Ecotoxicology (2019) 28:1210–1219
https://doi.org/10.1007/s10646-019-02129-8

Impacts of seven insecticides on *Cotesia flavipes* (Cameron) (Hymenoptera: Braconidae)

Thaís Fagundes Matioli[1] · **Odimar Zanuzo Zanardi**[2] · **Pedro Takao Yamamoto**[1]

Accepted: 16 October 2019 / Published online: 6 November 2019

Abstract
The endoparasitoid wasp *Cotesia flavipes* (Cameron) (Hymenoptera: Braconidae) is inundatively released in Brazilian sugarcane plantations to control the sugarcane borers *Diatraea saccharalis* (Fabricius) and *Diatraea flavipennella* (Box) (Lepidoptera: Crambidae). In conjunction with these releases, several synthetic insecticides are used to control the neonate larvae of these pests. We assessed the lethal and transgenerational sublethal effects of seven of these insecticides on *C. flavipes*. Leaf discs were sprayed at the highest field concentrations of chlorantraniliprole, lambda-cyhalothrin + chlorantraniliprole, chlorfluazuron, triflumuron, lambda-cyhalothrin + thiamethoxam, tebufenozide, and novaluron. Distilled water was used as a negative control. Newly emerged females (24 h old) were placed in Petri dishes containing the treated leaves, and the lethal and transgenerational sublethal effects were assessed for the next two generations. Lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam caused 100% mortality of the parasitoid and were highly persistent, causing more than 30% mortality at 30 days after spraying. Chlorantraniliprole, chlorfluazuron, novaluron, and triflumuron did not cause significant mortality compared to the negative control, but did have transgenerational sublethal effects. The length of the tibia of the right posterior leg, used as a growth measurement, was reduced in the progeny (F_1 generation) of exposed female parasitoids. In addition, chlorantraniliprole increased and chlorfluazuron reduced the proportion of females in the F_1 generation, whereas novaluron reduced the proportion of females in the F_2 generation. Overall, only tebufenozide was considered harmless to *C. flavipes*. The results of this study suggest that lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam are harmful to *C. flavipes*, although field studies are needed to obtain results for actual sugarcane crops.

Keywords *Diatraea saccharalis* · Larval parasitoid · Toxicity · Transgenerational sublethal effects · Integrated pest management

Introduction

Brazil is the world's largest sugarcane producer, with a harvest of 633 million tons on approximately 9 million hectares in 2017/2018 (Conab 2018). In spite of this high production, the incidence of pests is one of the major factors limiting further increases in crop yield (Oliveira et al. 2014).

The sugarcane borers *Diatraea saccharalis* (Fabricius) and *Diatraea flavipennella* (Box) (Lepidoptera: Crambidae) are key pests of sugarcane, due to their direct and indirect damage, biotic potential, adaptability to different environmental conditions, and the abundance of host plants (Joyce et al. 2014; Pavinato et al. 2018; Pinto et al. 2006). Neonate larvae initially feed on the leaf parenchyma, and the second-instar larvae migrate to the base of the plant where they penetrate the stem, opening longitudinal and transverse galleries that block the sap flow, reducing sucrose accumulation and crop yield. On young plants, these borers can dry the shoots, which prevents further growth and eventually kills the plant (Dinardo-Miranda 2008); and they weaken older plant stalks, which may topple in the wind (Trevisan et al. 2016).

Because the larvae develop almost completely inside the stem, *D. saccharalis* has been controlled preferably by

✉ Thaís Fagundes Matioli
thaisf.matioli@usp.br

[1] Department of Entomology and Acarology, "Luiz de Queiroz" College of Agriculture/University of São Paulo (ESALQ/USP), Piracicaba, São Paulo 13418-900, Brazil

[2] Department of Entomology, Fund for Citrus Protection (FUNDECITRUS), Araraquara, São Paulo 14708-040, Brazil

means of biological-control agents. The koinobiont parasitoid wasp *Cotesia flavipes* (Cameron) (Hymenoptera: Braconidae) is the most effective and widely used control agent to reduce the population levels and damage caused by sugarcane borers in production systems, where the levels of parasitism can vary from 13 to 43% (Dinardo-Miranda et al. 2014). Following the introduction of *C. flavipes* in Brazil in the 1970s, several companies and biofactories have begun to mass-produce this natural enemy, which is released on approximately 3.5 million hectares of sugarcane crops (Parra 2014; Vacari et al. 2012). The parasitoid females efficiently locate the larvae inside the stem through olfactory stimuli (Molnár et al. 2016; Sétamou et al. 2002). Parasitized sugarcane-borer larvae show reductions in food consumption and cellular immune capacity (Mahmoud et al. 2011). After the parasitoid exits, the larvae lose weight and die (Passos et al. 2014; Rossi et al. 2014). In the 1990s, inundative releases of *C. flavipes* reduced the sugarcane-borer populations from 10 to 2%, preventing approximately U$80 million in losses to growers (Vilela et al. 1998). Currently, the control of sugarcane borers with *C. flavipes* constitutes one of the largest applied biological-control programs in the world (Parra et al. 2014; Santos et al. 2015).

Although *C. flavipes* is an important biological-control agent of sugarcane borers in production systems, synthetic insecticides are sprayed on leaves to reduce the population of newly hatched larvae present in the crop, since the first- and second-instar larvae of *D. saccharalis* remain outside the stems (Van Leerdam et al. 1985; Wiedenmann et al. 1992). Diamide, benzoylurea, diacylhydrazine, pyrethroid, and neonicotinoid insecticides have been the synthetic insecticides most often used to control sugarcane borers and other pests that cause significant damage to the plants (MAPA 2019). However, the use of these compounds may also reduce the effectiveness of *C. flavipes* and affect *D. saccharalis* and *D. flavipennella* biological-control programs in sugarcane. In addition to mortality, these insecticides can also affect the biological (development of immature stages, fecundity, fertility, longevity, and sex ratio) and behavioral (parasitism, mobility, and orientation) parameters of natural enemies (Desneux et al. 2007; Guedes et al. 2016), thereby reducing the biocontrol services that they provide (Biondi et al. 2015). Several studies have determined the toxicity levels of insecticides to parasitoids belonging to the genus *Cotesia* Cameron (Hymenoptera: Braconidae) (Haseeb et al. 2004; Lin et al. 2007; Mardani et al. 2016; Ohta and Takeda 2015), but few have used the lethal and transgenerational sublethal effects to assess the impact of these compounds on *C. flavipes* (Fonseca et al. 2015).

In view of the importance of *C. flavipes* as a biological-control agent of *D. saccharalis* and *D. flavipennella*, and the need for studies to assess the compatibility of this natural enemy with chemical control, in this study we assessed the lethal and transgenerational sublethal effects of seven commonly used insecticides on *C. flavipes*. The results will contribute not only to understanding the impact of these insecticides on *C. flavipes*, but also to evaluating the practical implications of releasing this parasitoid in combination with insecticide sprayings, and will help to develop management strategies to reduce the impacts of these compounds in sugarcane production systems.

