Bay	120	120	3006	136	136
	Nelson	120	120	2981	248	243
	Waikato	120	120	3126	235	229

Mean parasitism rates recorded from November to March differed significantly ($p < 0.05$) among survey seasons across the five regions, with the lowest parasitism recorded in Season 1 (3 ± 1% SE). Mean parasitism did not differ significantly ($p > 0.05$) between Season 2 (7 ± 1% SE) and Season 3 (9 ± 6% SE).

During Season 1, the mean parasitism rates across regions were slightly higher in January (5 ± 2% SE). However, the mean parasitism rates did not differ significantly ($p > 0.05$) among the different months (Figure 4). Overall, mean parasitism rates in Season 2 differed significantly ($p < 0.05$) among the different months across regions, where mean parasitism reached a peak of 14 ± 2% SE in January (Figure 4). In the Season 3 egg parasitoid surveys, mean parasitism rates across regions also peaked on 18 January ± 5% SE, and overall mean parasitism rates did not differ significantly

(p > 0.05) among the different months (Figure 4). Statistical analysis of the interactions between months and survey seasons suggested that parasitism rates differed significantly (p < 0.05) across regions, where there was a trend for higher parasitism rates in the middle of summer (i.e. January) (Figure 4).

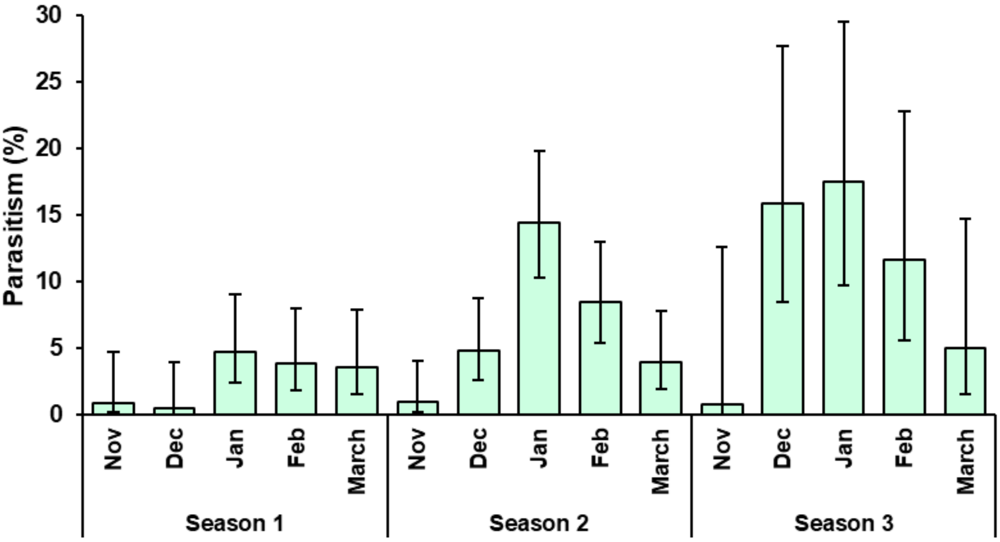

Figure 4. Estimated mean parasitism (with 95% confidence intervals) recorded on sentinel eggs deployed from November to March in the three seasons across the five regions. Bars are the back-transformed predicted means using the GLM model, and the vertical lines show the back-transformed confidence intervals. Overlapping confidence intervals suggest no evidence of a statistically significant difference.

In Season 1, mean parasitism rates in the Auckland region (7 ± 2% SE) were slightly higher than those observed in the other regions. No parasitism was recorded in Bay of Plenty during Season 1. No statistical evidence was found to suggest differences in parasitism rates among regions, across all survey months (all p-values > 0.05) (Figure 5). Mean parasitism rates in the Auckland region (9 ± 2% SE) in Season 2 appeared slightly higher than those observed in the other regions. However, similarly to Season 1, statistical analysis of observed parasitism rates suggested no significant difference in mean parasitism rates among regions in Season 2 (all p-values > 0.05) (Figure 5). During Season 3, mean parasitism rates were slightly higher in Waikato (16 ± 6% SE) than the other regions, but no statistical evidence was found to suggest differences in parasitism rates among regions, across all survey months (Figure 5). Statistical analysis of the interactions between regions and survey seasons suggested no significant differences (p > 0.05) in parasitism rates across survey months (Figure 5).

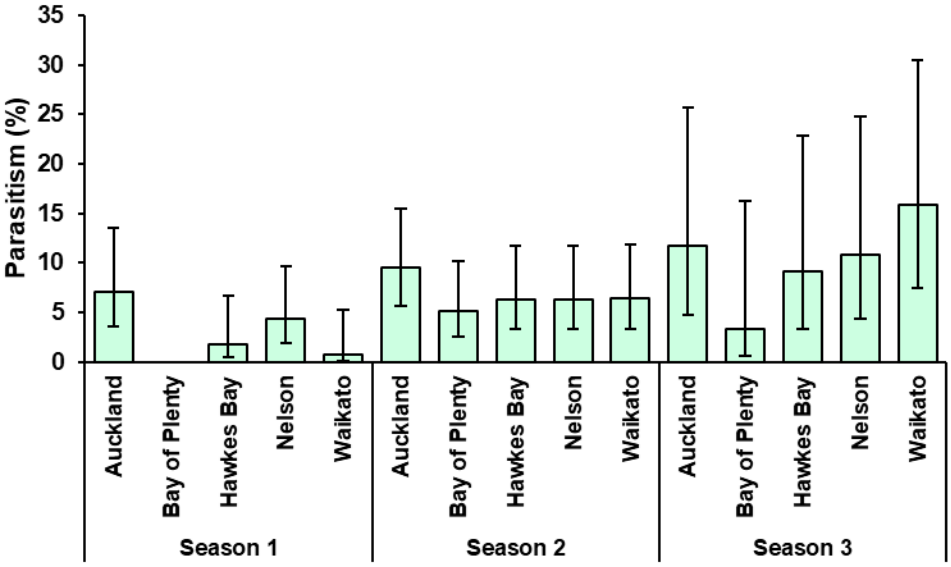

Figure 5. Estimated mean parasitism (with 95% confidence intervals) recorded on sentinel eggs deployed in each region during the three seasons across the survey period. Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Overlapping confidence intervals suggest no evidence of a statistically significant difference.

