Selectivity of mycoinsecticides and a pyrethroid to the egg parasitoid Cleruchoides noackae (Hymenoptera: Mymaridae)

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Plants of the genus Eucalyptus, cultivated in many countries, have great importance for the world economy. In Brazil, this culture occupies a total of 5.7 million hectares, but native and exotic insect pests can reduce its productivity. Thaumastocoris peregrinus Carpintero & Dellapé (Hemiptera: Thaumastocoridae), an exotic Australian pest, damages Eucalyptus plants. Biological control using the egg parasitoid Cleruchoides noackae Lin & Huber (Hymenoptera: Mymaridae), Heteroptera predators and entomopathogenic fungi, such as Beauveria bassiana and Metarhizium anisopliae, have potential for managing T. peregrinus. Chemical insecticides, including bifenthrin and acetamiprid + bifenthrin, also control this insect. The compatibility of chemical and biological control methods favors integrated pest management. The objective of this study was to evaluate the selectivity of commercial products based on B. bassiana, M. anisopliae and the chemical bifenthrin on the parasitoid C. noackae and its parasitism on T. peregrinus eggs. The selectivity test followed the standards recommended by the International Organization for Biological Control (IOBC). Beauveria bassiana has selectivity to parasitism as well as viability, but was slightly harmful to C. noackae adults; M. anisopliae was innocuous to adults and to the viability of the offspring of this parasitoid, but it reduced the parasitism rate; and bifenthrin did not show selectivity to this parasitoid.

The area of commercially planted forests in the world increased from 167.5 to 277.9 million hectares from 1990 to 20151. Brazil presently has 5.7 million hectares of Eucalyptus plantations with 24%, 17% and 15% of them in the states of Minas Gerais, São Paulo and Mato Grosso do Sul, respectively. The wood from these plantations is mainly destined for the pulp industry, with a production of 21 million tons in 20182,3.

Insect pests of Australian origin detected in planted forests during the last three decades on a global scale may reduce Eucalyptus productivity4. The bronze bug, Thaumastocoris peregrinus Carpintero & Dellapé (Hemiptera: Thaumastocoridae), was first detected in Brazil in 2008 in the states of São Paulo and Rio Grande do Sul, and has since dispersed to other Eucalyptus-producing states5. This insect develops and produces fertile offspring on most Eucalyptus plantations in Brazil6. Thaumastocoris peregrinus perforates and causes silvering, tanning, drying and defoliation from Eucalyptus plants7.

Biological control is the most widely-used method for managing T. peregrinus8. This method includes the egg parasitoid Cleruchoides noackae Lin & Huber (Hymenoptera: Mymaridae), imported from Australia8,9, the predators Atopozelus opsimus Elkins (Hemiptera: Reduviidae)10 and Supputius cincticeps Stål (Heteroptera: Pentatomidae)11,12 and entomopathogenic fungi13,14. Beauveria bassiana and Metarhizium anisopliae, registered

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commercially and considered to offer reduced risks, are the most studied entomopathogenic fungi. The chemical insecticides bifenthrin and acetamiprid + bifenthrin are also used to control T. peregrinus in Eucalyptus plantations.

Natural enemies are important in pest control in planted forests, justifying the search for compatible microbial and chemical products. The mycoinsecticides and chemical insecticides must have selectivity to the pest natural enemies in order to maintain the effectiveness of the combined use of these methods.

The objective of this study was to evaluate the effect of commercial products based on B. bassiana and M. anisopliae and of the chemical insecticide bifenthrin on the egg parasitoid C. noackae and on its parasitism on T. peregrinus eggs.

Results

Mortality of Cleruchoides noackae adults. The mortality of C. noackae adults was higher with bifenthrin after the first and tenth hours of exposure to this chemical, with 67% and 90.6%, respectively. Biological products based on B. bassiana and M. anisopliae caused mortality of 40.8% and 22.6%, respectively, of C. noackae adults after 10 h of exposure, higher than the control, distilled and autoclaved water, which was 18% (Fig. 1).