Material and methods

Insects

A colony of *D. saccharalis* was established from a population maintained under laboratory conditions, reared on an artificial diet based on soybean meal, wheat germ, sugar, vitamins, Wesson salts, ascorbic acid, and water as described by Hensley and Hammond (1968) and modified by Araújo et al. (1985). When the larvae reached the fifth instar, they were subjected to parasitism by females of *C. flavipes* obtained from a colony kept in the laboratory for several generations at the Iracema Farm headquarters of the São Martinho Group, municipality of Pradópolis, São Paulo, Brazil. About 60 newly emerged adult parasitoids (≤24 h old) were placed in plastic cages (6.0 cm in diameter × 6.0 cm high) with honey drops for 24 h, to allow them to mate. *D. saccharalis* fifth-instar larvae were exposed to the parasitoids through a hole in the cover of each plastic cage. The parasitized larvae were placed in Petri dishes (10 cm in diameter × 2 cm high) with the diet. Fifteen days after parasitism, parasitoid larvae started to leave the host and pupate. The pupae were removed from the Petri dishes and transferred to new plastic cages, where they were kept until the adult parasitoids emerged. The rearing was performed in a climate-controlled room with a temperature of 25 ± 1 °C, relative humidity (RH) 70 ± 10%, and 14 L: 10D h photoperiod. For all assays, newly emerged females (≤24 h old) of *C. flavipes* were used.

Chemicals

Seven commercial insecticides widely used for controlling *D. saccharalis* in sugarcane production systems were tested on *C. flavipes*, using the maximum field concentration recommended to control this pest by the manufacturers of the insecticides (MAPA 2019). The insecticides and concentrations assessed were as follows: chlorantraniliprole 84 mg L^{-1} (Altacor 35% w/w, diamide, wettable granules, Du Pont do Brasil Ltd., Barueri, SP, Brazil); lambda-cyhalothrin + chlorantraniliprole 33.5 + 67 mg L^{-1} (Ampligo 5 + 10% w/v, pyrethroid + diamide, concentrated suspension, Syngenta

Proteção de Cultivos Ltd., São Paulo, SP, Brazil); chlorfluazuron 85 mg L^{-1} (Atabron 5%, w/v, benzoylurea, emulsifiable concentrate, ISK Biosciences do Brasil Defensivos Agrícolas Ltd., Indaiatuba, SP, Brazil); triflumuron 129.6 mg L^{-1} (Certero 48% w/v, benzoylurea, concentrated suspension, Bayer S.A., São Paulo, SP, Brazil); lambda-cyhalothrin + thiamethoxam 100 + 141 mg L^{-1} (Engeo Pleno 10 + 14.1%, pyrethroid + neonicotinoid, w/v concentrated suspension, Syngenta); tebufenozide 480 mg L^{-1} (Mimic 24% w/v, diacylhydrazine, concentrated suspension, Iharabras S.A. Indústrias Químicas, Sorocaba, SP, Brazil); and novaluron 50 mg L^{-1} (Rimon 10% w/v, benzoylurea, emulsifiable concentrate, Adama Brasil S.A., Londrina, PR, Brazil) (IRAC 2019). Distilled water was used as a negative control treatment.

Toxicity of insecticides to *Cotesia flavipes* females

To assess the insecticide effects on *C. flavipes* females, discs (3.3 cm in diameter) of sugarcane leaves (cv. RB84-7515) were cut and placed in acrylic plates (3.5 cm in diameter) with a layer of an agar: water solution (2.5%), and used as experimental units. Then, the discs were sprayed with 2 mL of one of the solutions in a Potter tower (Burkard Scientific Co., Uxbridge, UK) adjusted to a 68.6 kPa pressure, resulting in 1.8 ± 0.1 mg cm^{-2} deposition of fresh residues, which is consistent with the criteria established by the Pesticides and Beneficial Organisms Working Group of the International Organization for Biological Control of Noxious Animals and Plants/West Palearctic Regional Section (IOBC/WPRS) for studies of pesticide toxicity to natural enemies (Hassan 1994). After spraying, the discs were kept in a climate-controlled room for 2 h to allow the residues to dry. Twelve *C. flavipes* females (24 h old) were anesthetized with CO_2 for 10 s and released in each experimental unit, with one larva per female for parasitizing. The experimental units were the acrylic plates covered with plastic caps with centrally drilled holes (2.5 cm in diameter) screened with voile fabric to allow gas exchange and to prevent excess moisture accumulation. A honey droplet (~1 mm^3) was used to feed the parasitoids during the assessment period. For each treatment, five replicates were used. The experimental units were kept in a climate-controlled room with a temperature of 25 ± 1 °C, 70 ± 10% RH, and 14 L: 10D h photoperiod. The number of live/dead parasitoids was recorded 24 h after exposure to the residues. Parasitoids that did not react to the touch of a thin brush were considered dead.

Transgenerational sublethal effects of insecticides on *Cotesia flavipes*

The transgenerational sublethal effects of insecticides were assessed for products that caused lower mortalities in the previous bioassay. For this purpose, 20 *C. flavipes* females surviving from each treatment were placed in individual flat-bottom glass tubes (2.5 cm in diameter × 8.5 cm high). Then, a *D. saccharalis* fifth-instar larva was placed in each tube, to allow parasitism for 30 s. The parasitized larvae were transferred to acrylic plates (6 cm in diameter) containing a refeeding diet (Hensley and Hammond 1968) with addition of acetic acid and no Wesson salts, and monitored until pupation.

The egg-pupa development time of the parasitoid was determined based on the duration (in days) between the parasitism and pupa formation (F_1 generation). Parasitoid pupae emerging from each parasitized borer larva were counted and weighed, using an analytical balance with precision 0.0001 g (Ohaus Explorer E02140, Stacey Cochiara, Gaithersburg, MD), 24 h after formation. The pupae were then transferred to flat-bottom glass tubes and maintained until the adults emerged. The pupal development time was determined based on the duration (in days) between the formation of the pupa and the parasitoid emergence. Adults were separeted by gender to determine the sex ratio and released inside a small cage (20 × 20 × 20 cm) for mating for 24 h. Next, 20 mated females from each treatment were randomly collected and transferred to flat-bottom glass tubes in order to assess the parasitism capacity of the F_2 generation, following the same procedure and criteria described above.

For the progeny (F_1) of exposed female parasitoids, the tibia length of the right hind leg was also measured and used as a criterion to estimate the transgenerational sublethal effects of these insecticides on *C. flavipes* development. For this purpose, 20 parasitoid females from each treatment were randomly collected and stored in individual Eppendorf tubes with a 70% ethanol solution for 7 days. Next, each female was cleared, following the same procedure used for *Trichogramma* spp. (Querino and Zucchi 2011), and mounted on a slide. The tibia length of each specimen was measured at 40 × magnification, under a Zeiss light microscope (Carl Zeiss do Brasil Ltd., São Paulo, SP, Brazil) coupled to a digital camera (IS300, Eurekam Bel 3.0 MP), using the software Bel Capture version 3.0.