Confirmed parasitised eggs ranged from 65–96% across the three survey seasons, and high rates of emerged adult parasitoids (>50%) were recorded from parasitised eggs recovered from all three season surveys across survey months and regions. Mean emerged parasitoids were significantly higher ($p < 0.05$) in Season 2 and Season 3, with 82 ± 3% SE and 81 ± 5% SE emergence recorded, respectively, compared with 58 ± 7% SE in Season 1 (Figure 6).

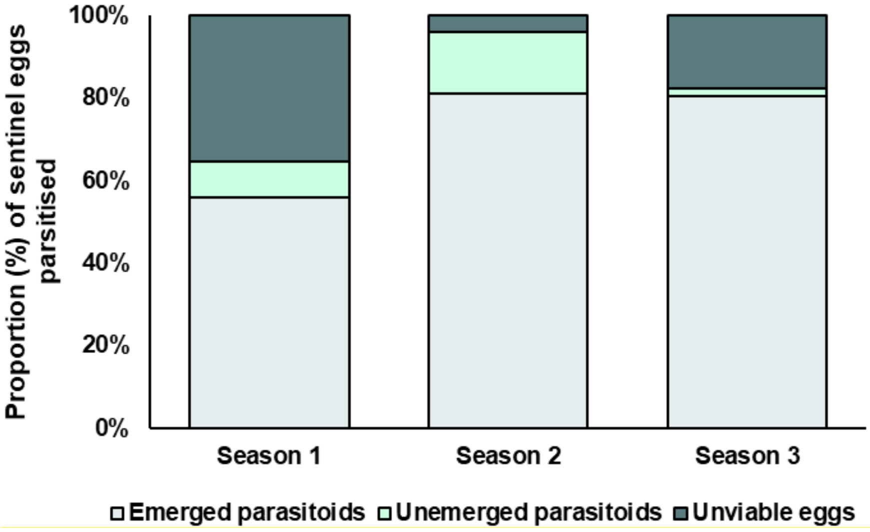

Figure 6. Relative proportion of parasitoid development per parasitised egg mass (raw data) recovered in each survey season. Arithmetic means are shown without SEs to allow visualisation, as the underlying distributions are not normal.

In Season 1, the mean emergence rates of parasitoids differed significantly ($p < 0.05$) among regions, with the highest emergence recorded in Waikato (Figure 7). Conversely, in Season 2 and Season 3, emergence rates did not differ significantly ($p > 0.05$) among regions (Figure 7). Statistical analysis of the interactions between regions and survey seasons across months suggested significant differences ($p < 0.05$) in emergence rates (Figure 7).

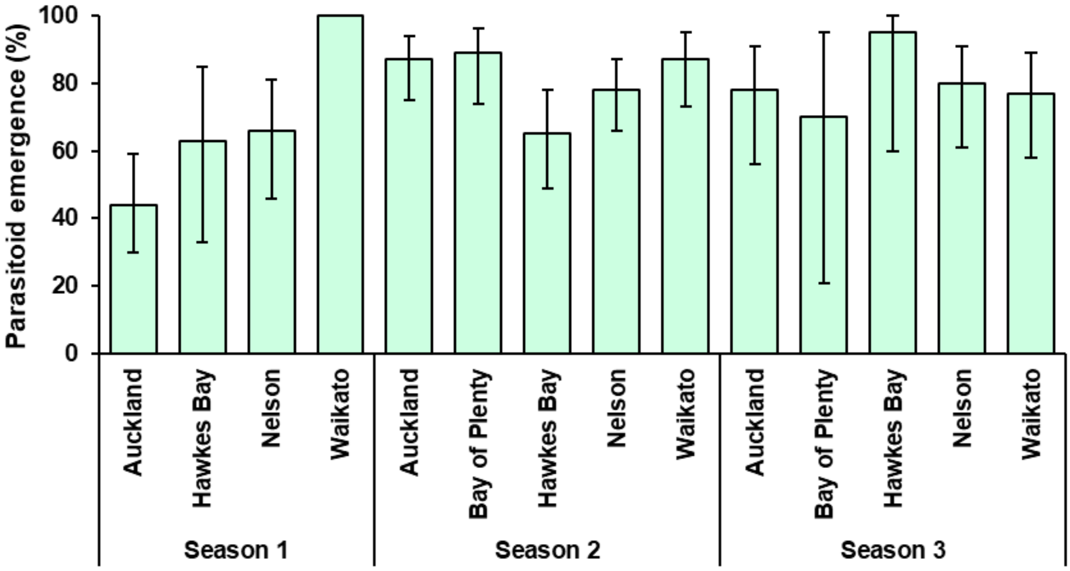

Figure 7. Estimated mean emergence of parasitoids (with 95% confidence intervals) recorded on sentinel eggs deployed in each region during the three seasons across the survey period. Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Overlapping confidence intervals suggest no evidence of a statistically significant difference.

Parasitoid species recovered and abundance

During Season 1, 2, and 3, 4,036 parasitoids (757, 2,438, and 841, respectively) were recovered from parasitised sentinel egg masses. Overall, 88% emergence was confirmed from successfully parasitised egg masses across the five regions in the three surveys.

In Season 1, two parasitoid species were recovered during the survey: *Trissolcus basalis* (Wollaston) and *T. oenone* (Dodd) (see Appendix). *T. basalis* was as abundant as *T. oenone* in Auckland and was the most predominant parasitoid species in the Hawke's Bay and Nelson regions, with an overall relative abundance of 90% and 63%, respectively (Figure 8). No parasitoids were recovered from the Bay of Plenty in Season 1. *T. basalis* and *T. oenone* accounted for an overall average of 67% and 33% of the relative abundance across the survey months and regions, respectively.

During the Season 2 egg parasitoid surveys, *T. basalis* and *T. oenone* were recovered across the five regions. Additionally, two undescribed species were detected: a *Trissolcus* sp. parasitoid and an *Acroclisoides* sp. hyperparasitoid (see Appendix). Similarly to Season 1, *T. basalis* and *T. oenone* were the two predominant species across all regions, accounting for an average relative abundance of 33% and 65%, respectively (Figure 8).

In Season 3, *T. basalis* and *T. oenone* were the only two parasitoid species recovered across the five experimental regions; *T. oenone* was the predominant parasitoid across all regions, accounting for an average relative abundance 65% (Figure 8). The egg parasitoid *T. mitsukurii* was not recovered from sentinel egg masses in any of the three surveys.

