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# Pyrethroid resistance and its inheritance in a field population of *Hippodamia convergens* (Guérin-Méneville) (Coleoptera: Coccinellidae)

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ABSTRACT

The convergent lady beetle (CLB), *Hippodamia convergens* (Guérin-Méneville), a species widely distributed and used in biological control, has exhibited high survival under field and laboratory conditions when treated with field rates of the pyrethroid λ-cyhalothrin, a highly unusual phenomenon for a natural enemy. This work investigated and characterized the phenomenon of pyrethroid resistance in a population of this species collected in Georgia, USA. The mechanism and level of resistance were evaluated by treating parental populations with λ-cyhalothrin ± piperonyl butoxide (PBO). The inheritance bioassay utilized parental crosses and backcrosses between parental populations to obtain testable progenies. Adult beetles from populations and progenies were topically treated with different doses of λ-cyhalothrin (technical grade) to calculate knockdown (KD) and lethal (LD) doses, and to investigate the dominance based on a single dose and whether resistance is autosomal and monogenic (null hypothesis). Genetic variation in the parental populations was examined by applying a discriminating dose for resistant individuals (0.5 g/L). The data indicate that resistance is due to at least two factors: knockdown resistance and enzymatic detoxification of the insecticide. The knockdown effect is recessive and linked to the X-chromosome. Variability in proportions of individuals within families dying following knockdown indicated genetic variation in the resistant population. Further studies should be done to investigate the role of sex linked inheritance of resistance in the species and interactions of the various mechanisms involved in resistance.



## 1. Introduction

Effective integration of insecticides and natural enemies has been a goal of integrated pest management (IPM) since the concept was first fully articulated by Stern et al. [1], although at the time and in the subsequent decades this integration has seemed highly unlikely. Most organophosphate, carbamate, and pyrethroid insecticides have broad activity spectra, with little selectivity toward natural enemies [2]. Insecticides can affect natural enemies, manifesting as death or alterations in behavior and fitness, via direct intoxication from insecticide application, or indirectly through consumption of contaminated prey or through scarcity of prey or hosts [3,4].

Overcoming this incompatibility is the most difficult aspect of integrating biological control agents and insecticides in IPM strategies. An ideal resolution is to replace all broad spectrum products with insecticides of greater selectivity [5,6], but this is highly impractical at present. Some efforts have been made to utilize insecticide-resistant natural enemies in IPM, but such resistance in natural enemies is highly unusual relative to that observed in pests.

Intensive insecticide use has selected for resistance to multiple classes of insecticides in numerous arthropod species, the vast majority of which are herbivores. Since 1914, when the first instance of resistance was observed in the San Jose scale, *Quadraspidiotus perniciosus* (Comstock) (Hemiptera: Diaspididae), more than 500 pest species resistant to insecticides have been recorded [7]. Insecticide resistance in natural enemies has also been reported, but much less frequently than for pest species. The predatory mite *Neoseiulus* (=*Amblyseius*) *fallacis* (Garman) (Acari: Phytoseiidae) was found to be resistant to azinphosmethyl in the 1970s [8]. Subsequently, more cases were observed in predatory mites [9,10]. Among insect natural enemies, field resistance has been reported for the parasitoid *Anisopteromalus calandrae* (Howard) (Hymenoptera: Pteromalidae) to malathion [11], and populations of the

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lacewing *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae) have exhibited resistance to carbaryl [12] and organophosphates and pyrethroids [2,13,14]. Similarly, Suckling et al. [9] found pyrethroid-resistant predatory mites in apple orchards in New Zealand.

Although Coccinellidae have been widely studied and used in biological control for over a century, insecticide resistance has rarely been reported in this group of natural enemies. Lady beetles commonly occur in many ecosystems and are valued for their contributions to biological control of soft-bodied arthropod pests, such as aphids, whiteflies, scales, and mites [6,15,16]. Relative to other entomophages, lady beetles tend to be less susceptible to insecticides than other aphidophagous natural enemies, such as lacewings, syrphids, hemipterans, and hymenopteran parasitoids [17]. Studies of different species and populations of lady beetles and insecticides reveal variation in lady beetle susceptibility to insecticides [18–24], and this variation may be fodder for selection of insecticide resistance in the field. Indeed, *Coleomegilla maculata* (De Geer) (Coleoptera: Coccinellidae) populations in cotton fields were found to be resistant to DDT and several organophosphates by Head et al. [25] and Graves et al. [26]. More recently, a population of another lady beetle species, *Eriopis connexa* (Germar) (Coleoptera: Coccinellidae), collected from cabbage fields in Brazil was found to be 20-fold resistant to the pyrethroid λ-cyhalothrin relative to other populations [24].