Persistence of the residual effects of insecticides on *Cotesia flavipes*

The duration of the residual effects of insecticides on *C. flavipes* was assessed for products that caused high mortalities in the first bioassay. For this purpose, 'RB84-7515' sugarcane plants at five months of age (70–90 cm high) grown in 20-L pots in a greenhouse were used as a substrate for spraying the treatments. For each treatment, five plants were sprayed with a volume corresponding to ~125 mL per plant, using a Jacto PJH manual sprayer (Jacto do Brasil S.A., Pompéia, SP, Brazil) equipped with a FL-5VS conical nozzle (Teejet Technologies Company, São Paulo, SP, Brazil). At 5, 15, and 30 days after spraying (DAS), two leaves were randomly collected from each plant, and in the laboratory, discs (3.3 cm in diameter) were cut, placed in acrylic plates (3.5 cm in diameter) with an agar: water solution (2.5%), and used as experimental units. Twenty newly emerged adults (≤24 h old) of *C. flavipes* were anesthetized with CO_2 for 10 s and released in each experimental unit. The experimental units were the acrylic plates covered with plastic caps with centrally drilled holes (2.5 cm in diameter) screened with voile fabric to allow gas exchange and to prevent excess moisture accumulation, and kept in a climate-controlled room as described above. For each treatment and assessment date, five replicates were used.

The number of live/dead parasitoids was recorded 24 h after the parasitoids were released in the experimental units. Parasitoids that did not react to the touch of a thin brush were considered dead. The effect of each insecticide was determined based on the number of dead parasitoids after 24 h of exposure.

Experimental design and data analysis

For all assays, a fully randomized experimental design was used. Generalized linear models (GLM) (Nelder and Wedderburn 1972) with quasi-binomial, quasi-Poisson, Gaussian, and binomial distributions were used for analysis of the proportion data (F_0 generation female mortality), counts (number of pupae and adults), duration (egg-pupa and pupa-adult development times), and sex ratio, respectively. In order to determine the duration of the residual effects of lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam on *C. flavipes* adults, the mortalities observed at different times (days after spraying, DAS) were subjected to a repeated-measure analysis using generalized linear mixed models (GLMM) of the "*lme4*" package (Bates et al. 2015) with binomial distribution. The effect of the explanatory variables (plants treated with insecticides and negative control) and the time were considered as fixed factors, while the repeated measure of each experimental unit (sugarcane leaf disc) in time was considered as random, assuming an intercept that was different for each individual. The effect of treatment × time was assessed by likelihood-ratio tests ($P < 0.05$) between a complete model and a model without the effect of treatment or time. The same test was used to determine the significance of the treatment interaction × time, comparing two models: one with interaction and another without interaction. For each time, a GLM with quasi-binomial was used to analyze the mortality data. For all assays, goodness-of-fit was assessed through half-normal plots with simulation envelopes using the "*hnp*" package (Demétrio et al. 2014). In case of significant differences among treatments, multiple comparisons with the Tukey test ($P < 0.05$) were performed, using the "*glht*" function of the "*multcomp*" package, with adjusted *P* values (Hothorn et al. 2008). All analyses were performed with the statistical software "*R*", version 3.4.4 (R Development Core Team 2018).

Results

Exposure of *C. flavipes* females to the insecticide residues indicated that lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam were highly harmful to this parasitoid (100% mortality). In contrast, chlorantraniliprole, chlorfluazuron, novaluron, tebufenozide, and triflumuron did not cause significant mortality, compared to the negative control (Table 1). Furthermore, chlorantraniliprole, chlorfluazuron, novaluron, tebufenozide, and triflumuron did not affect the egg-pupa and pupa-adult development periods, number of pupae, pupal weight, and progeny emergence (F_1 generation) (Table 1). However, these treatments did cause transgenerational sublethal effects. In the F_1 generation, chlorantraniliprole increased the proportion of females, whereas chlorfluazuron reduced the proportion of females; the effects differed from each other, but both did not differ statistically from the negative control (Table 1). In comparison to the negative control, significant reductions in tibia length due to triflumuron, novaluron, chlorfluazuron and chlorantraniliprole treatments were observed, whereas the tebufenozide treatment had no effect on *C. flavipes* (F_1 generation) (Table 1). The largest reductions in tibial length were observed in the offspring of females exposed to chlorfluazuron and triflumuron (Table 1).

For the F_1 progeny (F_2 generation), chlorantraniliprole, chlorfluazuron, novaluron, tebufenozide, and triflumuron did not affect the egg-pupa and pupa-adult development times, number of pupae, or pupal weight (Table 2). Chlorantraniliprole, chlorfluazuron, novaluron, tebufenozide, and triflumuron did not affect the sex ratio of emerging adults; however, novaluron significantly reduced the proportion of females of the F_2 generation (Table 2).

The duration of the residual effects indicated a significant interaction between treatment and time [days after spraying (DAS)] ($\chi^2 = 13.00$; $d.f. = 4$; $P = 0.0012$). The mortality of *C. flavipes* was significantly higher in lambda-cyhalothrin + thiamethoxam and lambda-cyhalothrin + chlorantraniliprole than in the negative control treatment at 5 DAS ($F = 178.28$; $d.f. = 2, 27$; $P < 0.0001$), 15 DAS ($F = 190.18$, $d.f. = 2, 27$; $P < 0.0001$), and 30 DAS ($F = 73.34$, $d.f. = 2, 27$; $P < 0.0001$) (Fig. 1). Among treatments, the longest duration of the residual effects was observed for lambda-

Table 1 Female mortality (F_0 generation) and transgenerational sublethal effects on the F_1 generation (egg-pupa and pupa-adult stage development time, number of pupae, pupal weight, emergence rate, sex ratio and tibia length) of the parasitoid *Cotesia flavipes* when females (F_0) were exposed to treated leaves

Treatment	F_0 generation mortality[a] (%)	Development period[b] (days)		Number of pupae[c]	Pupal weight[b] (mg)	Emergence rate[a] (%)	Sex ratio[d] (♀/♂ + ♀)	Tibia length[b] (mm)
		Egg-pupa	Pupa-adult					
Control	3.5 ± 2.14[b]	13.1 ± 0.21	7.3 ± 0.11	70.0 ± 5.14	0.07 ± 0.004	92.6 ± 1.06	0.71 ± 0.047[ab]	0.62 ± 0.004[a]
Chlorantraniliprole	6.7 ± 4.86[b]	12.9 ± 0.20	7.1 ± 0.18	80.5 ± 4.59	0.07 ± 0.003	92.1 ± 0.86	0.81 ± 0.050[a]	0.58 ± 0.008[bc]
Chlorfluazuron	10.0 ± 4.86[b]	13.1 ± 0.25	7.6 ± 0.29	63.1 ± 7.14	0.07 ± 0.006	93.3 ± 1.05	0.65 ± 0.058[b]	0.58 ± 0.008[c]
Lambda-cyhalothrin + chlorantraniliprole	100.0 ± 0.00[a]	–	–	–	–	–	–	–
Lambda-cyhalothrin + thiamethoxam	100.0 ± 0.00[a]	–	–	–	–	–	–	–
Novaluron	5.9 ± 2.52[b]	13.1 ± 0.24	7.2 ± 0.22	76.3 ± 8.01	0.08 ± 0.006	95.0 ± 0.85	0.76 ± 0.044[ab]	0.59 ± 0.006[bc]
Tebufenozide	11.4 ± 4.94[b]	12.8 ± 0.16	7.2 ± 0.14	70.9 ± 4.67	0.07 ± 0.003	94.1 ± 1.32	0.71 ± 0.057[ab]	0.61 ± 0.006[ab]
Triflumuron	5.0 ± 2.04[b]	13.0 ± 0.15	7.1 ± 0.20	77.0 ± 3.31	0.08 ± 0.003	90.5 ± 1.24	0.76 ± 0.067[ab]	0.57 ± 0.007[c]
	$F = 30.112$	$F = 0.328$	$F = 0.918$	$F = 1.200$	$F = 0.686$	$F = 2.088$	$\chi^2 = 8.099$	$F = 5.050$
	d.f. = 7, 32	*d.f.* = 5, 96	*d.f.* = 5, 96	*d.f.* = 5, 96	*d.f.* = 5, 96	*d.f.* = 5, 96	*d.f.* = 5	*d.f.* = 5, 114
	$P < 0.0001$	$P = 0.8950$	$P = 0.4730$	$P = 0.3150$	$P = 0.6350$	$P = 0.0734$	$P < 0.0001$	$P < 0.0001$

