Ecotoxicology and Environmental Safety 208 (2021) 111504

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Pesticide selectivity to the parasitoid *Trichogramma pretiosum*: A pattern 10-year database and its implications for Integrated Pest Management

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ARTICLE INFO

Keywords:
Egg parasitoid
Biological control
Meta-analysis
Chemical control
Temperate fruit trees
Annual crops

ABSTRACT

Trichogramma pretiosum is one of the main egg parasitoids used in the control of lepidopteran pests in Brazil. This natural enemy can be negatively affected by the use of insecticides, herbicides, and fungicides. The present work used a systematic review and meta-analysis to group information from multiple studies on the selectivity of pesticides (279 commercial products) in rice, corn, soybean, apple and peach crops for immature stages (egg-larva, pre-pupa, and pupa) and adult parasitoids. The selected studies used the International Organization for Biological and Integrated Control (IOBC) methodology with the same adaptations for *T. pretiosum*. The meta-analysis found that corn crops had the highest frequency of tests (2 0 7). The most frequently tested active ingredients (a.i.) were glyphosate, glyphosate isopropylamine salt, and sulfur at frequencies of 41, 32 and 24 tests, respectively. The pesticides registered for rice crops showed the greatest sublethal effects on *T. pretiosum,* with an approximately 47% reduction in parasitism (RP) or emergence (RE). The adult stage of the parasitoid showed greater sensitivity to the tested pesticides (65% RP), in comparison to the immature stages. In general, insecticides showed superior toxicity for all development stages of *T. pretiosum*, compared to herbicides and fungicides, regardless of the recommended dosage for the crop. The present study aggregates information related to selectivity for the four life stages of *T. pretiosum*, contributing significantly to the integration of biological control and chemical control in rice, corn, soybean, apple and peach crops in Brazil.

1. Introduction

The egg parasitoid *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) is one of the main natural enemies of lepidopteran pests that infest agricultural crops in Brazil, such as *Anticarsia gemmatalis* (Hübner) (Lepidoptera: Noctuidae) and *Chrysodeixis includens* (Walker) (Lepidoptera: Noctuidae) in soybean crops (Bueno et al., 2012), *Diatraea saccharalis* Fabricius (Lepidoptera: Crambidae) in rice crops (Ko et al., 2014), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) and *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) in corn crops (Foresti et al., 2013) and *Grapholita molesta* (Busk) (Lepidoptera: Tortricidae) in apple and peach crops (Rodrigues et al., 2011). Furthermore, this species is the most abundant natural enemy species in Latin American production fields (Querino and Zucchi, 2011; Stecca et al., 2016; Carvalho et al., 2019).

In Brazil, the use of *Trichogramma* spp. for the management of pest arthropods stands out mainly due to the ease of multiplication using mass rearing techniques in the laboratory (Coelho and Parra, 2013). This fact attracted the interest of several commercial companies that currently produce this natural enemy at a large scale (Parra, 2019). Thus, the use of this egg parasitoid is part of one of the largest biological control programs in the world (Parra, 2019; Parra and Coelho, 2019).

However, *T. pretiosum* can be affected by the use of insecticides, herbicides, and fungicides in production areas (Nicholls et al., 2007; Carvalho et al., 2019). Although herbicide and fungicide molecules target weeds and diseases, respectively, studies have shown that these pesticides can cause deleterious effects on nontarget organisms and compromise natural or applied biological control of pests (Rizzardi

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https://doi.org/10.1016/j.ecoenv.2020.111504
Received 24 April 2020; Received in revised form 8 October 2020; Accepted 12 October 2020
Available online 21 October 2020

et al., 2003; Stefanello et al., 2008a, 2008b; Bueno et al., 2017). In addition, the use of insecticides in the field usually occurs without considering the level of economic damage of pest arthropods, leading to the resurgence of pests, evolution of resistance, outbreaks of secondary pests and mortality of beneficial organisms (Song and Swinton, 2009; Fernandes et al., 2010; Torres and Bueno, 2018).

Aiming to improve the integration of chemical and biological control and promote the success of integrated pest management (IPM) in annual and fruit crops (Moura et al., 2005; Bueno et al., 2017; Torres and Bueno, 2018), the International Organization for Biological and Integrated Control (IOBC) proposed methodologies for assessing the selectivity of pesticides to natural enemies (Candolfi et al., 2000). The results obtained in the selectivity tests serve as a basis for choosing and using products that are lethal to pest insects but with a low impact on natural enemies.

Thus, to analyze studies developed with *T. pretiosum*, a systematic review and the statistical technique known as meta-analysis, whose purpose is to integrate the results of two or more independent studies on the same research, combining, in one measure summary, the results of studies, was used (Lovatto et al., 2007; Moher et al., 2009; Stewart et al., 2012). Based on the facts presented, the objective of this study was to combine data from multiple studies derived from a methodology standardized by the IOBC with the same methodological adaptation on the selectivity of pesticides registered for rice and/or irrigated rice (*Oryza sativa* L.), soybean (*Glycine max* (L.) Merrill), corn (*Zea mays* L.), peach (*Prunus persica* (L.) Batsch), and apple (*Malus domestica* (Borkh.)) crops in Brazil on *T. pretiosum*. Aggregated in a statistical meta-analysis, pesticides were classified according to their sublethal effects (impacts on parasitism or emergence) on the egg parasitoid *T. pretiosum* to generate selectivity information that supports the choice of commercial products more suitable for IPM.

2. Materials and methods

2.1. Database sources

It was used Science Direct, Scielo and Pubmed to generate a database of publications that evaluate the selectivity of pesticides to the egg parasitoid *T. pretiosum*. We also performed a manual search on Google Scholar. The search was limited to these databases because they contained research articles that were available in full text. In addition, our search has focused on publications written in Portuguese and English from 2005 to 2016. The search term with the respective Boolean operator was: "*Trichogramma pretiosum*" OR "IOBC".

2.2. Article screening

The search generated 614 records and, from these, we removed duplicates, reviews, conference and/or congress annals and book chapters. The remaining records were retrieved in full text and inspected in detail.

For study inclusion, four criteria were decisives: 1) Pesticide selectivity studies that quantified the sublethal effects (reduction in parasitism and/or reduction in the emergence) on *T. pretiosum*; 2) Pesticide selectivity studies on *T. pretiosum* carried out in Brazil (wich followed the manufacturer's instructions of pesticides registered in the Ministry of Agriculture, Cattle and Supply (MAPA); 3) Pesticide selectivity studies on *T. pretiosum* carried out under laboratory conditions and wich followed technical standards proposed by IOBC (excluding studies in extended laboratory (semi-field) and field conditions) and 4) Pesticide selectivity studies that used the methodology proposed by Hassan et al. (2000) for bioassays with adult insects and Hassan and Abdelgader (2001) for bioassays with immature stages, with the same methodological adaptations for the species *T. pretiosum* under laboratory conditions (excluding those with little methodological specification).

Based on this, a total of 17 publications met the criteria and were included in the present study (a flow diagram for the systematic review can be seen in Supplementary Material 1). Citations for all publications and extracted data are presented in Supplementary Material 2. We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009) (PRISMA statement) guidelines in including or excluding publications during screening stages.

2.3. Data extraction

2.3.1. Agrochemicals

In total, 279 commercial products were compiled and grouped into 147 a.i. (Supplementary Material 3) registered by the Ministry of Agriculture, Cattle and Supply (MAPA) (Brasil. Ministério da Agricultura, Pecuária e Abastecimento, 2020) for the management of upland rice and/or irrigated rice, soybean, corn, apple and peach pest arthropods from 2005 to 2016. The pesticides dosages used in the bioassays on the egg-larvae, pre-pupa, pupa and adult stages of T. *pretiosum* corresponded to the maximum registration of the pesticide to the respective agricultural crop ($n = 621$).

2.3.2. IOBC classification

The classification of the selectivity of pesticides according to IOBC standards consists of four classes: class 1: harmless (reduced parasitism (RP) or reduced emergence (RE) $< 30\%$); class 2: slightly harmful ($30\% \leq$ (RP/RE) $\leq 79\%$); class 3: moderately harmful ($80\% \leq$ (RP/RE) $\leq 99\%$); and class 4: harmful ((RP/RE) $> 99\%$). The median values of the compiled results were classified according to these standards.