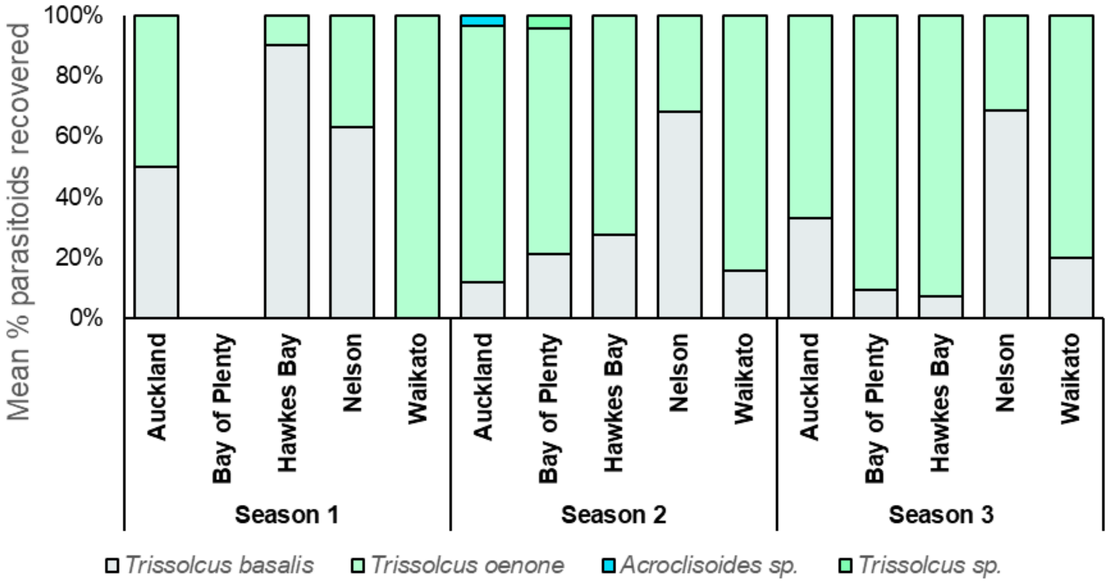

Figure 8. Relative abundance of parasitoid species (raw data) recovered from successfully parasitised sentinel egg masses deployed monthly in the five regions across survey months in the three different seasons. Arithmetic means are shown without SEs to allow visualisation, as the underlying distribution is not normal.

1.1.2 Egg parasitoid surveys by collection of wild stink bug eggs

Seasonal parasitism of wild egg masses

In total, 3,867 wild stink bug eggs from 343 egg masses (Season 2), and 1,388 eggs from 109 masses (Season 3) were retrieved during field surveys across all survey months and regions, which confirmed parasitism during all survey months and regions (Table 2).

Table 2. Number of parasitoids recovered and emerged from wild stink bug eggs collected in the five different survey regions during surveys conducted in Season 2 and Season 3.

Season	Region	No. of wild egg masses collected	No. of wild eggs collected	No. of parasitoids recovered	No. of emerged parasitoids
2	Auckland	30	479	364	281
	Bay of Plenty	48	882	501	486
	Hawke’s Bay	36	512	386	298
	Nelson	98	1661	1104	929
	Waikato	10	313	116	81
3	Auckland	10	453	128	76
	Bay of Plenty	5	329	91	51
	Hawke’s Bay	12	153	149	133
	Nelson	8	173	110	81
	Waikato	10	280	118	67

Mean parasitism rates were consistent throughout the three survey periods, where parasitism recorded in Season 2 (65 ± 4% SE) was significantly higher (p-value < 0.05) than that recorded in Season 3 (41 ± 8% SE).

During Season 2, mean parasitism rates differed significantly (*p*-value < 0.05) among the different survey months (Figure 9) across regions, where November was the month with the highest parasitism (100%) recorded and December the lowest (36 ± 7% SE).

Overall, mean parasitism rates in Season 3 did not differ significantly (*p*-value > 0.05) among the different months across regions. Statistical analysis of the interactions between months and survey seasons suggested parasitism rates differed significantly (*p*-value < 0.05) across regions (Figure 9).

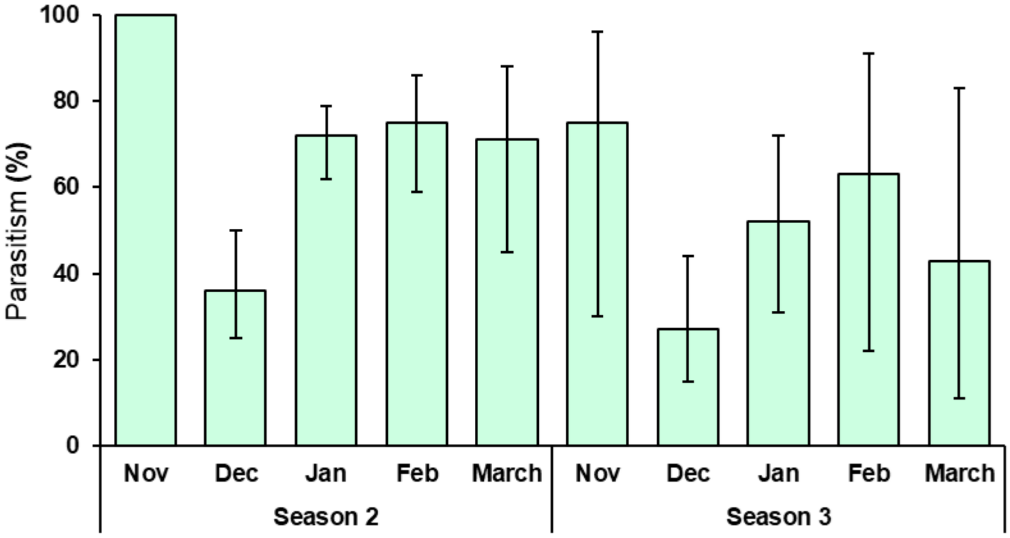

Figure 9. Estimated mean parasitism (with 95% confidence intervals) recorded from wild stink bug egg masses collected from November to December across the five regions during Season 2 and Season 3 surveys. Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Overlapping confidence intervals suggest no evidence of a statistically significant difference.