Bifenthrin was moderately harmful, B. bassiana was mildly harmful, and M. anisopliae was innocuous to C. noackae adults, presenting a reduction in the beneficial ability of the parasitoid [%E = 100 − (average for each insecticide/average for the percentage in the control treatment) × 100] of 90.60, 40.80 and 22.60, respectively, according to IOBC classification (Table 1). Table 1. Mortality (%) of Cleruchoides noackae (Hymenoptera: Mymaridae) adults, through contact with the biological insecticides Beauveria bassiana (B.b.) and Metarhizium anisopliae (M.a.) and the chemical bifenthrin (Bifenth.) as treatments (Treat.) (temp.: 25 ± 1°C, RH: 70 ± 10% and photophase: 12 h) and classes of these products (Cl.). Means followed by the same uppercase letter per line or lower case per column do not differ according to the Tukey test (p ≤ 0.05). a %E: reduction in the beneficial capacity of the parasitoid. b Cl—class 1—harmless (E < 30%), class 2—slightly deleterious (30% ≤ E ≤ 79%), class 3—moderately harmful (80% ≤ E ≤ 99%), class 4—harmful (E > 99%).

Parasitism and viability of C. noackae on treated T. peregrinus eggs. Parasitism by C. noackae differed between treatments (ANOVA; F = 4.9259, P = 0.01862), with a lower value for the bifenthrin than in the control, B. bassiana or M. anisopliae. Bifenthrin was moderately harmful (%E = 88.89), B. bassiana innocuous (%E = 2.8), and M. anisopliae slightly deleterious (%E = 36.12) to C. noackae parasitism on treated T. peregrinus eggs. The C. noackae viability ranged from 96 to 100% between treatments, with all the products being classified as harmless (%E = 0 to 5) (Table 2).
At the cellular level, these compounds stimulate the neurons to produce repetitive discharges, leading to membrane depolarization and synaptic disorders. Cyanide pyrethroids, such as organic acids involved in the infection process and linear and cyclic peptidic toxins such as beauvericin from the mycelium of this fungus, lead to that reported with this fungus on Cotesia flavipes because some isolates may be highly specific and others infect a wide host range. The mortality of galloi during the first day of this natural enemy life.

Viability of C. noackae in eggs parasitized and treated after one and 10 days of exposure to the insecticides. C. noackae viability in T. peregrinus eggs treated with the insecticides after one day of parasitism differed between treatments (ANOVA; F = 4.301, P = 0.0126), with a lower value for the bifenthrin than in the control and with the product B. bassiana having a value similar to that of M. anisopliae (Table 3). Bifenthrin reduced the viability of this natural enemy on parasitized eggs after 10 days (ANOVA; F = 6.460, P = 0.0018). This chemical was slightly harmful (%E = 30.11 and 34.08), and M. anisopliae (%E = 13.02 and 1.68) and B. bassiana (%E = 4.75 and 4.60) innocuous, after one and 10 days, respectively, for the parasitoid C. noackae (Table 3).

Table 2. Parasitism (Paras.) and viability (Viab.) (% ± SD) (%) and reduction in the beneficial capacity of the parasitoid Cleruchoides noackae (Hymenoptera: Mymaridae) (% E) on Thaumastocoris peregrinus (Hemiptera: Thaumastocoridae) eggs treated with different insecticides (temp.: 25 ± 1°C, RH: 70 ± 10% and photophase: 12 h) and class of these products (Cl.). Means followed by the same lowercase letter per column do not differ according to the Tukey test (p ≤ 0.05).

| Treatments                  | Paras. (%) | %E   | Cl | Viab. (%) | %E   | Cl |
|-----------------------------|------------|------|----|-----------|------|----|
| Control                     | 72 ± 15.94a| 0.00 | 1  | 100 ± 0.00a| 0.00 | -  |
| Beauveria bassiana          | 70 ± 8.94a | 2.80 | 1  | 96 ± 4.47a | 5.00 | 1  |
| Metarhizium anisopliae      | 46 ± 15.68ab| 36.12| 2  | 100 ± 0.00a| 0.00 | 1  |
| Bifenthrin                  | 8 ± 4.90b  | 88.89| 3  | 100 ± 0.00a| 0.00 | 1  |

Table 3. Viability (%) and reduction of the beneficial capacity (% E) of the parasitoid Cleruchoides noackae (Hymenoptera: Mymaridae) on Thaumastocoris peregrinus (Hemiptera: Thaumastocoridae) eggs treated with the fungi Beauveria bassiana and Metarhizium anisopliae and with the chemical bifenthrin after one and 10 days of parasitism (temp.: 25 ± 1°C, RH: 70 ± 10% and photophase: 12 h) and class of these insecticides (Cl.). Means followed by the same uppercase letter per line or lower case per column do not differ according to the Tukey test (p ≤ 0.05).