2.4. Statistical analysis

For conducting comparative analyses, a.i. that had a frequency (occurrence) greater than or equal to 3, that is, a.i. that were tested using more than 2 commercial products, a commercial product tested in more than 2 stages of life parasitoid, or a commercial product tested on 3 or more agricultural crops (with different dosages), were used. Of the total of a.i. tabulated, 62 a.i. were used for comparative analysis.

The data collected in the different studies referring to the reduction in parasitism (RP) and reduction in the emergence (RE) of the parasitoid (Supplementary Material 2) were synthesized following the frequency criteria described above, and from the medians of the results, these were analyzed through Kruskal−Wallis nonparametric analysis of variance and respective post hoc test at 5% probability to compare the effects of different agricultural crops, a.i. and life stages of the parasitoid. The analyzes were performed with the statistical software R (RDCT, 2019).

3. Results

Among the analyzed crops, corn corresponded to the highest number of evaluations (207), followed by soybean (179), peach (113), apple (99), and rice (23) ($n = 621$ tests) (Table 1). Apple and peach crops stood out for the high number of harmless pesticides (class 1) to *T. pretiosum*, at 74 and 80, respectively, representing approximately 70% of the total (Table 1). In contrast, corn and soybean crops showed the highest amount of products classified as harmful to the parasitoid (class 4); however, they corresponded to less than 15% of the total products tested on these crops (Table 1). Additionally, the results for rice crops showed that only five of the 23 products tested were harmful (class 4); however, notably, in rice, all products were tested only in the adult parasitoid stage (Table 1). Even in relation to the parasitoid life stages, in all crops analyzed, the highest frequency of tests (greater number of products tested) occurred for the adult stage than for the immature stages (Table 1).

Based on the analysis, the most frequent a.i. in the selectivity tests for *T. pretiosum* were glyphosate, glyphosate isopropylamine salt and sulfur, which were tested 41, 32 and 24 times, respectively, in different commercial products, cultures and life stages of the parasitoid (Fig. 1). The a. i. described as "other" were not used in the comparisons since they had

Table 1
Frequencies of pesticides analyzed in laboratory considering culture, life cycle stages and IOBC classification.

Crop	Type of pesticide			Life cycle stage of *T. pretiosum*				IOBC Classification*				Total
	Fungicide	Herbicide	Insecticide	Adult	Egg	Pre-pupa	Pupa	Class 1	Class 2	Class 3	Class 4	
Apple	48	22	29	51	16	16	16	74	9	7	9	99
Corn	32	60	115	69	46	46	46	127	33	15	32	207
Peach	25	22	66	47	22	22	22	80	10	8	15	113
Rice	8	5	10	23	0	0	0	10	5	3	5	23
Soybean	41	45	93	89	30	30	30	115	26	17	21	179

* IOBC classes: 1 = harmless (<30%); 2 = slightly harmful (30–79%); 3 = moderately harmful (80–99%); 4 = harmful (>99%).

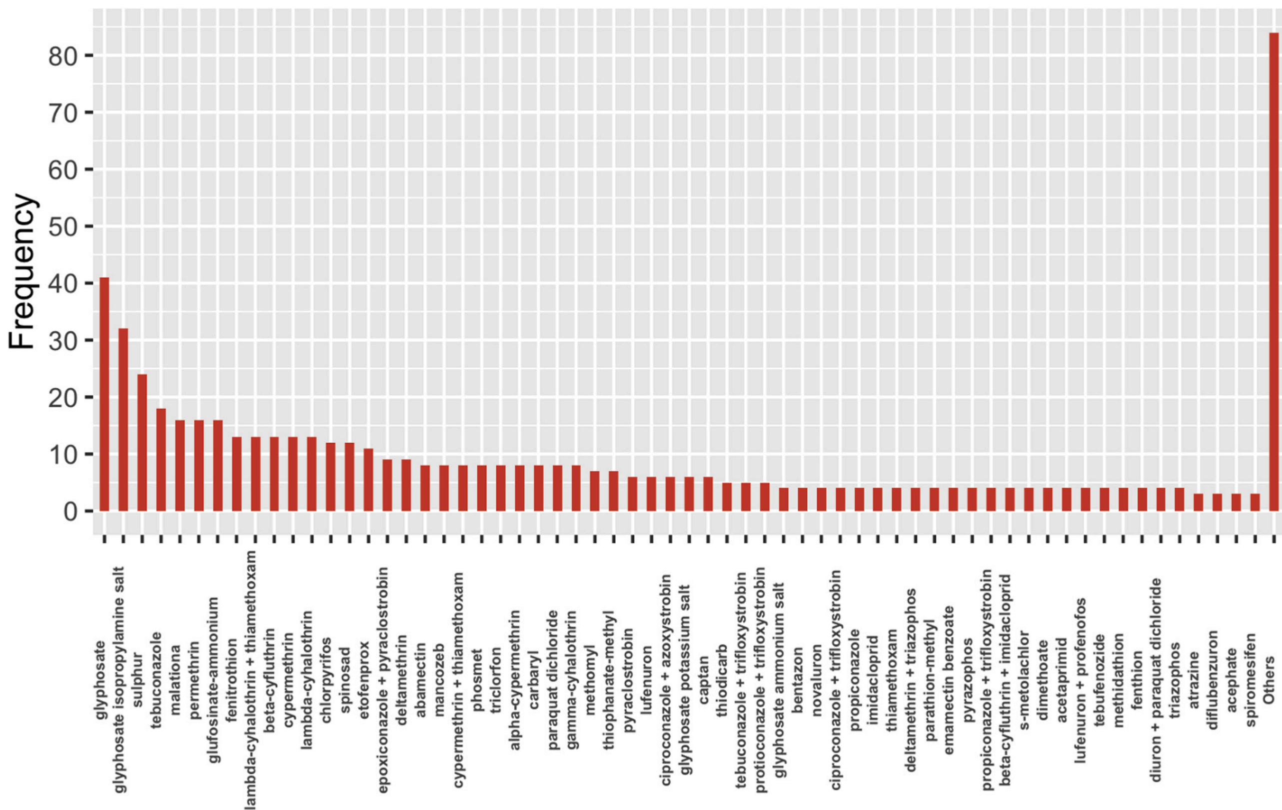

Fig. 1. Frequencies observed by the active ingredients used in the comparison tests for *Trichogramma pretiosum*. * Active ingredients grouped under "Others", were not used in the comparison tests, as they have a frequency below 3.

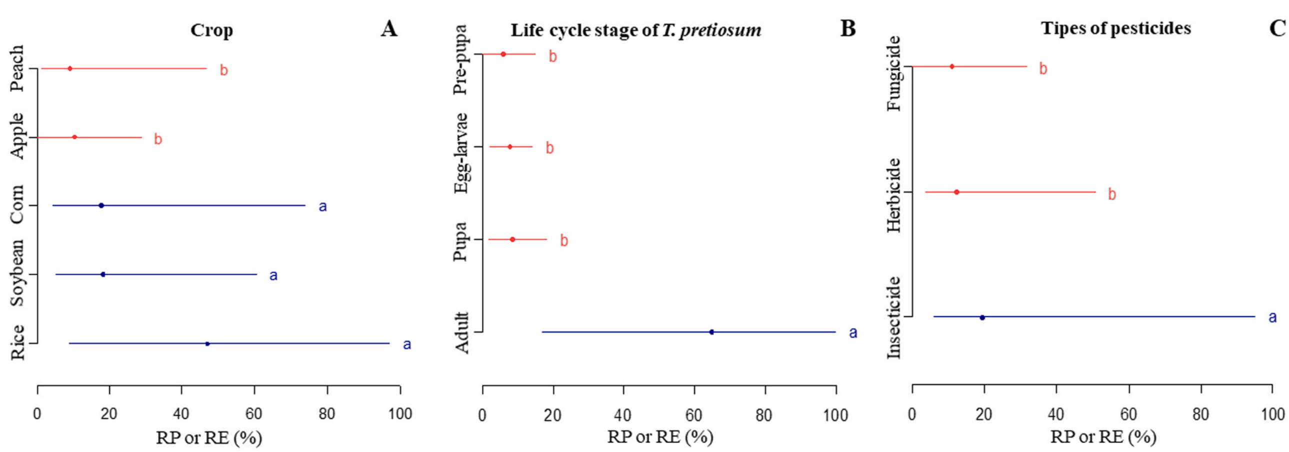

Fig. 2. Percentual reduction of parasitism (RP) or emergence (RE) of different cultures (A) life cycle stages of *Trichogramma pretiosum* (B) and pesticide evaluated (C). (A: kw = 17.22; df = 4; p-value = 0.0018); (B: kw = 184.45; df = 3; p-value < 0.0001); (C: kw = 23.71; df = 2; p-value < 0.0001). *Group median is represented by the dot. The size of the interquartile range (IQR) by the line segment. **Medians followed by the same letter do not differ statistically at 5% probability by the Dunn test.

frequencies of less than three (Fig. 1). However, the results of reducing parasitism or the emergence of commercial products belonging to these a.i. are included in the database (Supplementary Material 2).