In Season 2, no statistical evidence was found to suggest differences in parasitism rates among regions (all *p*-values > 0.05), where mean parasitism was slightly higher in the Auckland and Hawke’s Bay regions, with mean parasitism reaching 75 ± 10% SE and 77 ± 9% SE across the survey months, respectively (Figure 10). Similarly, during Season 3, mean parasitism rates did not differ significantly (*p*-value > 0.05) among regions. Mean parasitism rates were slightly higher in Hawke’s Bay (86 ± 14% SE) than the other regions, and lower in Auckland (29 ± 11% SE) and Bay of Plenty (22 ± 13% SE) (Figure 10). Statistical analysis of the interactions between regions and survey seasons suggested significant differences (*p*-value < 0.05) in mean parasitism rates across survey months (Figure 10).

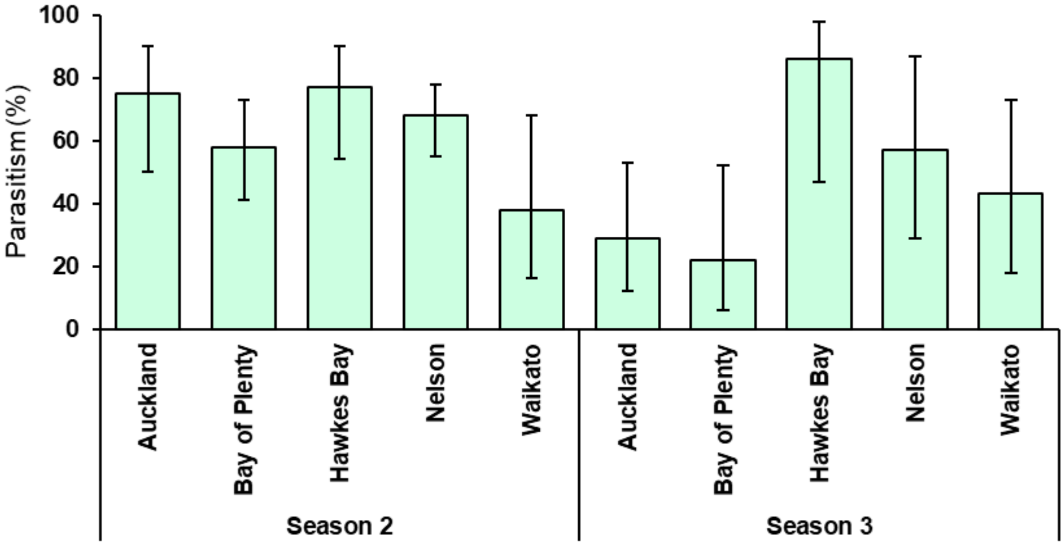

Figure 10. Estimated mean parasitism (with 95% confidence intervals) recorded from wild stink bug egg masses collected in each region across the survey months during Seasons 2 and 3. Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Overlapping confidence intervals suggest no evidence of a statistically significant difference.

High rates of emerged adult parasitoids (>70%) were recorded from parasitised wild eggs recovered from the two survey seasons across survey months and regions. Mean emerged parasitoids were significantly higher (*p*-value < 0.05) in Season 2, with 84 ± 3% SE of parasitoids emerging from parasitised wild eggs, compared with 68 ± 7% SE emergence in Season 3.

In Season 2, the mean emergence rates of parasitoids did not differ significantly (*p* > 0.05) among regions, with the Bay of Plenty region recording slightly higher emergence rates (97 ± 2% SE) across survey months (Figure 11). Similarly, in Season 3, emergence rates did not differ significantly (*p* > 0.05) among regions (Figure 11), with emergence rates being higher in Hawke's Bay (89 ± 8% SE). Statistical analysis of the interactions between regions and survey seasons across months suggested significant differences (*p* < 0.05) in emergence rates (Figure 11).

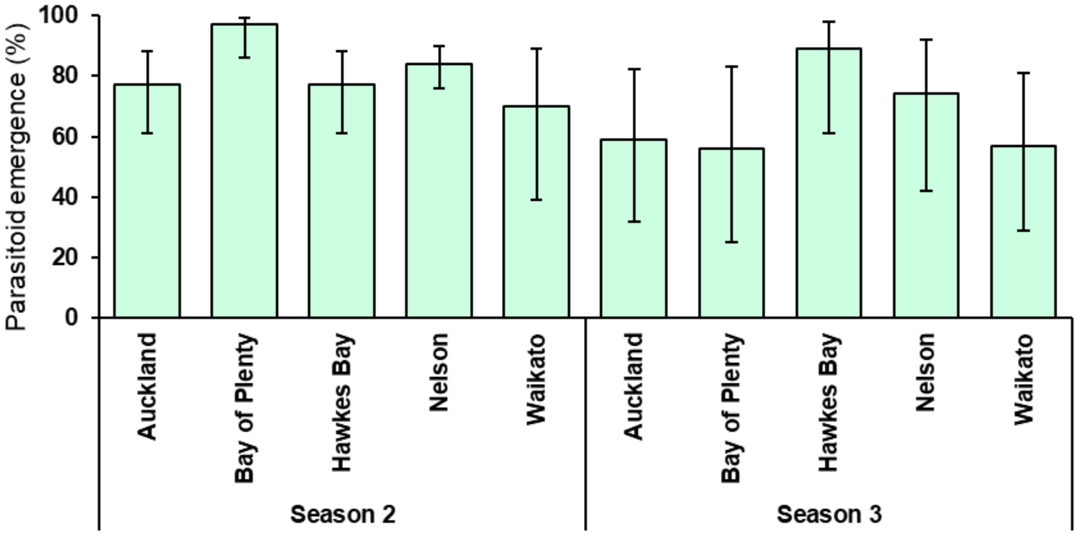

Figure 11. Estimated mean emergence of parasitoids (with 95% confidence intervals) recorded from parasitised wild stink bug egg masses collected in each region across the survey months during Seasons 2 and 3. Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Overlapping confidence intervals suggest no evidence of a statistically significant difference.

Parasitoid species recovered and abundance

During the Season 2 and Season 3 surveys, 2,487 parasitoids (2,079 and 408, respectively) were recovered from parasitised wild egg masses. Overall, 99.5% emergence was confirmed from successfully parasitised egg masses across the five regions in the two surveys.