| Treatments                  | Viability (%) | %E | Cl | 1 Day | %E | Cl | 10 days | %E | Cl |
|-----------------------------|----------------|----|----|-------|----|----|---------|----|----|
| Control                     | 99.36 ± 4.4Aa  | 0.00 | 1  | 94.92 ± 9.6Aa | 0.00 | -  |
| Beauveria bassiana          | 94.64 ± 7.3AA  | 4.75 | 1  | 90.55 ± 12.9AA| 4.60 | 1  |
| Metarhizium anisopliae      | 86.42 ± 13.4AAb | 13.02| 1  | 93.33 ± 14.9Ab| 1.68 | 1  |
| Bifenthrin                  | 69.44 ± 16.1Ab | 30.11| 2  | 62.57 ± 23.2Ab| 34.08| 2  |

Discussion
The entomopathogenic fungi tested were chosen according to the knowledge and use of these microorganisms in biological control, as well as their reduced environmental impact. Selectivity tests show the low impact of products on non-target organisms, and allow the recommendation of combinations of mycoinsecticides and chemical insecticides to manage harmful organisms.

The higher mortality of C. noackae adults produced by bifenthrin shows that this chemical is moderately harmful, like most pyrethroids that keep the sodium channels of the neuron membranes open and reach the insect peripheral and central nervous systems. At the cellular level, these compounds stimulate the neurons to produce repetitive discharges, leading to membrane depolarization and synaptic disorders. Cyanide pyrethroids cause hypersensitivity, choreoathetosis, tremors, paralysis and insect mortality. The classification of B. bassiana as slightly harmful to C. noackae adults may be related to the production of secondary metabolites, such as organic acids involved in the infection process and linear and cyclic peptidic toxins such as beauvericin from the mycelium of this fungus. The lack of Metarhizium anisopliae toxicity to C. noackae adults is similar to that reported with this fungus on Cotesia flavipes Cameron (Hymenoptera: Braconidae) and Trichogramma galloi Zucchi (Hymenoptera: Trichogrammatidae). Metarhizium anisopliae is important for biological control because some isolates may be highly specific and others infect a wide host range. The mortality of C. noackae adults at shorter intervals is due to the reduced longevity of this parasitoid: 0.8 to 1.6 days when they were not fed and 3.5 days when they were fed with undiluted honey, evidencing the importance of the evaluations during the first day of this natural enemy life.

The findings of lower C. noackae parasitism in T. peregrinus eggs treated with bifenthrin agree with reports that this compound is slightly to moderately harmful to Trichogramma chilonis Ishii, Trichogramma ostriniae Pang & Chen, and Trichogramma dendrolimi Matsumura (Hymenoptera: Trichogrammatidae) and harmful to Encarsia formosa Gahan, Encarsia pergandiella Howard (Hymenoptera: Aphelinidae), Theocolax elegans Westwood (Hymenoptera: Pteromalidae), Eretmocerus mundus Mercet (Hymenoptera: Aphelinidae) and Telenomus podisi Ashmead (Hymenoptera: Platygastriidae), a common impact related to the pyrethroid action mode. The effect of M. anisopliae, being slightly harmful to C. noackae parasitism on T. peregrinus eggs, differs from that reported for Spalangia cameroni Perkins (Hymenoptera: Pteromalidae), without reduction of its total female reproduction, and innocuous to Trichogramma pretiosum Riley and T. galloi (Hymenoptera: C. noackae in eggs parasitized and treated after one and 10 days of exposure to the insecticides. C. noackae viability in T. peregrinus eggs treated with the insecticides after one day of parasitism differed between treatments (ANOVA; F = 4.301, P = 0.0126), with a lower value for the bifenthrin than in the control and with the product B. bassiana having a value similar to that of M. anisopliae (Table 3). Bifenthrin reduced the viability of this natural enemy on parasitized eggs after 10 days (ANOVA; F = 6.460, P = 0.0018). This chemical was slightly harmful (%E = 30.11 and 34.08), and M. anisopliae (%E = 13.02 and 1.68) and B. bassiana (%E = 4.75 and 4.60) innocuous, after one and 10 days, respectively, for the parasitoid C. noackae (Table 3).
Trichogrammatidae) parasitism\textsuperscript{29,39}. These differences may be due to the specificity of cyclic peptidic toxins, called destruxins, related to \textit{M. anisopliae} pathogenicity\textsuperscript{46}. The lack of reduction of parasitism by \textit{B. bassiana} is similar to that observed with \textit{T. pretiosum} \textsuperscript{38}, evidencing the selectivity of this fungus to natural enemies. The similar \textit{C. noackae} viability on \textit{T. peregrinus} eggs between treatments demonstrates that the products tested are innocuous to the development of this parasitoid in eggs of this host.