For sublethal effects (% RP or RE), there was a significant difference between the medians analyzed for annual crops and fruit crops (kw = 17.22; df = 4; p-value = 0.0018) (Fig. 2A). The greatest effects on *T. pretiosum* were found in the products registered for rice (46.97% of RP/RE), corn (17.70% of RP/RE), and soybean (18.07% of RP/RE), differing statistically from those for apple (10.30% RP/RE) and peach (9.01% RP/RE) crops (Fig. 2A). Regardless of the crop in which the pesticide was recorded, the adult stage of *T. pretiosum* showed greater sensitivity to contact with the products, with approximately 65% RP, differing significantly from that of the immature stages (egg-larva, pre-pupa and pupa), which showed emergence reductions below 10% (kw = 184.45; df = 3; p-value < 0.0001) (Fig. 2B). For the classes of pesticides analyzed, in comparison to herbicides (12.30% RP/RE) and fungicides (10.89% RP/RE), insecticides were significantly more toxic (19.51% RP/RE) to *T. pretiosum*, regardless of the insect's stage of life (kw = 23.71; df = 2; p-value < 0.0001) (Fig. 2C).

Among the analyzed a.i., no significant difference was found (kw = 73.54; df = 61; p-value = 0.1302) (Fig. 3). However, it is worth highlighting that the median percentage values of RP or RE of the insecticides acephate (100%) and chlorpyrifos (98.02%) were classified as harmful (class 4) and moderately harmful (class 3), respectively. In addition, for the median trait of each boxplot, which considers the entire life cycle of the parasitoid (egg stage, pre-pupa, pupa and adult) and the different agricultural crops, approximately 87% of the medians of the a.i. analyzed were classified as harmless (class 1), with median values of RP or RE < 30%, following IOBC standards (Fig. 3).

However, when comparisons were made between crops, considering the parasitoid life stages and the class of pesticides analyzed, in the corn and rice crops, in comparison to the herbicides, the insecticides and fungicides showed significantly higher RP to adults of *T. pretiosum* (kw = 14.04, df = 2; p-value = 0.0009) (Table 2). In the soybean crops, in comparison to the insecticides, the fungicides and herbicides showed

Table 2
Percentual median values of reduction in parasitism (RP%) for adults, and reduction in emergence (RE%) for eggs pre-pupa and pupa on *Trichogramma pretiosum* in apple, corn, peach, rice and soybean cultures.

Crop	Life cycle stage	Product type		
		Insecticide	Fungicide	Herbicide
Apple	Adult	100,00aA	6,90bA	83,76aA
	Egg-larvae	13,14aB	9,55aA	16,68aB
	Pre-pupa	6,60aB	0,00bA	0,00 BCE
	Pupa	2,26aB	18,12aA	6,96aBC
Corn	Adult	100,00aA	99,24aA	74,04bA
	Egg-larvae	8,28aB	0,00 BCE	8,00aB
	Pre-pupa	20,07aB	1,78bBC	7,81abB
	Pupa	18,85aB	7,26bB	3,44bB
Peach	Adult	100,00aA	15,24b	82,90aA
	Egg-larvae	8,02aB	–	6,65aB
	Pre-pupa	6,05aB	–	2,61aB
	Pupa	5,27aB	–	3,90aB
Rice	Adult	98,27a	74,98a	8,34b
	Egg-larvae	–	–	–
	Pre-pupa	–	–	–
	Pupa	–	–	–
Soybean	Adult	95,16aA	49,27bA	31,42bA
	Egg-larvae	17,70aB	5,29abB	0,00 BCE
	Pre-pupa	6,21abC	0,00 BCE	12,25aBC
	Pupa	9,59aBC	1,89bBC	15,45aAB

*Means followed by the same letter (lower case in the lines and upper case in the columns) do not differ statistically at 5% probability by the Dunn test.

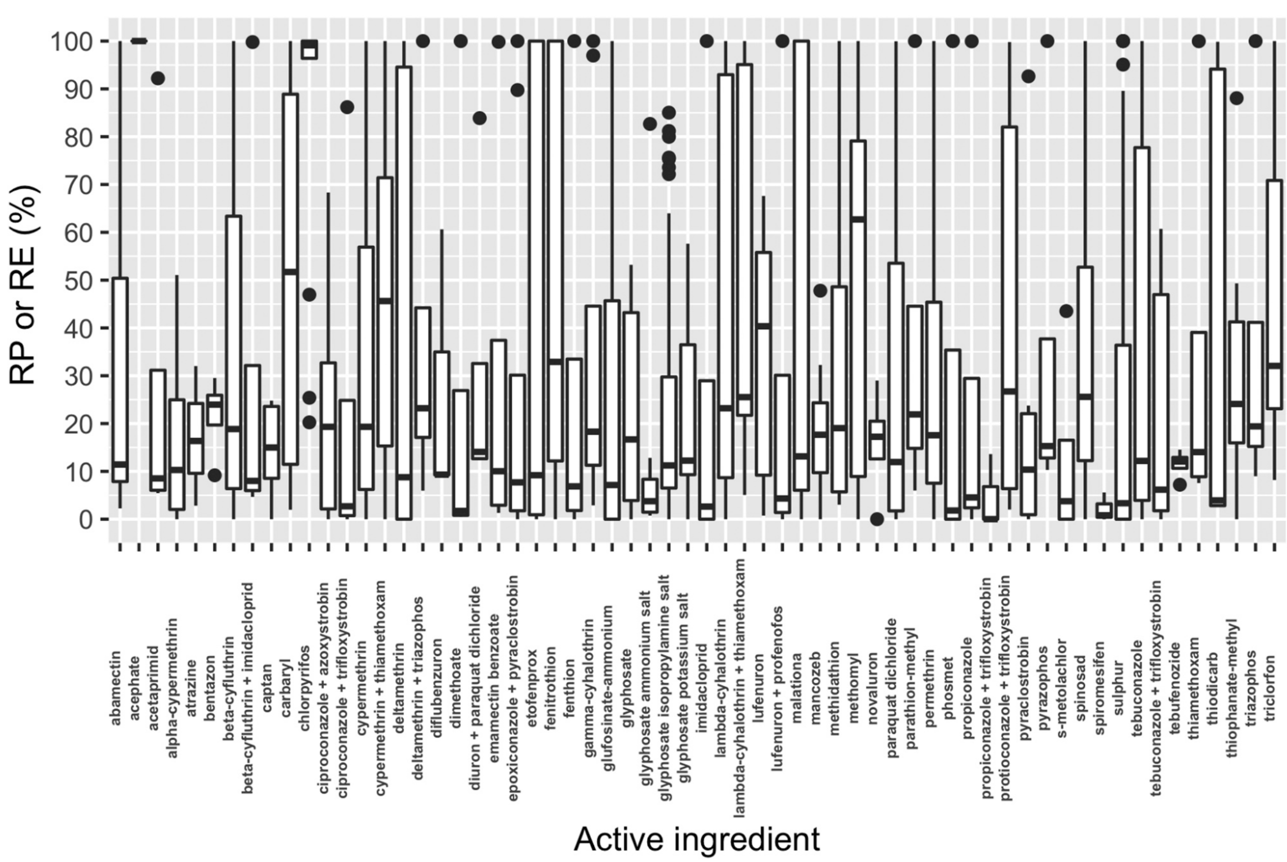

Fig. 3. Boxplot of the 62 active ingredients tested in *Trichogramma pretiosum* and which were used in the comparisons (kw = 73.54; df = 61; p-value = 0.1302). * Black dots correspond to "Outliers".

a significantly lower RP (kw = 24.18; df = 2; p-value < 0.0001). For the fruit (apple and peach), in comparison to the fungicides, the insecticides and herbicides had significantly higher median RP values (kw = 22.36; df = 2; p-value < 0.0001; kw = 13, 38; df = 2; p-value = 0.0012) (Table 2).