[a]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a quasi-binomial distribution, followed by post-hoc Tukey test; $P < 0.05$)

[b]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a Gaussian distribution, followed by post-hoc Tukey test; $P < 0.05$)

[c]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a quasi-Poisson distribution, followed by post-hoc Tukey test; $P < 0.05$)

[d]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a binomial distribution, followed by post-hoc Tukey test; $P < 0.05$)

cyhalothrin + thiamethoxam (100% mortality, 30 DAS), while lambda-cyhalothrin + chlorantraniliprole caused 45% mortality at the same assessment time (Fig. 1).

Discussion

This study evaluated the toxicity levels and transgenerational sublethal effects of seven insecticides on the parasitoid wasp *C. flavipes*. The results showed that lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam were highly toxic to adults of this parasitoid. Similar toxicity has also been observed for other parasitoid species, including *Telenomus podisi* Ashmead (Hymenoptera: Platygastridae) (Pazini et al. 2017), *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae) (Beloti et al. 2018), and *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) (Paiva et al. 2018) treated with lambda-cyhalothrin + thiamethoxam. Lambda-cyhalothrin + chlorantraniliprole caused lower mortality than lambda-cyhalothrin + thiamethoxam only after 15 and 30 DAS. These differences might be associated with the components of the commercial product, and mainly with the percentage of lambda-cyhalothrin in the formulation. Lambda-cyhalothrin acts on voltage-gated sodium channels and is a non-systemic insecticide that acts rapidly through contact and ingestion (IRAC 2019; Soderlund and Bloomquist 1989), causing high mortality to natural enemies (Momanyi et al. 2012). Thiamethoxam, which is a systemic insecticide and can act by contact, is a neonicotinoid that acts on the nicotinic acetylcholine receptors of the postsynaptic membranes of nerve-cell junctions (IRAC 2019; Wiesner and Kayser 2000), producing lethal and sublethal neurological effects over a long period of time (Prabhaker et al. 2011; Yao et al. 2015). There is a need to evaluate the potential sublethal effects of thiamethoxam on the behavior of *C. flavipes*, as recently found for another neonicotinoid, imidacloprid, on the braconid parasitoid *Lysiphlebus fabarum* (Marshall) (Hymenoptera: Braconidae) (Jam and Saber 2018). Chlorantraniliprole is also a systemic insecticide but is a member of the diamide group, acting on arthropod ryanodine receptors (Ebbinghaus-Kintscher et al. 2007; IRAC 2019). Upon activation, stored calcium is released from the sarcoplasmic reticulum, impairing the regulation of muscle contraction and causing paralysis and death of sensitive species (Cordova et al. 2006). This insecticide is highly selective to parasitoids since it acts mainly by ingestion, with little contact activity (Stecca et al. 2014). Even so, the results of this study suggest that lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam may reduce the effectiveness of *C. flavipes* as a biocontrol agent of *D. saccharalis* and *D. flavipenella* in sugarcane production systems.

Table 2 Transgenerational sublethal effects on the F_2 generation (egg-pupa and pupa-adult stage development time, number of pupae, pupal weight, emergence rate and sex ratio) of the parasitoid *Cotesia flavipes* when females (F_0) were exposed to treated leaves

Treatment	Development period (days)[a]		Number of pupae[b]	Pupal weight[a] (mg)	Emergence rate[a] (%)	Sex ratio[c] (♀/♂ + ♀)
	Egg-pupa	Pupa-adult				
Control	14.7 ± 0.21	6.5 ± 0.15	61.0 ± 5.81	0.07 ± 0.005	95.2 ± 1.04	0.75 ± 0.04[a]
Chlorantraniliprole	14.7 ± 0.28	6.6 ± 0.15	63.4 ± 5.35	0.07 ± 0.004	91.2 ± 2.15	0.76 ± 0.05[a]
Chlorfluazuron	14.9 ± 0.24	6.2 ± 0.13	52.8 ± 3.69	0.06 ± 0.006	94.3 ± 0.99	0.74 ± 0.05[a]
Novaluron	14.8 ± 0.25	6.3 ± 0.19	69.1 ± 5.71	0.08 ± 0.005	94.7 ± 1.44	0.53 ± 0.09[b]
Tebufenozide	14.6 ± 0.24	6.0 ± 0.26	67.9 ± 4.16	0.08 ± 0.004	92.4 ± 2.57	0.71 ± 0.06[a]
Triflumuron	14.6 ± 0.15	6.4 ± 0.19	71.0 ± 4.92	0.07 ± 0.004	94.7 ± 1.81	0.65 ± 0.07[a]
	$F = 0.310$	$F = 1.196$	$F = 1.588$	$F = 1.636$	$F = 0.788$	$\chi^2 = 7.348$
	$d.f. = 5, 103$	$d.f. = 5, 103$	$d.f. = 5, 102$	$d.f. = 5, 103$	$d.f. = 5, 102$	$d.f. = 5$
	$P = 0.9060$	$P = 0.3160$	$P = 0.1700$	$P = 0.2770$	$P = 0.5680$	$P < 0.0001$

[a]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a Gaussian distribution, followed by post-hoc Tukey test; $P < 0.05$)

[b]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a quasi-Poisson distribution, followed by post-hoc Tukey test; $P < 0.05$)

[c]Data (mean ± SE) followed by the same letter in a column do not differ significantly (GLM with a binomial distribution, followed by post-hoc Tukey test; $P < 0.05$)

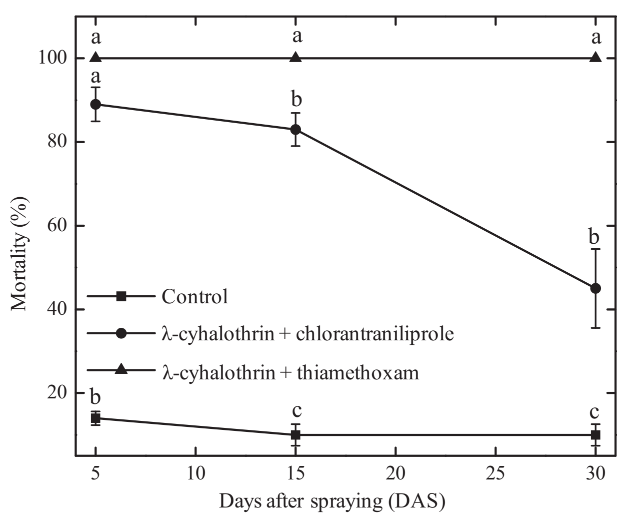

Fig. 1 Mortality of *Cotesia flavipes* adults after exposition to insecticide residues in sugarcane leaves at 5, 15 and 30 days after spraying (DAS) of insecticides. Data (mean ± SE) followed by the same letter at each time (DAS) did not differ significantly (GLM with a quasi-binomial distribution, followed by post-hoc Tukey test; $P < 0.05$)