The lower \textit{C. noackae} viability with bifenthrin, sprayed on \textit{T. peregrinus} eggs at one and 10 days after parasitism, classified as slightly deleterious, differs from the classification of this chemical as having extremely low toxicity for the parasitoids \textit{Eretmocerus tejanus} Rose & Zolnerowich and \textit{E. mundus} (Hymenoptera: Apheleidae), when applied at five and 14 days after parasitism\textsuperscript{41}. This may be related to differences in the host development stage, since \textit{C. noackae} is protected inside \textit{T. peregrinus} eggs\textsuperscript{42}, not allowing its direct contact with the insecticide. On the other hand, this differs from the effect on the larval parasitoids \textit{E. tejanus} and \textit{E. mundus}\textsuperscript{41} with a higher exposure to the chemical. The classification of mycoinsecticides as innocuous to \textit{C. noackae} viability on \textit{T. peregrinus} eggs parasitized at one and 10 days agrees with that observed for \textit{Palmistichus elaeisis} Delvare & LaSalle, \textit{Tetrastrichus howardi} Olliff and \textit{Trichospilus diatraeae} Cherian & Margabandhu (Hymenoptera: Eulophidae)\textsuperscript{43} and for \textit{Telenomus remus} Nixon (Hymenoptera: Platygastridae)\textsuperscript{44}, due to the specificity of the entomopathogenic fungi\textsuperscript{45} without impact on the development of egg parasitoids.

\textit{Beauveria bassiana} and \textit{M. anisopliae}, with high selectivity and low impact through contact with adults and in the parasitism and offspring of \textit{C. noackae}, respectively, have potential for joint use with this parasitoid in pest management programs. However, these mycoinsecticides should be applied 3 days after releasing this parasitoid, avoiding contact with their adults at the time of parasitism. Bifenthrin, the first chemical insecticide registered to control \textit{T. peregrinus}\textsuperscript{42}, cannot be used with the \textit{C. noackae} egg parasitoid to manage this pest.

\textit{Beauveria bassiana}-based mycoinsecticides have selectivity to parasitism and viability and are slightly harmful to \textit{C. noackae} adults; \textit{Metarhizium anisopliae} was innocuous to adults and to the viability of this natural enemy offspring, but it reduced \textit{C. noackae} parasitism on \textit{T. peregrinus}; bifenthrin did not show selectivity in all bioassays.

**Methods**

**Place of study.** The work was carried out at the Laboratory of Biological Control of Forest Pests (LCBPF), Department of Plant Protection, School of Agricultural Sciences, Campus of Botucatu, São Paulo, Brazil, at 25 ± 1 °C, 70 ± 10% relative humidity and photophase of 12 h.

**Rearing \textit{Thaumastocoris peregrinus}.** \textit{Thaumastocoris peregrinus} adults were collected on two-year-old \textit{Eucalyptus grandis} × \textit{E. urophylla} plants at the FCA/UNESP and taken to the laboratory for mass rearing\textsuperscript{46}.

Branches of the hybrid \textit{Eucalyptus urophylla} var. \textit{platyphylla} (clone 433) were collected from two-year-old trees, and arranged in bouquets with their bases in 250-ml Erlenmeyer flasks with water on a rectangular plastic tray (40 cm long × 35 cm wide × 8 cm high) to mass rear \textit{T. peregrinus} in the laboratory. These bouquets were changed every three or four days depending on the need and leaf conditions. On the day of the exchange, the oldest and driest bouquets were placed next to new ones to facilitate the insect migration to the latter\textsuperscript{46}.