When analyzing the RE (%) for each distinct stage of *T. pretiosum* development and a group of pesticides, the insecticides registered soybeans crop were the ones that most affected the egg stage (17.70%) (Table 2). In the pre-pupa and pupa stages, the highest observed values of RE for the insecticides occurred in corn at 20.07% and 18.85%, respectively. When analyzing the sublethal effects of the herbicides, the largest RE values occurred in the egg stage (16.68%) for products registered for apple crops (Table 2). However, for the pre-pupa (12.25%) and pupa (15.45%) stages, the highest RE rates were observed in the soybean crop (Table 2). Regarding fungicides, the highest values of RE were observed in apple for the egg (9.55%) and pupa (18.12%) stages and in corn for pre-pupa stage (1.78%) (Table 2).

4. Discussion

In the present study, a meta-analysis was carried out to determine the influence of different classes of pesticides (insecticides, herbicides and fungicides) widely used on immature and adult stages of *T. pretiosum* in Brazilian agriculture to manage agricultural pests in rice, corn, soybean, apple, and peach crops. After gathering and synthesizing the results of 279 commercial products grouped into 147 a.i., studied from 10 years of laboratory research following IOBC recommendations, it was found that in comparison to herbicides and fungicides, insecticides had the greatest sublethal effect (% RP or RE) on *T. pretiosum*, regardless of the dosage used.

Among the insecticides tested, the groups of organophosphates and carbamates showed high toxicity (classes 3 and 4). For these two chemical groups, the toxic effects (greater than 95%) and residual power have been reported more than 20 days after application on *Trichogramma* spp. (Hewa-Kapuge et al., 2003; Nörnberg et al., 2011; Stefanello et al., 2012; Wang et al., 2012; Paiva et al., 2018, 2020). The low selectivity of these groups occurs due to their ability to inactivate acetylcholinesterase (AChE) and, thus, cause excessive stimulation of cholinergic receptors, leading to the death of insect (Fukuto, 1990; Casida and Durkin, 2013). The use and prevalence of phosphorus-based insecticides in Brazil are associated with the high control efficiency over the main agricultural pests that infest the studied crops (Brown et al., 2012; Chaves et al., 2014; Perini et al., 2016; Marques et al., 2019). In addition, in comparison to other products, the commercial products belonging to these chemical groups have the lowest cost per hectare (US $/ha) (Leach and Mumford, 2008; Carmo et al., 2010; Ibama – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2019). Such aspects explain the large-scale use of these insecticides, even in Brazil, which is the largest consumer of pesticides in the world.

As a result of the constant use of only one control tactic for population suppression of pest arthropods, there are already more than 580 species reported to be resistant to more than 325 compounds worldwide (Sparks and Nauen, 2015). In Brazil, one of the most serious problems with the evolution of resistance occurs with *S. frugiperda*, an important pest in corn, soy, and rice crops, and insecticides such as lambda-cyhalothrin (Diez-Rodríguez and Omoto, 2001), chlorpyrifos (Carvalho et al., 2013), lufenuron (Nascimento et al., 2016), spinosad (Okuma et al., 2018), diamide (Bolzan et al., 2019), and spinetoram (Lira et al., 2020). Genetically modified plants carry the proteins Cry1F (Farias et al., 2014), Cry1Ab (Omoto et al., 2016), and Vip3Aa20 (Bernardi et al., 2016). In this scenario, in association with the recent introduction of *Helicoverpa armigera* (Hübner, 1808) (Lepidoptera: Noctuidae) in soybean crops (Pomari-Fernandes et al., 2015), studies with biological control options have intensified, highlighting the release of *T. pretiosum* (Bueno et al., 2010; Parra, 2019; Parra and Coelho, 2019).

Chemical control via the use of synthetic insecticides, as well as the use of herbicides and fungicides, is essential in Brazilian agriculture (Cardoso and Alves, 2012). The use of these last two classes of pesticides, despite presenting different control targets in relation to insecticides, can also negatively affect the performance of *T. pretiosum* (Khan and Ruberson, 2017; Bueno et al., 2017). However, even though herbicides and fungicides are generally classified as harmless (class 1) and slightly harmful (class 2), respectively, according to the IOBC, synthetic products for the management of weeds and diseases correspond to approximately 60% and 13%, respectively, of formulated product sales in Brazil (Ibama – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2019).

In addition, the widespread use of genetically modified crops tolerant to herbicides such as rice with Clearfield® technology (Basf SE) and Roundup Ready ™ soy and corn (Bayer SA) and the use of nonplant-selective herbicides (glyphosate and glufosinate) have significantly increased in the last harvests (Bonny, 2016; Ibama – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2019). However, it is worth noting that the presence of weeds in the field can directly influence biological control since they can serve as alternative hosts and provide food resources to maintain beneficial fauna in the area (Landis et al., 2000; Bianchi and Wäckers, 2008; Letourneau et al., 2011; Veres et al., 2013; Rusch et al., 2016).

In addition to the importance given to herbicides, fungicides are also gaining prominence, mainly in soybean crops (Godoy et al., 2016). This scenario has been observed since the 2000/01 harvest with the introduction of Asian soybean rust in Brazil caused by the fungus *Phakopsora pachyrhizi* Syd. & Syd. (Soares et al., 2004; Hartman et al., 2015). The occurrence of this disease in the soybean crop resulted in a high number of applications of this group of pesticides in the field during each cultivation cycle (Simões et al., 2017). Similarly, for the apple crop, the use of sulfur-based fungicides is considered one of the main methods of avoiding the presence of apple scab (*Venturia inaequalis* (Cooke) G. Winter) due to its protective effect (Holb and Kunz, 2016). The toxicity of sulfur-based compounds on natural enemies is associated with interference in biochemical processes, which form chelates with heavy metals causing damage to the respiratory system of insects (Magano et al., 2015; Devendar and Yang, 2019).

Based on this scenario, for the fruit sector, especially for peach and apple crops, the importance of integrated fruit production (IFP) in Brazil stands out. The IFP aims to integrate different agronomic techniques, emphasizing pest monitoring and biological control (Tibola et al., 2005; Kowata et al., 2011), as well as the controlled use of insecticides, fungicides, and herbicides with preference for those that are selective to natural enemies (Walker et al., 2017; Damos et al., 2015). This aspect may favor the use of *T. pretiosum* for the management of *G. molesta* (Rodrigues et al., 2011), considered one of the main pest arthropods in peach and apple crops in Brazil (Pastori et al., 2012; Arioli et al., 2014).

These data confirmed that the same product used in the same dosage can vary from innocuous to extremely toxic, depending on the development stage of *T. pretiosum*. This difference may be associated with specific characteristics of each life stage of the insects, mainly factors related to the structure and composition of the cuticle (Fernandes et al., 2010; Bueno et al., 2017; Grande et al., 2018). The relatively greater tolerance of the immature stages of parasitoids to pesticides may be linked to the location of the parasitoid within the host egg, which is protected against contact with the products by the chorion (Grützmacher et al., 2004; Souza et al., 2014; Stecca et al., 2016; Paiva et al., 2020). The ability of a substance to penetrate the chorion is directly related to its physical-chemical characteristics (Stock and Holloway, 1993; Stecca et al., 2016). These factors are closely linked to the greater toxicity of the products tested for rice cultivation on *T. pretiosum* as the tests occurred only on the adult stage of the parasitoid. This scenario occurred because the tests that follow the IOBC recommendations are always initiated by the adult stage of the parasitoid due to the greater sensitivity of this stage than other stages; therefore, products that are moderately harmful (class 3) and harmful (class 4) in this stage of life are tested in the immature stages.