The results of exposure of *C. flavipes* adults to residues of chlorantraniliprole, chlorfluazuron, novaluron, or triflumuron indicated that these insecticides did not cause significant mortality but did cause transgenerational sublethal effects (Desneux et al. 2007; Guedes et al. 2016). These effects have been observed when pests are exposed to sublethal doses or concentrations of pesticides, resulting in transgenerational hormesis (increasing the pre-oviposition period, fecundity, and larval and pupal survival) (Chen et al. 2016; Wang et al. 2017a; Margus et al. 2019) and reducing the longevity of the progeny and population increases (Hedayati et al. 2019). For natural enemies, the studies indicate that the insecticide residues can also alter the fitness of insects, due to contact or ingestion, and can cause negative effects on the next generations (Guedes et al. 2016). Reported negative transgenerational effects on parasitoids include reduction of emergence, alteration of the sex ratio (reducing the proportion of females) (Costa et al. 2014), reduction of fertility (Biondi et al. 2015), and increased egg-to-adult period (Fonseca et al. 2015). The alteration in the tibia length is often used as a model to observe alterations of insect growth by the action of pesticides and other factors (Fonseca et al. 2015; Soler et al. 2007).

Chlorantraniliprole also shows little or no toxicity to other beneficial parasitoid wasps, including *Cotesia chilonis* (Matsumura) (Hymenoptera: Braconidae) (Huang et al. 2011; Jia et al. 2011), *Cotesia plutellae* (Kurudjumov) (Hymenoptera: Braconidae) (Kishore et al. 2014), *Eretmocerus eremicus* Rose & Zolnerowich (Hymenoptera: Aphelinidae) (Gradish et al. 2011), and *Bracon hebetor* Say (Hymenoptera: Braconidae) (Muslim et al. 2018). High selectivity was recorded for *C. chilonis* (Huang et al. 2011), *C. plutellae* (Haseeb and Amano 2002; Shi et al. 2004), *Trichogramma* spp. (Hymenoptera: Trichogrammatidae) (Goulart et al. 2012), *Psyttalia* (*Opius*) *concolor* Szèpligueti (Hymenoptera: Braconidae) (Bengochea et al. 2012), and *T. pallidus* (Amarasekare et al. 2016), as well as the predators *Macrolophus basicornis* (Stal) (Hemiptera: Miridae) (Passos et al. 2018; Soares et al. 2019), *Orius laevigatus* (Fieber) (Hemiptera: Anthocoridae) (Biondi et al. 2012), *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae), and

Coleomegilla maculata DeGeer (Coleoptera: Coccinellidae) (Cabrera et al. 2018) treated with chlorfluazuron, novaluron, or triflumuron. The low toxicity of these insecticides is attributed not only to the low contact activity of chlorantraniliprole, but also to the action of the chitin synthesis-inhibitor insecticides on the endocrine system of immature stages of insects (Biddinger et al. 2014; Staal 1975; Wang et al. 2017b), which may explain the low toxicity to adult parasitoids. In addition, these insecticides have a low capacity to penetrate the insect cuticle (Sun et al. 2015; Wang et al. 2017b).

Despite this low penetration of the integument, these insecticides have high affinity to and retention capacity at target sites, which may lead to several sublethal effects (Schneider et al. 2003). In this study, chlorfluazuron, novaluron, and triflumuron reduced the tibia length of the F_1 generation of *C. flavipes*. Due to the action mechanism (chitin synthesis inhibitors), these compounds disorganize the integument ultrastructure, reducing and/or delaying the formation of new integument (Castro et al. 2012; Desneux et al. 2007; Perez-Farinos et al. 1998). This process may also increase the energy cost and consequently reduce the growth rate and size of insects (Schneider et al. 2003). Therefore, in this study *C. flavipes* females (F_0 generation) may have expended more energy to detoxify these compounds, and less on body growth of the F_1 generation. Reduction in parasitoids' body size can negatively affect their parasitism capacity (King 2000; Silva-Torres et al. 2009) and the effectiveness of natural enemies in pest control (Riddick 2006; Sétamou et al. 2002). However, no significant effect on the parasitism capacity was observed here, suggesting that these insecticides can be considered safe to use in sugarcane-borer control with minimal impact on *C. flavipes*.

Although chlorantraniliprole, chlorfluazuron, novaluron, and triflumuron were considered harmless to *C. flavipes* adults, they caused transgenerational sublethal effects, modifying the sex ratio of the F_1 and/or F_2 generations. Insecticides that affect the endocrine system can induce deformations in the ovaries and testes (Desneux et al. 2007). In this study, the proportion of females was reduced in both treated and untreated groups. Idris and Grafius (1993) suggested some possible reasons why insecticides may alter the sex ratio, including disruption of ovule fertilization, especially in haplodiploid species, and differential susceptibility between the sexes when exposed prior to the adult stage. The reason for the reduction in the proportion of females is unknown, but it may be due to a selective male mortality, as indicated by the reduction in adult emergence. Insects are particularly sensitive to IGRs (Insect Growth Regulators) during the larval to pupal molt, whereas the larval instars are rather insensitive (Menn and Beroza 1972; Tunaz and Uygun 2004). Additionally, chlorfluazuron, flufenoxuron, and triflumuron (insecticides of the same group) reduced the parasitism capacity of *C. plutellae* (Haseeb and Amano 2002), while flufenoxuron and lufenuron reduced the emergence rates of *Bracon brevicornis* (Wesmael) (Hymenoptera: Braconidae) and *Trichogramma evanescens* Westwood (Hymenoptera: Trichogrammatidae) (Tabozada et al. 2014) when females were treated with these insecticides.

In addition to toxicity, lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam maintained their harmful activity for more than 30 DAS. Similar persistence of these compounds was observed for other parasitoid species. In greenhouse conditions, Momanyi et al. (2012) found that lambda-cyhalothrin (Karate 1.75% EC) had a long residual persistence for the parasitoids *Trichogrammatoidea* sp. nr. *lutea* and *Trichogramma* sp. nr. *mwanzai* (Hymenoptera: Trichogrammatidae). High insecticide persistence can reduce the effectiveness of biocontrol agents in IPM programs. It also reduces the recolonization capacity of natural enemies and interferes with the establishment of ecological balance in agroecosystems (Parra 2014). Among the pyrethroids tested, lambda-cyhalothrin + chlorantraniliprole caused harmful effects to *C. flavipes* for shorter periods. The low concentration of lambda-cyhalothrin in the formulation may have contributed to the lower mortality compared to the lambda-cyhalothrin + thiamethoxam formulation. In addition, lambda-cyhalothrin + thiamethoxam includes a neonicotinoid (thiamethoxam) with high systemic and contact properties. This neonicotinoid also has a low log Kow (−0.13), which facilitates cuticle penetration and translocation in the insect body (Tomizawa and Casida 2005).