In Season 2, four parasitoid species and one hyperparasitoid species were recovered across the survey regions: *T. basalis*, *T. oenone*, an undescribed *Trissolcus* sp., an undescribed *Telenomus* sp., and an undescribed *Acroclisoides* sp. hyperparasitoid. *Trissolcus oenone* and the undescribed *Trissolcus* sp. (see Appendix) were the most predominant parasitoids across the regions, with overall relative abundances of 40% and 32%, respectively (Figure 12). *Trissolcus* sp. was the most predominant parasitoid in Waikato across the survey months, with an overall relative abundance of 71.6% (Figure 12). In Season 3, the same parasitoid species were recovered, except for the undescribed *Trissolcus* sp. During this season, *T. oenone* was the predominant species across all regions, accounting for an average relative abundance of 67% (Figure 12). Similar to the results from deployment of sentinel eggs, the egg parasitoid *T. mitsukurii* was not recovered from wild egg masses collected in any of the surveys.

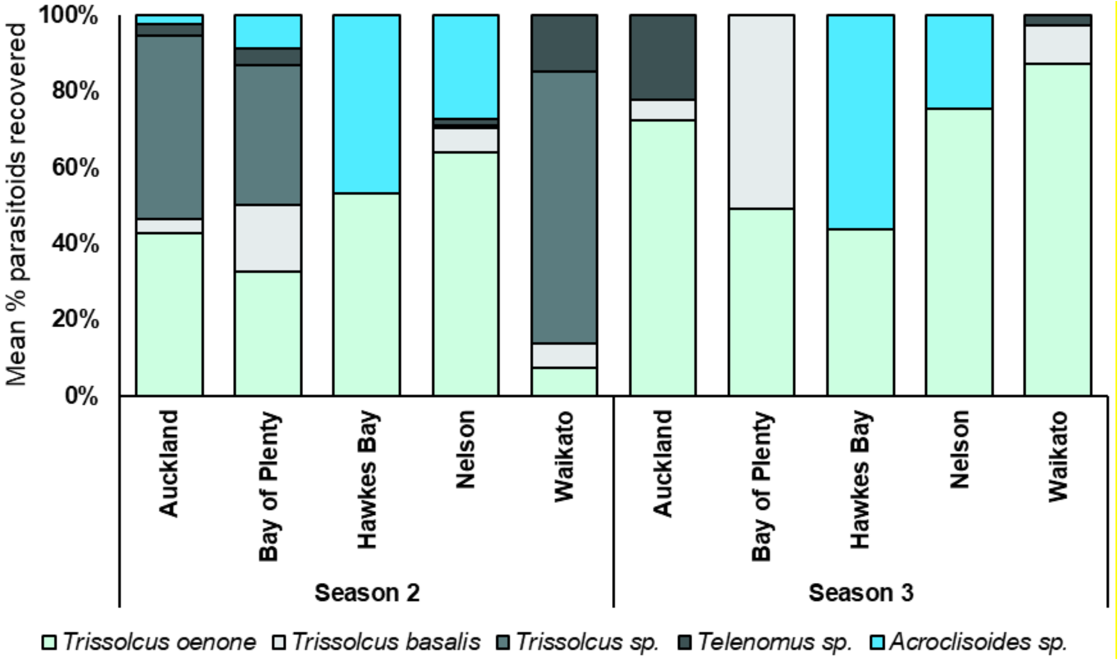

Figure 12. Relative abundance of parasitoid species (raw data) recovered from successfully parasitised wild stink bug egg masses collected monthly in the five regions during surveys conducted in Seasons 2 and 3. Arithmetic means are shown without SEs to allow visualisation, as the underlying distributions are not Normal.

Host-specificity testing of native egg parasitoids of New Zealand pentatomids against the brown marmorated stink bug

No-choice oviposition tests

All no-choice oviposition tests were conducted at CREA, Italy and CABI, Switzerland from 10–24 May and 26 June – 6 July 2025, respectively. In total, 6,411 BMSB eggs were tested across 52 replicates per treatment (e.g. *Trissolcus oenone, Trissolcus sp., Telenomus sp*. using fresh and frozen BMSB eggs, and a negative control). Although females of all parasitoid species readily probed and attacked BMSB eggs, the emergence of parasitoids from fresh BMSB eggs was negligible and did not differ significantly ($p > 0.05$) among parasitoid species (Figure 13). From all fresh BMSB eggs exposed (i.e. 6,411), only five, seven, and three *Trissolcus oenone, Telenomus sp*., and *Trissolcus sp.* emerged, respectively. The emergence of parasitoids from frozen BMSB eggs differed significantly (p-value < 0.05) among the three parasitoid species tested, where *T. oenone* produced the highest emergence (66 ± 3% SE) followed by *Trissolcus* sp. (15 ± 2% SE).

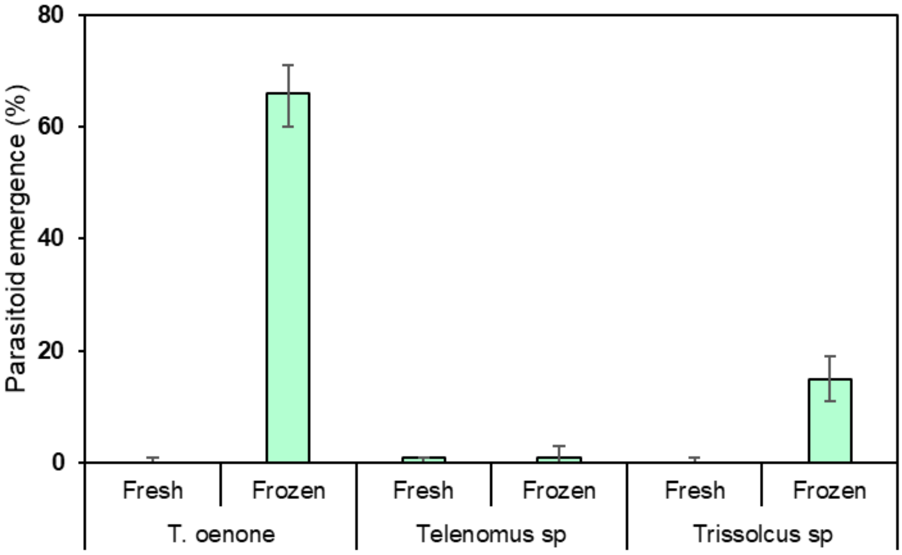

Figure 13. Estimated mean emergence (with 95% confidence intervals) of three New Zealand scelionid parasitoids (*Telenomus* sp., *Trissolcus oenone*, and *Trissolcus* sp.) exposed to fresh and frozen BMSB egg masses. Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Non-overlapping confidence intervals suggest evidence of a statistically significant difference.