Evaluating the toxicity of pesticides to natural enemies under laboratory conditions is considered the worst approach to expose insects to chemicals, regardless of the stage of development in which they are, as individuals are confined in arenas or cages that do not favor escape (Mills et al., 2016). In contrast, in a field situation, several factors can influence the toxicity to the parasitoid, including the rapid chemical degradation of the products due to climatic conditions (Das et al., 2020), the repellency of insects to some compounds (Paiva et al., 2018) or the attraction to the nectar of other flowers present in the margins of the crop (Bianchi and Wäckers, 2008). It is common for highly toxic pesticides in the laboratory to be less toxic under greenhouse and field conditions (Nörnberg et al., 2011; Stefanello et al., 2012; Pasini et al., 2017). However, especially in Brazil, the number of selectivity studies in semifield and field conditions is low, and studies under these conditions need to be conducted.

Finally, due to large agricultural extensions, we know that chemical control will continue to be one of the main tools within pest management programs. However, through more sustainable management practices, flooding or conservative biological control with the use of natural enemies has grown significantly. Thus, the systemic approach carried out in the present study by compiling data (10 years of studies) on the selectivity of different pesticides (279 commercial products) in terms of classes of insecticides, herbicides and fungicides on the developmental stages of *T. pretiosum* is very important for IPM, mainly in Brazil. In general, fungicides and herbicides are harmless to *T. pretiosum*. Acephate and chlorpyrifos are the only insecticides harmful to the immature and adult stages of *T. pretiosum* and, should not be used. Farmers, managers and researchers must be aware of the parasitoid's life stages to ascertain the selectivity of certain active ingredient. This information will assist in the choice of a chemical that is selective to a specific parasitoid with the aim of using more than one management strategy in the field.

CRediT authorship contribution statement

Matheus Rakes: Conceptualization, Methodology, Investigation, Data Curation, Writing – original draft. **Rafael Antonio Pasini:** Data Curation, Writing – original draft, Writing – review & editing. **Maíra Chagas Morais:** Data Curation, Writing – original draft, Writing – review & editing. **Mikael Bolke Araujo:** Data curation, Writing – original draft, Writing – review & editing. **Juliano de Bastos Pazini:** Formal analysis, Writing – review & editing. **Enio Junior Seidel:** Formal analysis, Writing – review & editing. **Daniel Bernardi:** Resources, Supervision, Writing – review & editing. **Anderson Dionei Grützmacher:** Resources, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the National Council for Scientific and Technological Development (CNPq), Research Support Foundation of the State of Rio Grande do Sul (FAPERGS), Coordination for the Improvement of Higher Education Personnel (CAPES) and Financier of Studies and Projects (FINEP) for their financial support for research execution and scholarships provisions.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2020.111504.

References

Arioli, C.J., Pastori, P.L., Botton, M., Garcia, M.S., Borges, R., Mafra-Neto, A., 2014. Assessment of SPLAT formulations to control *Grapholita molesta* (Lepidoptera: Tortricidae) in a Brazilian apple orchard. Chil. J. Agr. Res. 74, 184–190. https://doi.org/10.4067/S0718-58392014000200009.

Bernardi, O., Bernardi, D., Horikoshi, R.J., Okuma, D.M., Miraldo, L.L., Fatoretto, J., Medeiros, F.C.L., Burd, T., Omoto, C., 2016. Selection and characterization of resistance to the Vip3Aa20 protein from *Bacillus thuringiensis* in *Spodoptera frugiperda*. Pest Manag. Sci. 72, 1794–1802. https://doi.org/10.1002/ps.4223.

Bianchi, F.J., Wäckers, F.L., 2008. Effects of flower attractiveness and nectar availability in field margins on biological control by parasitoids. Biol. Control 46, 400–408. https://doi.org/10.1016/j.biocontrol.2008.04.010.

Bolzan, A., Padovez, F.E., Nascimento, A.R., Kaiser, I.S., Lira, E.C., Amaral, F.S., Kanno, R.H., Malaquias, J.B., Omoto, C., 2019. Selection and characterization of the inheritance of resistance of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to chlorantraniliprole and cross-resistance to other diamide insecticides. Pest. Manag. Sci. 75, 2682–2689. https://doi.org/10.1002/ps.5376.

Bonny, S., 2016. Genetically modified herbicide-tolerant crops, weeds, and herbicides: overview and impact. Environ. Manag. 57, 31–48. https://doi.org/10.1007/s00267-015-0589-7.

Brasil. Ministério da Agricultura, Pecuária e Abastecimento, 2020. Agrofit. ⟨http://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons⟩. Acessado em 06 março 2020.

Brown, S.A., Davis, J.A., Richter, A.R., 2012. Efficacy of foliar insecticides on eggs of *Nezara viridula* (Hemiptera: Pentatomidae). Fla. Entomol. 95, 1182–1186. https://doi.org/10.1653/024.095.0449.

Bueno, R.C.O.D.F., Bueno, A.D.F., Parra, J.R.P., Vieira, S.S., Oliveira, L.J.D., 2010. Biological characteristics and parasitism capacity of *Trichogramma pretiosum* Riley (Hymenoptera, Trichogrammatidae) on eggs of *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae). Rev. Bras. Entomol. 54, 322–327. https://doi.org/10.1590/S0085-56262010000200016.

Bueno, A.D.F., Carvalho, G.A., Santos, A.C.D., Sosa-Gómez, D.R., Silva, D.M.D., 2017. Pesticide selectivity to natural enemies: challenges and constraints for research and field recommendation. Cienc. Rural 47, e20160829. https://doi.org/10.1590/0103-8478cr20160829.

Bueno, A.F., Sosa-Gómez, D.R., Corrêa-Ferreira, B.S., Moscardi, F., Bueno, R.C.O.F., 2012. Inimigos naturais das pragas da soja. In: Hoffmann-campo, C.B., Corrêa-Merreira, B.S., Moscardi, F. (Eds.), Soja: manejo integrado de insetos e outros Artrópodes-praga. Embrapa, Brasília, pp. 493–630.

Candolfi S., M.P., Blümel, R., Forster, F.M., Bakker, C., Grimm, S.A., Hassan, U., Heimbach, M.A., Mead-Briggs, B., Reber, R., Schmuck, H., 2000. Vogt Guidelines to Evaluate Side-Effects of Plant Protection Products to Non-Target Arthropods 2000 International Organization for Biological and Integrated Control of Noxious Animals and Weeds. West Palearctic Regional Section (IOBC/WPRS), Ghent.

Cardoso, E.J.B.N., Alves, P.R.L., 2012. Soil ecotoxicology. In: Begum, G. (Ed.), Ecotoxicology. InTech. ⟨http://www.intechopen.com/books/ecotoxicology/soilecotoxicology⟩.

Carmo, E.L.D., Bueno, A.D.F., Vieira, S.S., Goulart, M.M.P., Carneiro, T.R., Bueno, R.C.O.D.F., 2010. Seletividade de produtos fitossanitários utilizados na cultura da soja para pupas de *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: Trichogrammatidae). Arq. Inst. Biol. 27, 283–290.

Carvalho, G.A., Grützmacher, A.D., Passos, L.C., Oliveira, R.L., 2019. Physiological and ecological selectivity of pesticides for natural enemies of insects. In: Souza, B., Vázquez, L., Marucci, R. (Eds.), Natural Enemies of Insect Pests in Neotropical Agroecosystems. Springer, Cham, pp. 469–478.

Carvalho, R.A., Omoto, C., Field, L.M., Williamson, M.S., Bass, C., 2013. Investigating the molecular mechanisms of organophosphate and pyrethroid resistance in the fall armyworm *Spodoptera frugiperda*. PLoS One 8, e62268. https://doi.org/10.1371/journal.pone.0062268.

Casida, J.E., Durkin, K.A., 2013. Neuroactive insecticides: targets, selectivity, resistance, and secondary effects. Annu. Rev. Entomol. 58, 99–117. https://doi.org/10.1146/annurev-ento-120811-153645.