To establish an integrated management program for sugarcane borers involving *C. flavipes*, knowledge of the effects of commonly used insecticides on the parasitoid is essential. Few studies have assessed the lethal and transgenerational sublethal effects of insecticides on this parasitoid. Parasitoids were exposed to the insecticides via residual contact on leaves, because in fields the compounds are sprayed on the aerial parts of plants to control neonate larvae of sugarcane borers. Assessments of the height that the insecticides can reach on the sugarcane plant and the parasitoids' contact with the residues are needed to confirm the possible harmful effects in the field. The present results showed that lambda-cyhalothrin + chlorantraniliprole and lambda-cyhalothrin + thiamethoxam were highly harmful and persistent to *C. flavipes*. On the other hand, chlorantraniliprole, chlorfluazuron, novaluron, and triflumuron did not cause high mortality, but did induce transgenerational sublethal effects. Tebufenozide was the only safe active ingredient for *C. flavipes*, causing no lethal or sublethal effects. However, field studies where environmental conditions cannot be manipulated are needed to better understand the effects of these insecticides on this parasitoid. Therefore, these insecticides should be used at different times from the *C. flavipes* releases. In conclusion, residues of the novel, low-risk insecticide tebufenozide appeared to be relatively harmless to *C. flavipes* adults, and therefore this insecticide could be safely applied prior to release and/or establishment of this parasitoid in sugarcane production systems.

Acknowledgements The authors thank the Department of Entomology and Acarology at "Luiz de Queiroz" College of Agriculture/University of São Paulo (ESALQ/USP), Piracicaba, São Paulo, Brazil. They are grateful to Janet W. Reid for help with the manuscript.

Funding This study was funded by the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (CAPES), with financial support and award of a scholarship.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

Amarasekare KG, Shearer PW, Mills NJ (2016) Testing the selectivity of pesticide effects on natural enemies in laboratory bioassays. Biol Control 102:7–16

Araújo JR, Botelho PSM, Araújo SMSS, Almeida LC, Degaspari N (1985) Nova dieta artificial para criação da *Diatraea saccharalis* (Fabr.). Saccharum Apc Rev Tecnol Ind Açúcar Álcool 36:45–48

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48

Beloti VH, Alves GR, Moral RA, Demétrio CGB, Yamamoto PT (2018) The toxicity of fresh and aged residues of pesticides to the parasitoid *Tamarixia radiata* and to the HLB-bacteria vector *Diaphorina citri*. Neotrop Entomol 47:403–411

Bengochea P, Christiaens O, Amor F et al. (2012) Ecdysteroid receptor docking suggests that dibenzoylhydrazine-based insecticides are devoid of any deleterious effect on the parasitic wasp *Psyttalia concolor* (Hym. Braconidae). Pest Manag Sci 68:976–985

Biddinger DJ, Leslie TW, Joshi NK (2014) Reduced-risk pest management programs for Eastern US peach orchards: effects on arthropod predators, parasitoids, and select pests. J Econ Entomol 107:1084–1091

Biondi A, Campolo O, Desneux N, Siscaro G, Palmeri V, Zappala L (2015) Life stage-dependent susceptibility of *Aphytis melinus* DeBach (Hymenoptera: Aphelinidae) to two pesticides commonly used in citrus orchards. Chemosphere 128:142–147

Biondi A, Desneux N, Siscaro G, Zappalà L (2012) Using organic-certified rather than synthetic pesticides may not be safer for biological control agents: selectivity and side effects of 14 pesticides on the predator *Orius laevigatus*. Chemosphere 87:803–812

Cabrera P, Cormier D, Lucas E (2018) Sublethal effects of two reduced-risk insecticides: when the invasive ladybeetle is drastically affected, whereas the indigenous not. J Pest Sci 91:1153–1164

Castro AA, Lacerda MC, Zanuncio TV, Ramalho FS, Polanczyk RA, Serrão JE, Zanuncio JC (2012) Effect of the insect growth regulator diflubenzuron on the predator *Podisus nigrispinus* (Heteroptera: Pentatomidae). Ecotoxicology 21:96–103

Chen X, Ma K, Li F, Liang P, Liu Y, Guo T, Song D, Desneux N, Xiwu G (2016) Sublethal and transgenerational effects of sulfoxaflor on the biological traits of the cotton aphid, *Aphis gossypii* Glover (Hemiptera: Aphididae). Ecotoxicology 25:1841–1848

Conab (2018) Companhia Nacional de Abastecimento. Levantamento de safra da cana-de-açúcar. https://www.conab.gov.br/info-agro/safras/cana. Accessed 23 Jan 2019

Cordova D, Benner EA, Sacher MD, Rauh JJ, Sopa JS, Lahm GP, Selby TP, Stevenson TM, Flexner L, Gutteridge S, Rhoades DF, Wu L, Smith RM, Tao Y (2006) Anthranilic diamides: a new class of insecticides with a novel mode of action, ryanodine receptor activation. Pestic Biochem Physiol 84:196–214

Costa MA, Moscardini VF, Gontijo P, da C, Carvalho GA, Oliveira RL, Oliveira HN (2014) Sublethal and transgenerational effects of insecticides in developing *Trichogramma galloi* (Hymenoptera: Trichogrammatidae). Ecotoxicology 23:1399–1408

Demétrio CGB, Hinde J, Moral RA (2014) Models for overdispersed data in entomology. In: Ferreira CP, Godoy WAC (eds) Ecological modeling applied to entomology. Springer, Cham, pp 219–259

Desneux N, Decourtye A, Delpuech JM (2007) The Sublethal effects of pesticides on beneficial arthropods. Annu Rev Entomol 52:81–106

Dinardo-Miranda LL (2008) Pragas. In: Dinardo-Miranda LL, Vasconcelos ACM, Landell MGA (eds) Cana-de-açúcar. Instituto Agronômico, Campinas, pp 349–404

Dinardo-Miranda LL, Fracasso JV, Costa VP, da, Lopes DOT (2014) Dispersal of *Cotesia flavipes* in sugarcane field and implications for parasitoid releases. Bragantia 73:163–170

Ebbinghaus-Kintscher U, Raming K, Masaki T, Yasokawa N (2007) Flubendiamide, the first insecticide with a novel mode of action on insect ryanodine receptors. Pflanzenschutz Nachr Bayer 60:117–140

Fonseca APP, Marques EJ, Torres JB, Silva LM, Siqueira HAA (2015) Lethal and sublethal effects of lufenuron on sugarcane borer *Diatraea flavipennella* and its parasitoid *Cotesia flavipes*. Ecotoxicology 24:1869–1879

Gradish AE, Scott-Dupree CD, Shipp L, Ron-Harris C, Ferguson G (2011) Effect of reduced risk pesticides on greenhouse vegetable arthropod biological control agents. Pest Manag Sci 67:82–86

Goulart RM, Volpe HXL, Vacari AM, Thuler RT, Bortoli SA (2012) Insecticide selectivity to two species of *Trichogramma* in three different hosts, as determined by IOBC/WPRS methodology. Pest Manag Sci 68:240–244

Guedes RNC, Smagghe G, Stark JD, Desneux N (2016) Pesticide-induced stress in arthropod pests for optimized integrated pest management programs. Annu Rev Entomol 61:43–62

Haseeb M, Amano H (2002) Effects of contact, oral and persistent toxicity of selected pesticides on *Cotesia plutellae* (Hym., Braconidae), a potential parasitoid of *Plutella xylostella* (Lep., Plutellidae). J Appl Entomol 126:8–13