Despite the negligible success of all three parasitoid species in completing development in fresh BMSB eggs, exposure to parasitoids markedly reduced egg viability. Egg mortality differed significantly ($p < 0.05$) among treatments (Figure 14). The mean egg mortality in the negative control was 20 ± 1% SE, whereas significantly higher levels of egg mortality were observed in treatments conducted with *T. oenone* (37 ± 1%SE) and *Telenomus sp.* (30 ± 1% SE) (Figure 14).

Patterns in host nymph emergence mirrored mortality trends in fresh BMSB eggs, where the mean emergence of BMSB nymphs in controls (80 ± 3% SE) was significantly different from that observed in *T. oenone* (63 ± 4% SE) (Table 3).

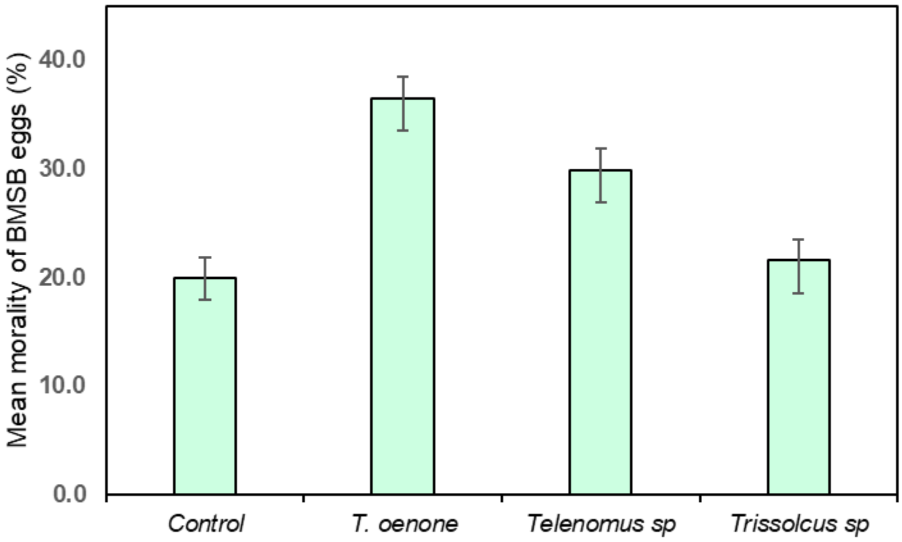

Figure 14. Estimated mean mortality (with 95% confidence intervals) of fresh BMSB eggs exposed to three New Zealand scelionid parasitoids (*Telenomus* sp., *Trissolcus oenone*, and *Trissolcus* sp.) compared with a negative control (no parasitoid exposure). Bars are the back-transformed predicted means by the GLM model; the vertical lines show the back-transformed confidence intervals. Non overlapping confidence intervals suggest evidence of a statistically significant difference.

Table 3. Nymph emergence and mortality of fresh BMSB eggs after exposure to New Zealand parasitoids in no-choice oviposition tests. Means not sharing a letter indicate evidence of a statistically significant difference.

Treatment	No .of BMSB eggs tested	No. of BMSB eggs	Mean nymph emergence (%) ± SE	Mean egg mortality (%) ± SE	No. of parasitoids emerged (%)
Control	54	1406	80 ± 3.3 a	20 ± 3.3 c	0
Trissolcus oenone	52	1410	63 ± 3.9 b	37 ± 3.9 a	5
Telenomus sp.	52	1308	69 ± 3.9 abc	30 ± 3.9 b	7
Trissolcus sp.	52	1377	78 ± 3.4 ac	22 ± 3.4 c	3

Discussion

This 3-year regional survey of stink bug egg parasitoids provides the first comprehensive assessment of the abundance, diversity, and seasonal dynamics of resident scelionid and encyrtid fauna in New Zealand. Although *Halyomorpha halys* has not yet established in New Zealand, understanding which parasitoids are already present and active across habitats is critical for preparedness should the pest arrive. By combining field surveys of egg parasitoids of stink bugs with laboratory host testing with native parasitoid species recovered from surveys, this study links natural parasitoid community structure with functional performance on BMSB, offering an evidence-based evaluation of potential biocontrol contributions from local species.

More than 120,000 sentinel eggs (i.e. > 4,000 egg masses) of New Zealand stink bug species were exposed to natural parasitism in five different regions across three consecutive seasons. The results showed that overall parasitism of sentinel eggs remained low (3–9%) across the survey seasons, and yet when parasitism occurred, individual egg masses frequently showed very high within-mass attack rates (65–96%) and high emergence success (58–92%). In contrast, parasitism of naturally laid egg masses was substantially higher and more consistent, ranging from 41% to 65% of egg masses parasitised and emergence rates of 69% to 84%. These differences highlight that naturally occurring eggs provide a more realistic measure of field parasitism, as they carry natural host and plant cues that attract foraging parasitoids; therefore, sentinel eggs likely underestimate true field activity (Jones et al. 2014; Herlihy et al. 2016; Tillman et al. 2023). These patterns are consistent with the higher parasitism of field-laid eggs reported in similar egg parasitoid surveys conducted in North America (Tillman 2010; Abram et al. 2017) and Europe (Haye et al. 2015b).

Seasonal patterns were consistent across years, with a strong midsummer peak (January) in both sentinel and wild egg parasitism, which were both lowest early and late in the survey period. No significant regional differences were detected, although parasitism was slightly higher in Auckland and Waikato. These temporal peaks could be explained by a higher abundance of stink bug egg masses (i.e. host availability) during mid-summer and warmer temperatures favouring parasitoid activity, aligning with observations that scelionid activity is temperature dependent and synchronised with host reproduction (Abram et al. 2017; Tillman et al. 2023). Emergence rates in wild egg masses were high and consistent across years (>70%), indicating successful parasitoid development and confirming that the active parasitoid populations were well established and healthy across regions. The persistence of parasitism across all regions and years, even when rates were low in the case of sentinel eggs, demonstrates that resident parasitoids are active in most major agroecological zones in New Zealand.