Chaves, C.C., Baronio, C.A., Botton, M., Garcia, M.S., 2014. Effect of insecticides in different stages of development of *Grapholita molesta* (Busck, 1916) (Lepidoptera: Tortricidae) and vegetative structures of apple and peach. Rev. Bras. Frutic. 36, 842–852. https://doi.org/10.1590/0100-2945-390/13.

Coelho Jr., A., Parra, J.R.P., 2013. Effect of carbon dioxide (CO_2) on mortality and reproduction of *Anagasta kuehniella* (Zeller, 1879), in mass rearing, aiming at the production of *Trichogramma spp*. Acad. Bras. Cienc. 85, 823–831.

Damos, P., Colomar, L.A.E., Ioriatti, C., 2015. Integrated fruit production and pest management in Europe: the apple case study and how far we are from the original concept? Insects 6, 626–657. https://doi.org/10.3390/insects6030626.

Das, S., Hageman, K.J., Taylor, M., Michelsen-Heath, S., Stewart, I., 2020. Fate of the organophosphate insecticide, chlorpyrifos, in leaves, soil, and air following application. Chemosphere 243, e125194. https://doi.org/10.1016/j.chemosphere.2019.125194.

Devendar, P., Yang, G.F., 2019. Sulfur-containing agrochemicals. Sulfur Chemistry. Springer,, Cham, pp. 35–78.

Diez-Rodríguez, G.I., Omoto, C., 2001. Herança da resistência de *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) a lambda-cialotrina. Neotrop. Entomol. 30, 311–316.

Farias, J.R., Andow, D.A., Horikoshi, R.J., Sorgatto, R.J., Fresia, P., Santos, A.Cd, Omoto, C., 2014. Field-evolved resistance to Cry1F maize by *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Brazil. Crop Prot. 64, 150–158. https://doi.org/10.1016/j.cropro.2014.06.019.

Fernandes, F.L., Bacci, L., Fernandes, M.S., 2010. Impact and selectivity of insecticides to predators and parasitoids. EntomoBrasilis 3, 1–10.

Foresti, J., Bernardi, O., Zart, M., Garcia, M.S., 2013. Comportamento de oviposição de *Helicoverpa zea* (Boddie, 1850) (Lepidoptera: Noctuidae) em milho semente e simulação de controle. Rev. Bras. Milho Sorgo 12, 78–84. https://doi.org/10.18512/1980-6477/rbms.v12n1p78-84.

Fukuto, T.R., 1990. Mechanism of action of organophosphorus and carbamate insecticides. Environ. Health Perspect. 87, 245–254. https://doi.org/10.1289/ehp.9087245.

Godoy, C.V., Almeida, A.M.R., Costamilan, L.M., Meyer, M., Dias, W.P., Seixas, C.D.S., Soares, R.M., Henning, A.A., Yorinori, J.T., Ferreira, L.P., Silva, J.F.V., 2016. Doenças Da Soja. In: Amorim, L., Rezende, J.A.M., Bergamin Filho, A., Camargo, L.E. A. (Eds.), Manual de Fitopatologia. Doenças das Plantas Cultivadas, 5 ed. Ceres, São Paulo, pp. 657–675.

Grande, M.L.M., Braz, E.C., Bueno, Ad.F., Silva, D.B., Queiroz, A.P., Ventura, U.M., 2018. Effect of increasing rate of insecticides on its selectivity for *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae). Semin.: Cienc. Agrar. 39, 933–946. https://doi.org/10.5433/1679-0359.2018v39n3p933.

Grützmacher, A.D., Zimmermann, O., Yousef, A., Hassan, S.A., 2004. The side-effects of pesticides used in integrated production of peaches in Brazil on the egg parasitoid *Trichogramma cacoeciae* Marchal (Hym., Trichogrammatidae). J. Appl. Entomol. 128, 377–383. https://doi.org/10.1111/j.1439-0418.2004.00800.x.

Hartman, G.L., Sikora, E.J., Rupe, J.C., Rust, P., 2015. In: Hartman, G.L., Rupe, J.C., Sikora, E.J., Domier, L.L., Davis, J.A., Steffey, K.L. (Eds.), Compendium of Soybean Diseases, 5th. ed. APS Press, Saint Paul, pp. 56–59.

Hassan, S.A., Abdelgader, H., 2001. A sequential testing program to assess the effects of pesticides on *Trichogramma cacoeciae* Marchal (Hym., Trichogrammatidae). IOBC/WPRS Bull. 24 (4), 71–81.

Hassan, S.A., Halsall, N., Gray, A.P., Kuehner, C., Moll, M., Bakker, F.M., Roembke, J., Yousef, A., Nasr, F., Abdelgader, H., 2000. A laboratory method to evaluate the side effects of plant protection products on *Trichogramma cacoeciae* Marchal (Hym., Trichogrammatidae). In: Candolfi, M.P., Blümel, S., Forster, R., Bakker, F.M., Grimm, C., Hassan, S.A., Heimbach, U., Mead-Briggs, M.A., Reber, B., Schmuck, R., Vogt, H. (Eds.), Guidelines to Evaluate Side-Effects of Plant Protection Products to Non-Target Arthropods. IOBC/WPRS, Gent, pp. 107–119.

Hewa-Kapuge, S., McDougall, S., Hoffmann, A.A., 2003. Effects of methoxyfenozide, indoxacarb, and other insecticides on the beneficial egg parasitoid *Trichogramma* nr. brassicae (Hymenoptera: Trichogrammatidae) under laboratory and field conditions. J. Econ. Entomol. 96, 1083–1090. https://doi.org/10.1093/jee/96.4.1083.

Holb, I.J., Kunz, S., 2016. Integrated control of apple scab and powdery mildew in an organic apple orchard by combining potassium carbonates with wettable sulfur, pruning, and cultivar susceptibility. Plant. Dis. 100, 1894–1905. https://doi.org/10.1094/PDIS-12-15-1416-RE.

Ibama – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2019. ⟨http://www.ibama.gov.br/agrotoxicos/relatorios-de-comercializacao-de-agrotoxicos⟩. Acessed in 06 march 2020.

Khan, M.A., Ruberson, J.R., 2017. Lethal effects of selected novel pesticides on immature stages of *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae). Pest. Manag. Sci. 73, 2465–2472. https://doi.org/10.1002/ps.4639.

Kowata, L.S., Amorim, L., Fachinello, J.C., Mio, L.L.M.D., 2011. Adoption of integrated production of peach system in Paraná State. Bragantia 70, 325–333. https://doi.org/10.1590/S0006-87052011000200011.

Ko, K., Liu, Y., Babendreier, D., Zhang, F., Song, K., 2014. Evaluation for potential *Trichogramma* (Hymenoptera: Trichogrammatidae) strains for control of the Striped stem borer (Lepidoptera: Crambidae) in the Greater Mekong Subregion. J. Econ. Entomol. 107, 955–963. https://doi.org/10.1603/EC13481.

Landis, D.A., Wratten, S.D., Gurr, G.M., 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annu. Rev. Entomol. 45, 175–201. https://doi.org/10.1146/annurev.ento.45.1.175.

Leach, A.W., Mumford, J.D., 2008. Pesticide environmental accounting: a method for assessing the external costs of individual pesticide applications. Environ. Poll. 151, 139–147. https://doi.org/10.1016/j.envpol.2007.02.019.

Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., Mejía, J.L., Rangel, A.M.A., Rangel, J.H., Rivera, L., Saavedra, C.A., Torres, A.M., Trujillo, A.R., 2011. Does plant diversity benefit agroecosystems? A synthetic review. Ecol. Appl. 21, 9–21. https://doi.org/10.1890/09-2026.1.

Lira, E.C., Bolzan, A., Nascimento, A.R., Amaral, F.S., Kanno, R.H., Kaiser, I.S., Omoto, C., 2020. Resistance of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to spinetoram: Inheritance and cross-resistance to spinosad. Pest Manag. Sci. 76, 2674–2680. https://doi.org/10.1002/ps.5812.