Haseeb M, Liu TX, Jones WA (2004) Effects of selected insecticides on *Cotesia plutellae*, endoparasitoid of *Plutella xylostella*. BioControl 49:33–46

Hassan SA (1994) Activities of the IOBC/WPRS Working Group "Pesticides and Beneficial Organisms". IOBC/WPRS Bull 17:1–5

Hedayati M, Sadeghi A, Maroufpoor M, Ghobari H, Güncan A (2019) Transgenerational sublethal effects of abamectin and pyridaben on demographic traits of *Phytonemus pallidus* (Banks) (Acari: Tarsonemidae). Ecotoxicology 28:467–477

Hensley SD, Hammond Jr AM (1968) Laboratory technique for rearing the sugarcane borer on an artificial diet. J Econ Entomol 61:1742–1743

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biom J 50:346–363

Huang J, Wu S, Ye G (2011) Evaluation of lethal effects of chlorantraniliprole on *Chilo suppressalis* and its larval parasitoid, Cotesia chilonis. Agric Sci China 10:1134–1138

Idris AB, Grafius E (1993) Field studies on the impact of pesticides on the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) and parasitism by *Diadegma insulare* (Cresson) (Hymenoptera: Ichneumonidae). J Econ Entomol 86:1196–1202

IRAC (2019) Insecticide Resistance Action Committee IRAC. Mode of Action Classification Scheme. IRAC Int. MoA Work Gr. Version 9.3:1–30. https://www.irac-online.org/modes-of-action/

Jam NA, Saber M (2018) Sublethal effects of imidacloprid and pymetrozine on the functional response of the aphid parasitoid, *Lysiphlebus fabarum*. Entomol Gen 38:173–190

Jia H, Shun-Fan W, Gong-Yin Y (2011) Evaluation of lethal effects of chlorantraniliprole on *Chilo suppressalis* and its larval parasitoid, Cotesia chilonis. Agr Sci China 10:1134–1138

Joyce AL, White WH, Medina RF (2014) Host plants impact courtship vibration transmission and mating success of a parasitoid wasp, *Cotesia flavipes* (Hymenoptera: Braconidae). Evol Ecol 28:361–372

King BH (2000) Sex ratio and oviposition responses to host age and the fitness consequences to mother and offspring in the parasitoid wasp *Spalangia endius*. Behav Ecol Sociobiol 48:316–320

Kishore MN, Krishnamoorthy SV, Kuttalam S (2014) Safety of chlorantraniliprole 18.5 SC to *Cotesia plutellae* (Kurudjumov) a larval endoparasitoid of *Plutella xylostella* L. J. Res. Angrau 42:4–8

Lin YW, Wu G, Miyata T (2007) Insecticide susceptibility of surviving *Cotesia plutellae* (Hym: Braconidae) and *Diaeretiella rapae* (M'Intosh) (Hym: Aphidiidae) as affected by sublethal insecticide dosages on host insects. Pest Manag Sci 63:841–850

Mahmoud AMA, Luna-Santillana D, Rodriguez-Perez MA (2011) Parasitism by the endoparasitoid, *Cotesia flavipes* induces cellular immunosuppression and enhances susceptibility of the sugar cane borer, *Diatraea saccharalis* to *Bacillus thuringiensis*. J Insect Sci 11:1–15

MAPA (2019) Ministério da Agricultura, Pecuária e Abastecimento AGROFIT: Sistema de Agrotóxicos Fitossanitários. MAPA/CGAF/DFIA/DAS, Brasília, Brazil. http://www.extranet.agricultura.gov.br/agrofit_cons/principal_agrofit_cons. Accessed 12 Jan 2019

Mardani A, Sabahi Q, Almasi A (2016) Susceptibility of pupal and adult stages of the parasitoid *Lysiphlebus fabarum* Marshall (Hym.: Braconidae) to insecticides thiacloprid + deltamethrin, pirimicarb and pymetrozine. Plant Pest Res 6:61–71

Margus A, Piiroinen S, Lehmann P, Tikka S, Karvanen J, Lindström L (2019) Sublethal pyrethroid insecticide exposure carries positive fitness effects over generations in a pest insect. Sci Rep 9:1–10

Menn JJ, Beroza M (1972) Insect juvenile hormones, chemistry and action. Academic Press, New York, NY

Molnár S, López I, Gámez M, Garay J (2016) A two-agent model applied to the biological control of the sugarcane borer (*Diatraea saccharalis*) by the egg parasitoid *Trichogramma galloi* and the larvae parasitoid *Cotesia flavipes*. Biosystems 141:45–54

Momanyi G, Maranga R, Sithanantham S, Agong S, Matoka CM, Hassan SA (2012) Evaluation of persistence and relative toxicity of some pest control products to adults of two native trichogrammatid species in Kenya. BioControl 57:591–601

Muslim M, Ansari MS, Hasan F (2018) Non-target toxicity of synthetic insecticides on the biological performance and population growth of *Bracon hebetor* Say. Ecotoxicology 27:1019–1031

Nelder JA, Wedderburn RWM (1972) Generalized linear models. J R Stat Soc 135:370–384

Ohta I, Takeda M (2015) Acute toxicities of 42 pesticides used for green peppers to an aphid parasitoid, *Aphidius gifuensis* (Hymenoptera: Braconidae), in adult and mummy stages. Appl Entomol Zool 50:207–212

Oliveira CM, Auad AM, Mendes SM, Frizzas MR (2014) Crop losses and the economic impact of insect pests on Brazilian agriculture. Crop Prot 56:50–54

Paiva ACR, Beloti VH, Yamamoto PT (2018) Sublethal effects of insecticides used in soybean on the parasitoid *Trichogramma pretiosum*. Ecotoxicology 27:448–456

Parra JRP (2014) Biological control in Brazil: an overview. Sci Agric 71:420–429

Parra JRP, Botelho PSM, Pinto AS (2014). Biological control of pests as a key component for sustainable sugarcane production. In: Cortez LAB (Coord.) Sugarcane bioethanol—R&D for productivity and sustainability. Edgard Blücher, São Paulo, p 441–450

Passos EM, Wanderley-Teixeira V, Marques EJ, Teixeira ÁAC, Brayner FA (2014) *Cotesia flavipes* (CAM) (Hymenoptera: Braconidae) supresses immune responses in *Diatraea flavipennella* (BOX) (Lepidoptera: Crambidae). Acad Bras Ciênc 86:2013–2024

Passos LC, Soares MA, Collares LJ, Malagoli I, Desneux N, Carvalho GA (2018) Lethal, sublethal and transgenerational effects of insecticides on *Macrolophus basicornis*, predator of *Tuta absoluta*. Entomol Gen 38:127–143

Pavinato VAC, Michel AP, Campos JB, Omoto C, Zucchi MI (2018) Influence of historical land use and modern agricultural expansion on the spatial and ecological divergence of sugarcane borer, *Diatraea saccharalis* (Lepidoptera: Crambidae) in Brazil. Heredity 120:25–37

Pazini JB, Pasini R, Seidel E, Rakes M, Martins JFS, Grützmacher AD (2017) Side-effects of pesticides used in irrigated rice areas on *Telenomus podisi* Ashmead (Hymenoptera: Platygastridae). Ecotoxicology 26:782–791