The convergent lady beetle (CLB) *Hippodamia convergens* (Guérin-Méneville) is a cosmopolitan species important in numerous agroecosystems [27]. Being widely distributed, populations of CLB are exposed to a wide variety of insecticides across time and space [19,23,28–30]. This fact may explain differential survival among lady beetle species of cotton fields in Georgia, USA, when exposed to λ-cyhalothrin, a broad spectrum pyrethroid insecticide frequently used in various crops [23,28,30,31].

This study was conducted to investigate pyrethroid resistance (specifically, λ-cyhalothrin) in CLB in Georgia and to determine if the metabolism involved is suppressed by the synergist piperonyl butoxide (PBO). Furthermore, inheritance of the resistance and number of factors involved in the resistance were also examined.

## 2. Materials and methods

This study was carried out at the Biological Control Laboratory of the Tifton Campus of the University of Georgia (Tifton, GA).

### 2.1. Chemicals

The insecticide used in the experiments was the pyrethroid λ-cyhalothrin (technical grade 99.5%; Chem Service, West Chester, PA, USA) and the synergist piperonyl butoxide (PBO) at 80% (Endura PB 80 EC-NF, 80% PBO, Endura Fine Chemicals, Bologna, Italy).

### 2.2. Sources of H. convergens (CLB) populations

Two populations of *H. convergens* were established and maintained in the laboratory. One population (designated 'Hc-CA'), which originated from field collections in California (Central Valley near Fresno, CA), was purchased in April 2011 from ARBICO Organics (Oro Valley, AZ). The second population (designated 'Hc-GA') was established from beetles collected in crimson clover in Decatur County, Georgia, USA (coordinates 30°45′45.34″N and 84°28′49.75″W) in April 2011.

### 2.3. CLB maintenance

Larvae and adults were reared using eggs of *Ephestia kuehniella* (Zeller) (Lepidoptera: Pyralidae), obtained from Beneficial Insectary Inc. (Redding, CA, USA). Beetles were held in environmentally controlled conditions of 25 ± 1 °C, and a photoperiod of 14:10 h (L:D) for all rearing and bioassays. The two populations were maintained separately. Adults were kept in cylindrical plastic containers (30 cm long, wide and high) containing openings on the sides closed with nylon mesh. Later, individual pairs were held in 500-ml plastic containers with a mesh-covered opening in the lid to allow ventilation, and a piece of paper towel as an oviposition substrate. Eggs were transferred to transparent 30-ml plastic cups. Eggs produced by at least 20 adult pairs were used to maintain the colonies and to provide insects for bioassays. Newly eclosed larvae were held individually in 30-ml plastic cups and provided *ad libitum* with eggs of *E. kuehniella*.

### 2.4. Dose–response curves

Adults of the $F_1$ generation from both populations (Hc-CA and Hc-GA) were treated with the insecticide λ-cyhalothrin to determine the lethal dose ($LD_{50}$). Preliminary bioassays were carried out to define doses which resulted in mortality from 0% to 100%. Insects were topically treated by applying a 0.5 μl droplet of the appropriate solution to the venter of the adult abdomen using a Hamilton syringe (25 μl-volume). Based on preliminary tests six doses for each population (0.001, 0.002, 0.004, 0.006, 0.008, and 0.01 g a.i./L for Hc-CA; and 0.1, 0.3, 0.5, 0.7, 1.0, and 1.3 g a.i./L for Hc-GA) were selected for calculating the dose-mortality curve and the $LD_{50}$. At least 20 adults (8–10 days old) were tested per dose.

Treated and control groups were kept in petri dishes (12 cm diameter, and 1.5 cm high) lined with filter paper and provided with a 10% honey solution soaked in cotton batting inside the petri dishes. Petri dishes with insects were stored in a climatic chamber at 25 ± 1 °C and photoperiod 14:10 h (L:D). Knockdown and mortality were assessed 2 and 24 h after insecticide application, respectively. A beetle was considered to be knocked down or dead if it was unable to turn upright and begin to walk after being placed on its dorsum at the respective observation intervals.