**Rearing the parasitoid \textit{Cleruchoides noackae}.** \textit{Thaumastocoris peregrinus} eggs, parasitized by \textit{C. noackae}, were obtained from the LCBPF. Paper towel strips (1.5 cm wide × 15.0 cm long) were arranged in the upper portion of the leaves of the \textit{T. peregrinus} breeding bouquets to obtain their eggs. \textit{Cleruchoides noackae} were multiplied with \textit{T. peregrinus} eggs with two to three days of age in transparent polystyrene bottles (7.5 cm high × 3.0 cm diameter).

Newly emerged \textit{C. noackae} adults were transferred with a brush to another transparent polystyrene flask with paper towel strips with two- to three-day-old eggs obtained from the \textit{T. peregrinus} rearing. \textit{Cleruchoides noackae} were fed with 50% honey solution in filter paper strips (7.0 cm high × 1.5 cm wide)\textsuperscript{47}.

**Selectivity test.** The selectivity of mycoinsecticides and the bifenthrin-based insecticide to \textit{C. noackae} adults and to their parasitism was evaluated in four treatments (Table 4), according to the protocol of the IOBC with the standard test cage\textsuperscript{48}.

| AP          | TM              | Man       | Conc       | Dose     | For       |
|------------|-----------------|-----------|------------|----------|-----------|
| \textit{B. bassiana} | BOVERIL® WP PL63 | KBS       | 1.0 × 10⁷ conidia/g | 2 kg/ha | WP        |
| \textit{M. anisopliae} | METARRIL® WP E9  | KBS       | 1.0 × 10⁷ conidia/g | 0.5 kg/ha | WP        |
| Bifenthrin | CAPTURE 400 EC   | FMC       | 400 g/L    | 100 ml/ha | EC        |
| Control    | –                | –         | –          | –        | –         |

*Table 4. Active principle (AP) and trademark (TM), manufacturer (Man.), concentration (Conc.), dose and formulation (For.) wettable powder (WP) and emulsifiable concentrate (EC) of the biological insecticides, based on \textit{Beauveria bassiana} (\textit{B. bassiana}) and \textit{Metarhizium anisopliae} (\textit{M. anisopliae}), and the chemical bifenthrin used in the selectivity tests with the parasitoid \textit{Cleruchoides noackae} (Hymenoptera: Mymaridae). KBS Koppert Biological Systems, FMC FMC Química do Brasil Ltda.*
One ml per replication of the biological and chemical products was applied in a Potter Tower on the surface of the cages designed according to the standard described by the IOBC and on parasitized or non-parasitized *T. peregrinus* eggs. Three bioassays were performed. The first test evaluated the indirect action in the mortality of the parasitoid, exposed to contact with the biological and chemical products, using 100 new individuals per treatment, in five replications of 20 individuals each (per cage). The control had only distilled and autoclaved water. The parasitoids were released in the treated cages and their mortality, after contact with the treated surface, was evaluated.

The second bioassay evaluated the direct action on parasitism and the viability of *C. noackae* on *T. peregrinus* eggs treated with the insecticides, with five replications per treatment and 10 eggs, each one offered to a pair of the parasitoids per cage. Paper towel strips with one-day-old *T. peregrinus* eggs were treated with the insecticides, dried at room temperature and offered to each *C. noackae* couple for 24 h.

The third bioassay evaluated the *C. noackae* viability with the products. One-day-old *T. peregrinus* eggs, exposed to each *C. noackae* couple for 24 h, were treated in a Potter Tower after one and 10 days post-parasitism, respectively. Five replications with 10 eggs each were used per treatment (Table 4) and age after parasitism (one and 10 days), totaling 400 eggs.

**Data evaluation.** Mortality, parasitism and viability (%) of *C. noackae* were evaluated. Mortality of this parasitoid was evaluated after the first hour of contact with the insecticides and then every three hours until completing 10 h, due to its reduced longevity. Parasitism and viability of *C. noackae* were evaluated after 13 days of parasitism (parasitoid cycle), considering emerged and retained parasitoids and non-parasitized and infertile eggs. The percentage of reduction in parasitoid beneficial ability was calculated for each of the analyzed variables (survival, parasitism and viability; %E) with the equation: %E = [(100 − (average for each insecticide/average for the percentage in the control treatment)) × 100] to classify the products according to IOBC standards: class 1—innocuous (E < 30%); class 2—slightly deleterious (30 ≤ E ≤ 79%); class 3—moderately harmful (80 ≤ E ≤ 99%); and class 4—harmful (E > 99%).