Lovatto, P.A., Lehnen, C.R., Andretta, I., Carvalho, A.D., Hauschild, L., 2007. Meta analysis in scientific research: a methodological approach. R. Bras. Zootec. 36, 285–294. https://doi.org/10.1590/S1516-35982007001000026.

Magano, D.A., Grützmacher, A.D., Armas, F.S., Paulus, L.F., Panozzo, L.E., Mentnech, K. J., Zotti, M.J., 2015. Evaluating the selectivity of registered fungicides for soybean against *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: Trichogrammatidae). Afr. J. Agric. Res. 10, 3825–3831. https://doi.org/10.5897/AJAR2014.9083.

Marques, R.P., Filho, A.C., Melo, A.A., Guedes, J.V.C., Carli, C., Rohrig, A., Pozebon, H., Perini, C.R., Ferreira, D.R., Bevilaqua, J.G., Patias, L.S., Forgiarini, S.E., Padilha, G., Leitão, J.V., Moro, D., Hahn, L., Arnemann, J., 2019. Managing stink bugs on soybean fields: insights on chemical management. J. Agric. Sci. 11, 225–235. https://doi.org/10.5539/jas.v11n6p225.

Mills, N.J., Beers, E.H., Shearer, P.W., Unruh, T.R., Amarasekare, K.G., 2016. Comparative analysis of pesticide effects on natural enemies in western orchards: a synthesis of laboratory bioassay data. Biol. Control 102, 17–25. https://doi.org/10.1016/j.biocontrol.2015.05.006.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D., The PRISMA Group, 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6, e1000097 https://doi.org/10.1371/journal.pmed.1000097.

Moura, A.P., Carvalho, G.A., Rigitano, R.L.D.O., 2005. Toxicity of insecticides used in tomato crop to *Trichogramma pretiosum*. Pesqui. Agropecu. Bras. 40, 203–210. https://doi.org/10.1590/S0100-204×2005000300002.

Nascimento, A.R.B.D., Farias, J.R., Bernardi, D., Horikoshi, R.J., Omoto, C., 2016. Genetic basis of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) resistance to the chitin synthesis inhibitor lufenuron. Pest Manag. Sci. 72, 810–815. https://doi.org/10.1002/ps.4057.

Nicholls, C.I., Altieri, M.A., Ponti, L., 2007. Controle biológico de pragas através de manejo de agroecossistemas. Departamento de Assistência Técnica e Extensão Rural Brasília, MDA, Brasilia, p. 31.

Nörnberg, S.D., Grützmacher, A.D., Kovaleski, A., Finatto, J.A., Paschoal, M.D.F., 2011. Persistence of pesticides used in integrated production of apple to *Trichogramma pretiosum*. Cienc. Agrotec. 35, 305–313. https://doi.org/10.1590/S1413-70542011000200011.

Okuma, D.M., Bernardi, D., Horikoshi, R.J., Bernardi, O., Silva, A.P., Omoto, C., 2018. Inheritance and fitness costs of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) resistance to spinosad in Brazil. Pest Manag. Sci. 74, 1441–1448. https://doi.org/10.1002/ps.4829.

Omoto, C., Bernardi, O., Salmeron, E., Sorgatto, R.J., Dourado, P.M., Crivellari, A., Carvalho, R.A., Willse, A., Martinelli, S., Head, G.P., 2016. Field-evolved resistance to Cry1Ab maize by *Spodoptera frugiperda* in Brazil. Pest Manag. Sci. 72, 1794–1802. https://doi.org/10.1002/ps.4201.

Paiva, A.C.R., Beloti, V.H., Yamamoto, P.T., 2018. Sublethal effects of insecticides used in soybean on the parasitoid *Trichogramma pretiosum*. Ecotoxicology 27, 448–456. https://doi.org/10.1007/s10646-018-1909-5.

Paiva, A.C.R., Iost Filho, F.H., Parro, E.A., Barbosa, D.P., Yamamoto, P.T., 2020. Do ready-mix insecticides cause lethal and sublethal effects on *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae) pupa? J. Econ. Entomol. https://doi.org/10.1093/jee/toaa031.

Parra, J.R.P., 2019. Controle Biológico na Agricultura Brasileira. Entomol. Commun. 1, ec01002. https://doi.org/10.37486/2675-1305.ec0100.

Parra, J.R.P., Coelho, A., 2019. Applied biological control in Brazil: from laboratory assays to field application. J. Insect Sci. 19, 1–6. https://doi.org/10.1093/jisesa/iey112.

Pasini, R.A., Grützmacher, A.D., Spagnol, D., Armas, F.S.D., Normberg, A.V., Carvalho, H.J.D.S., 2017. Residual action of pesticides sprayed on corn plants on *Trichogramma pretiosum*. Rev. Ceres 64, 242–249. https://doi.org/10.1590/0034-737×201764030004.

Pastori, P.L., Arioli, C.J., Botton, M., Monteiro, L.B., Stoltman, L., Mafra-Neto, A., 2012. Integrated control of two tortricid (Lepidoptera) pests in apple orchards with sex pheromones and insecticides. Rev. Colomb. Entomol. 38, 224–230.

Perini, C.R., Arnemann, J.A., Melo, A.A., Pes, M.P., Valmorbida, I., Beche, M., Guedes, J. V.C., 2016. How to control *Helicoverpa armigera* on soybean in Brazil? What we have learned since its detection. Afr. J. Agric. Res. 11, 1426–1432. https://doi.org/10.5897/AJAR2016.10903.

Pomari-Fernandes, A., Bueno, A.F., Sosa-Gomez, D.R., 2015. *Helicoverpa armigera*: current status and future perspectives in Brazil. Curr. Agric. Sci. Tech. 21, 1–7. https://doi.org/10.18539/cast.v21i1.4234.

Querino R.B., Zucchi R.A., 2011. Guia de identificação de *Trichogramma* para o Brasil. Embrapa Meio-Norte-Livro científico (ALICE). ⟨https://www.embrapa.br/busca-de-publicacoes/-/publicacao/895211/guia-de-identificacao-de-trichogramma-para-o-brasil⟩.

RDCT, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. ⟨http://www.r-project.org/⟩.

Rizzardi, M.A., Fleck, N.G., Agostinetto, D., Balbinot, J.R.A.A., 2003. Herbicides action in plant defence mechanisms to pathogens. Cienc. Rural 33, 957–965. https://doi.org/10.1590/S0103-84782003000500026.

Rodrigues, M.L., Garcia, M.S., Nava, D.E., Botton, M., Parra, J.R., Guerrero, M., 2011. Selection of *Trichogramma pretiosum* Lineages for Control of *Grapholita molesta* in Peach. Fla. Entomol. 94, 398–403. https://doi.org/10.1653/024.094.0303.

Rusch, A., Chaplin-Kramer, R., Gardiner, M.M., Hawro, V., Holland, J., Landis, D., Thies, C., Tscharntke, T., Weisser, W.W., Winqvist, C., Woltz, M., Bommarco, R., 2016. Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. Agric. Ecosyst. Environ. 221, 198–204. https://doi.org/10.1016/j.agee.2016.01.039.

Simões, K., Hawlik, A., Rehfus, A., Gava, F., Stammler, G., 2017. First detection of a SDH variant with reduced SDHI sensitivity in *Phakopsora pachyrhizi*. J. Plant Dis. Prot. https://doi.org/10.1007/s41348-017-0117-5.

Soares, R.M., Rubin, S.A.L., Wielewicki, A.P., Ozelame, J.G., 2004. Fungicides on the control of soybean rust (*Phakopsora pachyrhizi*) and soybean yield. Cienc. Rural 34, 1245–1247. https://doi.org/10.1590/S0103-84782004000400045.

Song, F., Swinton, S.M., 2009. Returns to integrated pest management research and outreach for soybean aphid. J. Econ. Entomol. 102, 2116–2125. https://doi.org/10.1603/029.102.0615.

Souza, J.R., Carvalho, G.A., Moura, A.P., Couto, M.H., Maia, J.B., 2014. Toxicity of some insecticides used in maize crop on *Trichogramma pretiosum* (Hymenoptera, Trichogrammatidae) immature stages. Chil. J. Agr. Res. 74, 234–239. https://doi.org/10.4067/S0718-58392014000200016.