Four parasitoid and one hyperparasitoid species were identified over the survey period: *Trissolcus oenone*, *T. basalis*, an undescribed *Trissolcus* sp., an undescribed *Telenomus* sp., and an undescribed hyperparasitoid *Acroclisoides* sp. *Trissolcus oenone* was the dominant species, comprising about around 60% and 50% of all parasitoids recovered from sentinel and wild egg masses, respectively, and being prevalent in all regions and years. *T. basalis* was consistently present but generally less abundant. The findings of an undescribed *Trissolcus* and *Telenomus* species are a breakthrough for this project, which add significantly to the known biodiversity of New Zealand's scelionids and warrant taxonomic and ecological study. Notably, *T. mitsukurii*—an effective BMSB parasitoid present in Australia (Caron et al. 2021)—was not detected in any year.

In New Zealand, the dominance of *T. oenone* across habitats contrasts with patterns reported from Australia, where *T. basalis* was the dominant parasitoid, attacking eggs of all 10 pentatomid species collected in cropping regions of south-eastern Queensland, while *T. oenone* was recorded from only three pentatomid hosts (Loch & Walter 1999; Saunders et al. 2022). *T. basalis* was introduced to New Zealand in the 1940s and has since established as a generalist parasitoid (Saunders et al. 2022), so its consistent recovery in the egg parasitoid surveys conducted in this study confirms its broad host use and persistence across agricultural and semi-natural habitats. The discovery of new *Trissolcus* and *Telenomus* species highlights that New Zealand's parasitoid fauna remains incompletely described, and that cryptic diversity may contribute additional ecological resilience.

In North America and Europe, native parasitoids rarely achieve high parasitism of BMSB eggs, typically under 10% (Haye et al. 2015b; Abram et al. 2017). When parasitism occurs, development is often incomplete, which may be related to the lower efficiency of venom injected during oviposition (Haye et al. 2015b). By contrast, the co-evolved Asian species *Trissolcus japonicus* and *T. mitsukurii* routinely achieve parasitism rates of 50–80% in their native region (Zhang et al. 2017; Zapponi et al. 2021; Simaz et al. 2023). The relatively high parasitism rates recorded in our survey, particularly of naturally laid eggs (65% in Season 2), demonstrate the strong functional capacity of New Zealand's resident parasitoid guild against native pentatomids, even if their direct impact on BMSB remains speculative.

Our finding that *T. oenone* and *T. basalis* dominate New Zealand's scelionid fauna aligns with results from similar field surveys conducted elsewhere, where generalist *Trissolcus* species were also among the most abundant parasitoids of native stink bugs and occasionally attacked BMSB eggs, though with limited reproductive success (Haye et al. 2015b; Herlihy et al. 2016; Abram et al. 2017). In contrast, *T. mitsukurii*, another primary parasitoid of BMSB and other stink bugs (e.g. *Nezara viridula*) and frequently associated with stink bug eggs in the Asia–Pacific region, was not detected in our surveys. This contrasts with Australia, where *T. mitsukurii* is already established and considered as a promising biological control agent of BMSB (Caron et al. 2021; Yonow et al. 2021).

Our study showed that parasitism occurred in all habitat types surveyed, but rates were consistently higher in modified environments such as crop and orchard sites compared with native vegetation areas. This pattern suggests that agricultural landscapes likely provide more abundant hosts and suitable microclimates for parasitoid foraging. This led us to modify our methodology after Season 1, such that we prioritised to continue surveying in modified environments to maximise the chances of recovering different parasitoid species. Similar habitat-related variation was documented in North American field studies, where the relative prevalence of indigenous parasitoid species differs among habitat types, particularly between crop and non-crop habitats, suggesting that landscape structure may influence community composition (Abram et al. 2017).

Complementary no-choice oviposition assays conducted in Italy and Switzerland demonstrated that *T. oenone*, *Telenomus* sp., and *Trissolcus* sp. can recognise and probe BMSB eggs but rarely complete development. Emergence rates were extremely low (i.e. 0.4 %, 0.5 %, and 0.2 %, respectively), yet *T. oenone* and *Telenomus* sp. significantly increased mortality of BMSB eggs (i.e. 37% and 30%, respectively) relative to controls (20%), while *Trissolcus* sp. did not. These results are consistent with the phenomenon of parasitoid-induced egg abortion, whereby oviposition or probing kills the host embryo without parasitoid emergence (Abram et al. 2014; Kaser et al. 2018; Abram et al. 2019; Hepler et al. 2020). Quantitative studies have shown that such non-reproductive impacts can equal or exceed successful parasitism, influencing host population dynamics (Abram et al. 2014; Haye et al. 2015b; Kaser et al. 2018; Hepler et al. 2020; Zapponi et al. 2021). These mechanisms may include effects of parasitoid venoms or ovipositional fluids altering host physiology (Moreau & Guillot 2005), or other physical interactions such as probing or injection activity, though direct evidence from egg parasitoids is limited. Fitness constraints associated with parasitoid size may modulate their capacity to produce such effects (Boivin & Martel 2012). Hidden mortality of this kind can be ecologically significant but easily overlooked because aborted eggs resemble unhatched ones (Abram et al. 2016; Kaser et al. 2018; Hepler et al. 2020). Our laboratory findings indicate that although *T. oenone* and *Telenomus* sp. are unlikely to establish as primary biocontrol agents of BMSB, they can potentially impose substantial egg mortality through non-reproductive mechanisms. In natural settings, such hidden mortality could complement the impact of co-evolved agents like *T. japonicus*, providing additive or synergistic suppression.

Collectively, the field and laboratory data suggest a layered potential response if BMSB arrives in New Zealand. Resident parasitoids are abundant and widely distributed, with demonstrated ability of *T. oenone* and *Telenomus* sp. to kill BMSB eggs even without reproduction. Their ecological services could therefore complement a classical biological control agent by increasing total egg mortality. In contrast, reliance solely on native species would be insufficient for long-term population regulation, given their minimal reproductive success. Classical biological control using co-evolved egg parasitoids such as *Trissolcus japonicus* and *T. mitsukurii* remains one of the most promising long-term strategies for suppressing BMSB. This view is supported by laboratory and host-range studies (Sabbatini-Peverieri et al. 2020, 2021), field detections of adventive populations of these species (Sabbatini-Peverieri et al. 2018), as well as biocontrol field releases (Bergh et al. 2023; Simaz et al. 2023). Importantly, host-specificity studies as part of a pre-emptive biological control approach against BMSB in New Zealand have shown low non-target risk for *T. japonicus* (Avila & Charles 2018; Charles et al. 2019), supporting its potential deployment if BMSB establishes.