The design was completely randomized, the data submitted to variance analysis and the means compared by the Tukey test at 5% probability using the R Studio software.

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**References**

1. Payn, T. *et al.* Changes in planted forests and future global implications. *For. Ecol. Manag.* 357, 57–67 (2015).
2. [IBÁ] *Indústria Brasileira De Árvores. Cenários Ibá Dezembro de 2018.* https://www.iba.org/datafiles/e-mail-marketing/cenarios/56-cenarios_2.pdf. Accessed 07 March 2019.
3. Carvalho, K. H. A., Silva, M. L. & Soares, N. S. Efeito da área e da produtividade na produção de celulose no Brasil. *Rev. Árvore* 36, 1119–1128. https://doi.org/10.1590/S0100-67622012000600012 (2012).
4. Paine, T. D., Steinbauer, M. J. & Lawson, S. A. Native and exotic pests of *Eucalyptus*: A worldwide perspective. *Annu. Rev. Entomol.* 56, 181–201 (2011).
5. Wilcken, C. F. *et al.* Bronze bug *Thaumastocoris peregrinus* Carpentero & Dellapi (Hemiptera: Thaumastocoridae) on *Eucalyptus* in Brazil and its distribution. *J. Plant Prot. Res.* 50, 201–205 (2010).
6. Soliman, E. P. *et al.* Biology of *Thaumastocoris peregrinus* in different *Eucalyptus* species and hybrids. *Phytoparasitica* 40, 223–230 (2012).
7. Lima, A. C. V., Wilcken, C. F., Ferreira-Filho, P. J., Serrão, J. E. & Zanuncio, J. C. Intra-plant spatial distribution of *C. noackae* (survival, parasitism and viability; %E) with the equation: %E = [(100 − (average for each insecticide/average for the percentage in the control treatment)) × 100] to classify the products according to IOBC standards: class 1—innocuous (E < 30%); class 2—slightly deleterious (30 ≤ E ≤ 79%); class 3—moderately harmful (80 ≤ E ≤ 99%); and class 4—harmful (E > 99%).
8. Nadel, R. L. & Noack, A. E. Current understanding of the biology of *Thaumastocoris peregrinus* in the quest for a management strategy. *Int. J. Pest Manag.* 58, 257–266 (2012).
9. Barbosa, L. R. *et al.* Development of *Cleruchoides noackae*, an egg-parasitoid of *Thaumastocoris peregrinus*, in eggs laid on different substrates, with different ages and post-cold storage. *Biocontrol* 63, 193–202. https://doi.org/10.1016/j.biocontrol.2015.08.002 (2015).
10. Dias, T. K. R. *et al.* Predation of *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae) by *Atopezelus opimus* (Hemiptera: Reduviidae) in Brazil. *ISI-Invert. Surviv.* J. 11, 224–227 (2014).
11. Souza, G. K. *et al.* First record of a native heteropteran preying on the introduced *Eucalyptus* pest, *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae), in Brazil. *Fla. Entomol.* 95, 517–520 (2012).
12. Zanuncio, J. C., Tavares, W. D. S., Fernandes, B. V., Wilcken, C. F. & Zanuncio, T. V. Production and use of *Heteroptera* predators for the biological control of *Eucalyptus* pests in Brazil. *Ekologia* 23, 98–104 (2014).
13. Lorenzetti, G.A.T. *et al.* Eficiência de *Beauveria bassiana* Vuill. e *Isaria* sp. para o controle de *Thaumastocoris peregrinus* Carpentero & Dellapi (Hemiptera: Thaumastocoridae) em substratos de *Eucalyptus* grandis. *Phytoparasitica* 44, 411–418. https://doi.org/10.1007/s12680-016-0526-1 (2016).
14. Nadel, R. L. & Noack, A. E. Current understanding of the biology of *Thaumastocoris peregrinus* in the quest for a management strategy. *Int. J. Pest Manag.* 58, 257–266 (2012).
15. Barbosa, L. R. *et al.* Development of *Cleruchoides noackae*, an egg-parasitoid of *Thaumastocoris peregrinus*, in eggs laid on different substrates, with different ages and post-cold storage. *Biocontrol* 63, 193–202. https://doi.org/10.1016/j.biocontrol.2015.08.002 (2015).