Sparks, T.C., Nauen, R., 2015. IRAC: mode of action classification and insecticide resistance management. Pestic. Biochem. Phys. 121, 122–128. https://doi.org/10.1016/j.pestbp.2014.11.014.

Stecca, C.S., Bueno, A.D.F., Pasini, A., Silva, D.M., Andrade, K., 2016. Side-effects of glyphosate to the parasitoid *Telenomus remus* Nixon (Hymenoptera: Platygastridae). Neotrop. Entomol. 45, 192–200. https://doi.org/10.1007/s13744-016-0363-4.

Stefanello Jr., G.J., Grützmacher, A.D., Grützmacher, D.D., Dalmazo, G.O., Paschoal, M.D.F., Härter, W.R., 2008a. The effect of insecticides used in corn crops on the parasitism capacity of *Trichogramma pretiosum* Riley, 1879 (hymenoptera: trichogrammatidae). Arq. Inst. Biol. 75, 187–194.

Stefanello Jr., G.J., Grützmacher, A.D., Grützmacher, D.D., Lima, C.A.B., Dalmozo, D.O., Paschoal, M.D.F., 2008b. Selectivity of herbicides registered on corn to *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae). Planta Daninha 26, 343–351. https://doi.org/10.1590/S0100-83582008000200010.

Stefanello Jr., G.J., Grutzmacher, A.D., Spagnol, D., Pasini, R.A., Bonez, C., Moreira, D.C., 2012. Persistence of pesticides used in corn field to the parasitoid *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: Trichogrammatidae). Cienc. Rural 42, 17–23. https://doi.org/10.1590/S0103-84782012000100004.

Stewart, G.B., Altman, D.G., Askie, L.M., Duley, L., Simmonds, M.C., Stewart, L.A., 2012. Statistical analysis of individual participant data meta-analyses: a comparison of methods and recommendations for practice. PloS One 7, e46042. https://doi.org/10.1371/journal.pone.0046042.

Stock, D., Holloway, P.J., 1993. Possible mechanisms for surfactant-induced foliar uptake of agrochemicals. Pestic. Sci. 38, 165–177. https://doi.org/10.1002/ps.2780380211.

Tibola, C.S., Fachinello, J.C., Grützmacher, A.D., Picolotto, L., Krüger, L., 2005. Manejo de pragas e doenças na produção integrada e convencional de pêssegos. Rev. Bras. Frutic. 27, 215–218. https://doi.org/10.1590/S0100-29452005000200008.

Torres, J.B., Bueno, A.F., 2018. Conservation biological control using selective insecticides – a valuable tool for IPM. Biol. Control 126, 53–64. https://doi.org/10.1016/j.biocontrol.2018.07.012.

Veres, A., Petit, S., Conord, C., Lavigne, C., 2013. Does landscape composition affect pest abundance and their control by natural enemies? A review. Agric. Ecosyst. Environ. 166, 110–117. https://doi.org/10.1016/j.agee.2011.05.027.

Walker, J.T., Suckling, D.M., Wearing, C.H., 2017. Past, present, and future of integrated control of apple pests: the New Zealand experience. Annu. Rev. Entomol. 62, 31–248. https://doi.org/10.1146/annurev-ento-031616-035626.

Wang, Y., Yu, R., Zhao, X., Chen, L., Wu, C., Cang, T., Wang, Q., 2012. Susceptibility of adult *Trichogramma nubilale* (Hymenoptera: Trichogrammatidae) to selected insecticides with different modes of action. Crop Prot. 34, 76–82. https://doi.org/10.1016/j.cropro.2011.12.007.

Further reading

Giolo, F.P., Grützmacher, A.D., Manzoni, C.G., Fachinello, J.C., Nörnberg, S.D., Stefanello Jr Júnior, G.J., 2005a. Side-effects of pesticides used in integrated production of peach on *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: trichogrammatidae). Rev. Bras. Frutic. 27, 222–225. https://doi.org/10.1590/S0100-29452005000200010.

Giolo, F.P., Grützmacher, A.D., Manzoni, C.G., Lima, C.A.B.D., Härter, W.D.R., Müller, C., 2007a. Selectivity of pesticides used in peach orchard to Trichogramma pretiosum Riley, 1879 (Hymenoptera: Trichogrammatidae). Cienc. Agrotec. 31, 1396–1401. https://doi.org/10.1590/S1413-70542007000500019.

Giolo, F.P., Grützmacher, A.D., Manzoni, C.G., Lima, C.A.B.D., Nörnberg, S.D., 2007b. Toxicity of pesticides used in peach orchard on adults *Trichogramma pretiosum*. Bragantia 66, 423–431. https://doi.org/10.1590/S0006-87052007000300008.

Giolo, F.P., Grützmacher, A.D., Procópio, S.O., Manzoni, C.G., Lima, C.A.B., Nörnberg, S.D., 2005b. Side-effects of glyphosate formulations on *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae). Planta Daninha 23, 458–462. https://doi.org/10.1590/S0100-83582005000300009.

Magano, D.A., 2012. Toxicidade de agrotóxicos registrados para a cultura da soja sobre Trichogramma pretiosum Riley, 1879 (Hymenoptera: Trichogrammatidae). Federal University of Pelotas (Dissertation).

Magano, D.A., Krolow, I.R., Grützmacher, A.D., Panozzo, L.E., Armas, F.S., Zimmer, M., 2013. Efeitos secundários de herbicidas aplicados em soja sobre *Trichogramma pretiosum*. Pesq. Agropec. Gau. 19, 49–56.

Manzoni, C., Grützmacher, A., Giolo, F., Härter, W., Castilhos, R., Paschoal, M., 2007. Side-effects of pesticides used in integrated production of apples to parasitoids of *Trichogramma pretiosum* Riley and *Trichogramma atopovirilia* Oatman & Platner (Hymenoptera: Trichogrammatidae). BioAssay 2, 1–7. https://doi.org/10.14295/BA.v2.0.50.

Manzoni, C.G., Grützmacher, A.D., Giolo, F.P., Härter, W.D.R., Müller, C., 2006a. Side effects of pesticides used in integrated production of apple in adults of *Trichogramma pretiosum*. Pesq. Agropec. Bras. 41, 1461–1467.

Manzoni, C.G., Grützmacher, A.D., Giolo, F.P., Lima, C.A.B.D., Nörnberg, S.D., Härter, W.D.R., Müller, C., 2006b. Selectivity of pesticides used in intregated production of apple on *Trichogramma pretiosum* Riley, 1879 (Hym.: Trichogrammatidae) in laboratory conditions. Rev. Bras. Frutic. 28, 254–257. https://doi.org/10.1590/S0100-29452006000200022.

Manzoni, C.G., Grützmacher, A.D., Giolo, F.P., Lima, C.A., Nörnberg, S.D., Müller, C., Härter, W.D.R., 2006c. Susceptibility of *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) adults to fungicides used to control apple diseases. Neotrop. Entomol. 35, 223–230. https://doi.org/10.1590/S1519-566×2006000200011.

Nörnberg, S.D., Grützmacher, A.D., Giolo, F.P., Junior, G.J.E., Lima, C.A.B., Grützmacher, D.D., 2008. Selectivity of glyphosate formulations applied on immature stages of *Trichogramma pretiosum*. Planta daninha 26, 611–617. https://doi.org/10.1590/S0100-83582008000300017.

Pazini, J.D.B., Grützmacher, A.D., Martins, J.F.D.S., Pasini, R.A., Rakes, M., 2016. Selectivity of pesticides used in rice crop on *Telenomus podisi* and *Trichogramma pretiosum*. Pesqui. Agropecu. Trop. 46, 327–335. https://doi.org/10.1590/1983-40632016v4640844.

Stefanello Jr G.J., 2010. Efeitos de agrotóxicos registrados para a cultura do milho sobre *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: Trichogrammatidae). Thesis, Federal University of Pelotas.

Stefanello Jr., G.J., Grutzmacher, A.D., Pasini, R.A., Bonez, C., Moreira, D.C., Spagnol, D., 2011. Selectivity of herbicides registered for corn at the immature stages of *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae). Planta Daninha 29, 1069–1077. https://doi.org/10.1590/S0100-83582011000500014.