Perez-Farinos G, Smagghe G, Marco V, Tirry L, Castañera P (1998) Effects of topical application of hexaflumuron on adult sugar beet weevil, *Aubeonymus mariaefranciscae*, on embryonic development: pharmacokinetics in adults and embryos. Pestic Biochem Physiol 61:169–182

Pinto AS, Garcia JF, Botelho BSM (2006) Controle biológico na cana-de-açúcar. In: Pinto AS, Nava DE, Rossi MM, Malerbo-Souza DT (eds) Controle biológico de pragas na prática. Embrapa (Alice), Piracicaba, pp 65–74

Prabhaker N, Castle SJ, Naranjo SE, Toscano NC, Morse JG (2011) Compatibility of two systemic neonicotinoids, imidacloprid and thiamethoxam, with various natural enemies of agricultural pests. J Econ Entomol 104:773–781

Querino RB, Zucchi RA (2011) Guia de identificação de Trichogramma para o Brasil. Embrapa Informação Tecnológica, Brasília

R Development Core Team (2018). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Riddick EW (2006) Egg load and body size of lab-cultured *Cotesia marginiventris*. BioControl 51:603–610

Rossi GD, Salvador G, Cônsoli FL (2014) The parasitoid, *Cotesia flavipes* (Cameron) (Hymenoptera: Braconidae), influences food consumption and utilization by larval *Diatraea saccharalis* (F.) (Lepidoptera: Crambidae). Arch Insect Biochem Physiol 87:85–94

Santos RF, Vacari AM, Bortoli SA, Bortoli CP, Santos JA (2015) Development of a new container for storage and release of the parasitoid *Cotesia flavipes* (Hymenoptera: Braconidae). J Econ Entomol 108:969–974

Schneider MI, Smagghe G, Gobbi A, Viñuela E (2003) Toxicity and pharmacokinetics of insect growth regulators and other novel insecticides on pupae of *Hyposoter didymator* (Hymenoptera: Ichneumonidae), a parasitoid of early larval instars of lepidopteran pests. J Econ Entomol 96:1054–1065

Sétamou M, Bernal JS, Legaspi JC, Mirkov TE (2002) Effects of snowdrop lectin (*Galanthus nivalis* Agglutinin) expressed in transgenic sugarcane on fitness of *Cotesia flavipes* (Hymenoptera: Braconidae), a parasitoid of the nontarget pest *Diatraea saccharalis* (Lepidoptera: Crambidae). Ann Entomol Soc Am 95:75–83

Shi ZH, Guo SJ, Lin WC, Liu SS (2004) Evaluation of selective toxicity of five pesticides against *Plutella xylostella* (Lep: Plutellidae) and their side-effects against *Cotesia plutellae* (Hym: Braconidae) and *Oomyzus sokolowskii* (Hym: Eulophidae). Pest Manag Sci 60:1213–1219

Silva-Torres CSA, Ramos-Filho IT, Torres JB, Barros R (2009) Superparasitism and host size effects in *Oomyzus sokolowskii*, a parasitoid of diamondback moth. Entomol Exp Appl 133:65–73

Soares MA, Passos LC, Campos MR, Collares LJ, Desneux N, Carvalho GA (2019) Side effects of insecticides commonly used against *Tuta absoluta* on the predator *Macrolophus basicornis*. J Pest Sci 92:1447–1456

Soderlund DM, Bloomquist JR (1989) Neurotoxic Actions of Pyrethroid Insecticides. Annu Rev Entomol 34:77–96

Soler R, Bezemer TM, Cortesero AM, Van der Putten WH, Vet LEM, Harvey JA (2007) Impact of foliar herbivory on the development of a root-feeding insect and its parasitoid. Plant Anim Interact 152:257–264

Staal GB (1975) Insect growth regulators with juvenile hormone activity. Ann Rev Entomol 20:417–460

Stecca CS, Pasini A, Bueno AF, Denez MD, Silva DM, Mantovani MAM (2014) Insecticide selectivity for *Doru lineare* (Dermaptera: Forficulidae). Rev Bras Milho Sorgo 13:107–115

Sun R, Liu C, Zhang H, Wang Q (2015) Benzoylurea chitin synthesis inhibitors. J Agric Food Chem 63:6847–6865

Tabozada EK, El-Arnaouty SA, Sayed SM (2014) Effectiveness of two chitin synthesis inhibitors; lufenoxuron and lufenuron on *Spodoptera littoralis* (Lepidoptera: Noctuidae) and side effects of sublethal concentrations of them on two hymenopteran parasitoids. Life Sci J 11:239–245

Tomizawa M, Casida JE (2005) Neonicotinoid insecticide toxicology: mechanisms of selective action. Annu Rev Pharmacol Toxicol 45:247–268

Trevisan M, De Bortoli SA, Vacari AM, Laurentis VL, Ramalho DG (2016) Quality of the exotic parasitoid *Cotesia flavipes* (Hymenoptera: Braconidae) does not show deleterious effects after inbreeding for 10 generations. PLoS ONE 11:e0160898

Tunaz H, Uygun N (2004) Insect growth regulators for insect pest control. Turk J Agric 28:377–387

Vacari AM, Genovez GS, Laurentis VL, De Bortoli SA (2012) Fonte proteica na criação de *Diatraea saccharalis* e seu reflexo na produção e no controle de qualidade de *Cotesia flavipes*. Bragantia 71:355–361

Van Leerdam MB, Smith JW, Fuchs TW (1985) Frass-mediated, host-finding behavior of *Cotesia flavipes*, a braconid parasite of *Diatraea saccharalis* (Lepidoptera: Pyralidae). Ann Entomol Soc Am 78:647–650

Vilela EF, Fernandes JB, Parra JRP, Moscardi F, Rabinovitch L (1998) Controle biológico e feromônios de insetos no âmbito do agronegócio. UFV, Viçosa, p 74

Wang S, Qi Y, Desneux N, Shi X, Biondi A, Gao X (2017a) Sublethal and transgenerational effects of short-term and chronic exposures to the neonicotinoid nitenpyram on the cotton aphid *Aphis gossypii*. J Pest Sci 90:389–396

Wang Y, Xu F, Yu G, Shi J, Li C, Dai A, Liu Z, Xu J, Wang F, Wu J (2017b) Synthesis and insecticidal activity of diacylhydrazine derivatives containing a 3-bromo-1-(3-chloropyridin-2-yl)-1H-pyrazole scaffold. Chem Cent J 11:50

Wiedenmann RN, Smith JW, Darnell PO (1992) Laboratory rearing and biology of the parasite *Cotesia flavipes* (Hymenoptera: Braconidae) using *Diatraea saccharalis* (Lepidoptera: Pyralidae) as a host. Environ Entomol 21:1160–1167

Wiesner P, Kayser H (2000) Characterization of nicotinic acetylcholine receptors from the insects *Aphis craccivora, Myzus persicae*, and *Locusta migratoria* by radioligand binding assays: relation to thiamethoxam action. J Biochem Mol Toxicol 14:221–230

Yao F, Zheng Y, Zhao J, Desneux N, Hea YX, Wenga QY (2015) Lethal and sublethal effects of thiamethoxam on the whitefly predator *Serangium japonicum* (Coleoptera: Coccinellidae) through different exposure routes. Chemosphere 128:49–55