16. Soliman, E. P. *et al.* Susceptibility of *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae), a *Eucalyptus* pest, to entomopathogenic fungi. *Sci. Agr.* 55, 255–260 (2019).
17. [Agrofit] *Ministério da Agricultura, pecuária e abastecimento Brasil Sistema de Agrótocicos Fitossanitários.* https://agrofit.agricultura.gov.br/agrofit/cons_consul_produtos/consumidor?ap_id_consul_produtos=48780_b7954d6d-1c7b-4e6d-9f6b-8c3093f6576f. Accessed 27 Jan 2019.
18. Zimmermann, G. *Review on safety of the entomopathogenic fungi Beauveria bassiana and Beauveria brongniartii.* *Biocontrol Sci. Techn.* 17, 553–596 (2007).
19. Zimmermann, G. *Review on safety of the entomopathogenic fungus Metarhizium anisopliae.* *Biocontrol Sci. Techn.* 17, 879–920 (2007).
20. Feltrin-Campos, E., Ringenberg, R., Carvalho, G.A., Glasser, D.E. & Oliveira, H.N. Selectivity of insecticides against adult *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) on cassava. *J. Agri. Sci.-Camb.* 114, 546–552 (2019).
21. Wei, D. A. I. *et al.* Selectivity and sublethal effects of some frequently-used biopesticides on the predator *Cyrtothrips luidipennis* Reuter (Hemiptera: Miridae). *J. Integr. Agr.* 18, 124–133 (2019).
22. Maciel, C. G. *et al.* *Trichoderma spp* no biocontrole de *Cyndrocladium cadwaladerum* em mudas de *Eucalyptus saligna*. *Rev. Árvore* 36, 825–832 (2012).
23. Lacey, L. A. *et al.* Insect pathogens as biological control agents: back to the future. *J. Invertebr. Pathol.* 132, 1–41 (2015).
22. Scott, J. G. Life and death at the voltage-sensitive sodium channel: evolution in response to insecticide use. *Annu. Rev. Entomol.* **64**, 243–257 (2019).
23. Dong, K. et al. Molecular biology of insect sodium channels and pyrethroid resistance. *Insect Biochem. Mol. Biol.* **50**, 1–17 (2014).
24. Soderlund, D. M. & Bloomquist, J. R. Neurotoxic actions of pyrethroid insecticides. *Annu. Rev. Entomol.* **34**, 77–96 (1989).
25. Narahashi, T. Neuronal ion channels as the target sites of insecticides. *Basic Clin. Pharmacol.*, **79**, 1–14 (1996).
26. Logrieco, A. et al. Beauvericin production by *Fusarium* species. *Appl. Environ. Microbiol.* **64**, 3084–3088 (1998).
27. Hugo, M. C. V., Navarro, S. R., Florido, J. E. B., Sierra, R. T. & Tovar, D. C. Metabolites y coníodos de *Beauveria bassiana* como control de mosco negro fungoso, bajo condiciones de invernadero. *Southwest. Entomol.* **43**, 691–703 (2018).
28. Rossoni, C. et al. *Metarhizium anisopliae* and *Beauveria bassiana* (Hypocreales: Clavicipitaceae) are compatible with *Cotesia flavipes* (Hymenoptera: Braconidae). * Fla Entomol.* **97**, 1794–1804 (2014).
29. Oliveira, H. N., Antigo, M. D. R., Carvalho, G. A., Glaeser, D. F. & Pereira, F. F. Selectivity of insecticides used in the sugar-cane on adults of *Trichogramma gallii* Zucchi (Hymenoptera: Trichogrammatidae). *Biosci.* **J.** **29**, 1267–1274 (2013).
30. Clarkson, J. M. & Charnley, A. K. New insights into the mechanisms of fungal pathogenesis in insects. *Trends Microbiol.* **4**, 197–203 (1996).
31. Mutti, E. K. et al. Biology and rearing of *Cleruchoides noaakae* (Hymenoptera: Mymaridae), an egg parasitoid for the biological control of *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae). *J. Econ. Entomol.* **106**, 1979–1985 (2013).
32. Souza, A. R. et al. Longevity of *Cleruchoides noaakae* (Hymenoptera: Mymaridae), an egg parasitoid of *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae), with various honey concentrations and at several temperatures. *Fla. Entomol.* **99**, 33–37 (2016).