Conclusions and recommendations

This integrated study demonstrates that New Zealand harbours a diverse and functionally active assemblage of scelionid parasitoids capable of exerting substantial pressure on native pentatomids and inducing mortality in BMSB eggs. *Trissolcus oenone* emerges as the dominant and most widespread parasitoid of native stink bug species in New Zealand. *Telenomus* sp. and *Trissolcus oenone* can cause significant non-reproductive mortality of BMSB, implying that, although they cannot sustain population control alone, they could enhance overall suppression when acting alongside an introduced specialist such as *T. japonicus*.

Recommendations:

1. **Evaluate the interactions between New Zealand's resident parasitoids and *T. japonicus*.** Interspecific competition studies are required to determine whether local species might interfere with *T. japonicus* establishment by attacking the same eggs or acting as secondary exploiters of killed eggs. Such experiments will also clarify the extent of biotic resistance that resident parasitoids may provide, a factor that will influence release strategies and the numbers of *T. japonicus* required for successful establishment during eradication or long-term management.
2. **Host location laboratory experimentation:** Development of large-scale behavioural assays in controlled-environment rooms (e.g. mesh cages containing potted host plants) to test the ability of parasitoids to locate, recognise, and oviposit in BMSB eggs under more natural but still contained conditions. These experiments will enable the assessment of parasitoid searching ability and host-finding behaviour which will better reflect the biocontrol potential of parasitoids.
3. **Population modelling** – Incorporate parasitoid-induced egg abortion into host–parasitoid models to predict the consequences on BMSB suppression and indirect effects on native pentatomid hosts under both egg- and time-limited scenarios.
4. **Quantify hidden mortality** in native–host and BMSB systems using molecular assays (e.g. species-specific PCR) to accurately estimate total parasitoid impact.
5. **Retain regulatory readiness** for the potential introduction of *T. japonicus* if BMSB establishes, integrating native parasitoid impacts into predictive biocontrol models.

Ultimately, the findings of this study highlight both the potential and the challenges of integrating native parasitoids into a comprehensive biocontrol strategy against BMSB in New Zealand. While resident species alone are unlikely to suppress this invasive pest, they may enhance mortality rates and interact with *T. japonicus* parasitoids (when released) in complex ways that must be considered when planning future biocontrol activities.

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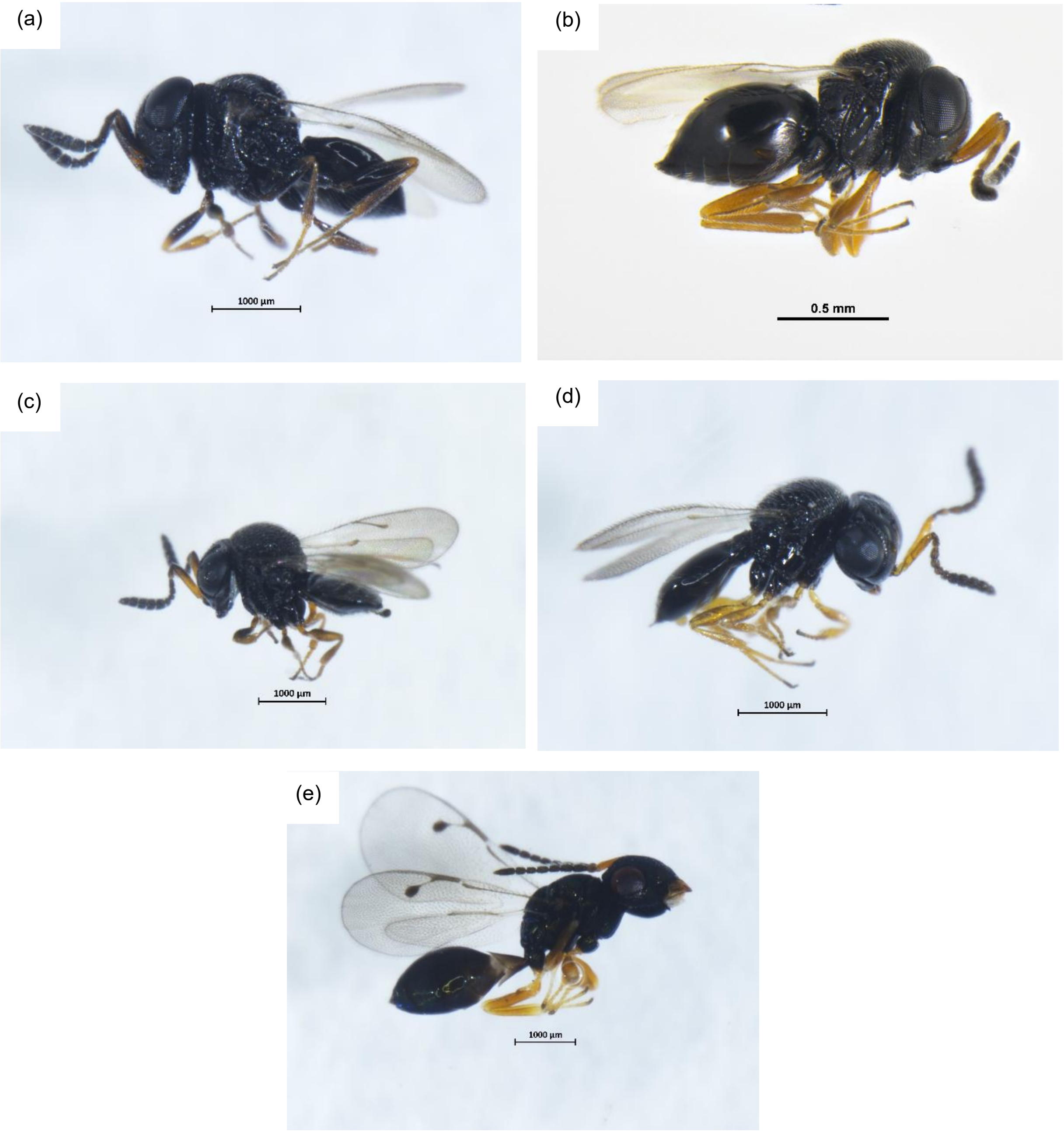
Appendix



Adult parasitoid species recovered during field surveys conducted during three consecutive summer seasons (Nov–March) in five different regions in New Zealand: (a) *Trissolcus oenone*, (b) *Trissolcus basalis*, (c) *Trissolcus* sp., (d) *Telenomus* sp., and (e) *Acroclisoides* sp. (hyperparasitoid).

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