33. Cheng, S. et al. Comparative susceptibility of thirteen selected pesticides to three different insect egg parasitoid *Trichogramma* species. *Ecotox. Environ. Safe.* **166**, 86–91 (2018).
34. Jones, W. A., Wolfenbarger, D. A. & Kirk, A. A. Response of adult parasitoids of *Bemisia tabaci* (Hom.: Aleyrodidae) to leaf residues of selected cotton insecticides. *Entomophaga* **40**, 153–162 (1995).
35. Oliveira, E. E., Aquiar, R. W. S., Sarmento, R. A., Tuelher, E. S. S. and Guedes, R. N. C. Seletividade de inseticidas a *Thecolax elegans* parasitode de *Sitophilus zeamais*. *Biosci. J.* **18**, 11–16 (2002).
36. Fernández, M. D. M. et al. Effect of a long-lasting bifenthrin-treated net against horticultural pests and its compatibility with the predatory mite *Amblyseius swirskii* and the parasitic wasp *Eretmocerus mundus*. * Pest Manag. Sci.* **73**, 1689–1697 (2017).
37. Stecca, C. S. et al. Impact of insecticides used in soybean crops to the egg parasitoid *Telenomus podisi* (Hymenoptera: Platygastriidae). *Neotrop. Entomol.* **47**, 281–291 (2018).
38. Nielsen, C., Skogvård, H. & Steenberg, T. Effect of *Metarhizium anisopliae* (Deuteromycotina: Hypocreaceae) on survival and reproduction of the fly fly parasitoid, *Spalangia cameroni* (Hymenoptera: Pteromalidae). *Environ. Entomol.* **34**, 133–139 (2005).
39. Potrich, M. et al. Seletividade de *Beauveria bassiana* e *Metarhizium anisopliae* a *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae). *Neotrop. Entomol.* **38**, 822–826 (2009).
40. Kershaw, M. J., Moorhouse, E. R., Bateman, R., Reynolds, S. E. & Charnley, A. K. The role of destruxins in the pathogenicity of *Metarhizium anisopliae* for three species of insect. *J. Invertebr. Pathol.* **74**, 213–223 (1999).
41. Jones, W. A., Giompikerl, M. A. & Wolfenbarger, D. A. Lethal and sublethal effects of insecticides on two parasitoids attacking *Bemisia argentifolii* (Homoptera: Aleyrodidae). *Biocontrol* **11**, 70–78 (1998).
42. Souza, G. K. et al. Reproductive tract histology of *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae). *Ann. Entomol. Soc. Am.* **107**, 853–857 (2014).
43. Rossoni, C. et al. Development of *Eulophidae* (Hymenoptera) parasitoids in *Diatraea saccharalis* (Lepidoptera: Crambidae) pupae exposed to entomopathogenic fungi. *Can. Entomol.* **148**, 716–723 (2016).
44. Amaro, J. T. et al. Selectivity of different biological products to the egg parasitoid *Telenomus remus* (Hymenoptera: Platygastriidae). *Rev. Bras. Entomol.* **62**, 195–197 (2018).
45. Sarwar, M. Biopesticides: an effective and environmentally friendly insect-pests inhibitor line of action. *Int. J. Eng. Adv. Res. Technol.*, **1**, 10–15 (2015).
46. Barbosa, L.R. et al. Criação massal do percevejo bronzeado, *Thaumastocoris peregrinus*: Carpinheiro e Dellapé, 2006 (Hemiptera, Thaumastocoridae). https://ainfo.cnptia.embrapa.br/digital/bitstream/item/145907/1/Criacao-massal-do-percevejo-bronzeado. pdf (2016). Accessed 02 Nov 2018.
47. Barbosa, L.R. et al. Orientações para a criação massal e liberação em campo de *Cleruchoides noaakae* para controle biológico do percevejo bronzeado do eucalipto. https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1081194/1/LivroTA1393comp-leto.pdf (2017). Accessed 02 Nov 2018.
48. Hassan, S. A. Guidelines for testing the effects of pesticides on beneficial organisms: Description of test methods. *Bull. OILB SROP/ IOBC WPRS Bull.* **15**, 186p (1992).

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**Competing interests**

The authors declare no competing interests.

**Additional information**

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