### 2.5. Dose–response curves with the synergist PBO

The insecticide λ-cyhalothrin (99.5% technical grade) and the synergist PBO were applied in the bioassay diluted in acetone. Previous tests of varying doses of PBO indicated that 10 g a.i. of PBO/L (10 ppm) was the maximum sublethal dose and could be used in the dilutions to be tested. Thus, the synergism ratio using PBO was determined for Hc-GA and Hc-CA populations by treating the insects with λ-cyhalothrin dosage including PBO at 10 g a.i./L. The tested dosages of λ-cyhalothrin alone began with a high dosage of 1 g a.i./L, which was then serially diluted by factors of 10 during the preliminary test to obtain the final dosages. The dosages of λ-cyhalothrin + PBO used were: 0.0002, 0.0004, 0.0006, 0.0008, 0.001, and 0.003 g a.i./L for Hc-CA; and 0.005, 0.01, 0.03, 0.05, 0.08, 0.10, and 0.5 g a.i./L for Hc-GA. The bioassay was conducted using λ-cyhalothrin + PBO, as well as control treatments using only PBO or acetone.

### 2.6. Dominance and role of sex linkage in resistance

The $F_1$ progeny was tested to evaluate possible sex linkage related to the resistance. Females and males were kept individually in transparent 30-ml plastic cups. Sexes were differentiated based on the shape of the distal margin of the fourth visible abdominal sternite. The posterior margin of the fourth sternite has a concave shape in males while in females it is a straight line. Reciprocal crosses between virgin females ($n = 30$) and males ($n = 30$) from resistant (Hc-GA) and susceptible (Hc-CA) populations were made

to obtain $F_1$ progeny SR (♀ Hc-CA × ♂ Hc-GA) and RS (♀ Hc-GA × ♂ Hc-CA). Free mating choice was allowed by pairing females and males of the two parental populations in plastic containers (30 cm long, wide and high). Each $F_1$ cross progeny (SR and RS) was reared separately to obtain sufficient adults to calculate the $LD_{50}$.

To test for sex linkage, males from both $F_1$ reciprocal crosses ($n = 30$) (SR and RS) were backcrossed with parental females: BC1 (♀ Hc-GA × ♂ $F_1$ RS); BC2 (♀ Hc-GA × ♂ $F_1$ SR); BC3 (♀ Hc-CA × ♂ $F_1$ RS); and BC4 (♀ Hc-CA × ♂ $F_1$SR). The progenies obtained from backcross pairings were reared separately to obtain sufficient adults for each backcross to calculate the $LD_{50}$ using 6–10 λ-cyhalothrin doses.

### 2.7. Dominance of resistance in H. convergens to λ-cyhalothrin based on a single dose

In this bioassay we used 8-d old adults of the population groups Hc-CA ($n = 120$), HC-GA ($n = 120$), $F_1$ RS ($n = 120$) and $F_1$ SR ($n = 120$). Five previously determined doses of λ-cyhalothrin (0.001, 0.01, 0.1, 0.5, and 1.0 g of a.i./L) were administered to adults of the different population groups as previously described. The control group was treated only with acetone ($n = 10$). The knockdown effect and mortality were assessed 2 and 24 h after insecticide application, respectively.

### 2.8. Genetic variation within susceptible and resistant populations of H. convergens

We tested Hc-CA and Hc-GA for homozygosity of resistance traits in the respective populations. Individual virgin females and males ($n = 5$) were paired for mating and egg production to compose five separate families. Then virgin female and male offspring of Hc-CA, Hc-GA, $F_1$ reciprocal crosses, $F_1$ RS and SR, and the four backcrosses (BC1 to BC4) were tested with a discriminating dose of 0.5 g a.i of λ-cyhalothrin/L for homozygous resistance ($X^RX^R$ and $X^Ry$) following the same procedures used in the previous tests. Each adult pair corresponded to a population family or specified cross progeny. By examining offspring in individual families we could compare observed results with what would be expected for a homozygous population in detail, allowing us to discern individual deviations from homozygosity that could otherwise confound interpretation of results [32,33]. As a component of this, the sex determination system of *H. convergens* must be considered in evaluating a sex linkage model for inheritance of insecticide resistance. The CLB has been characterized as $2n = 18$ autosomal and having homogametic females (XX) and heterogametic (Xy) males [34]. Therefore, males will be homozygous for traits acquired from the female on the X chromosome.

### 2.9. Data analysis

The number of individuals exhibiting knockdown, death or survival per dose in the resistance inheritance and synergism tests were used to calculate the knockdown dose (KD) and the lethal dose (LD) for each population or progeny with the computer program Polo PC [35], based on Probit analysis [36]. Correction for natural mortality was unnecessary since control survival in all cases was 100%. A $\chi^2$ goodness-of-fit test was used to test for parallelism and equality of the dose-mortality curves between populations. Data from resistance inheritance bioassays were used to obtain the resistance ratio (RR) between resistant and susceptible populations based on the KD and LD calculated for each population, $F_1$ progenies, and backcrosses. Likewise, the synergism ratio (SR) and the resistance ratio (RR) were calculated for treatments with λ-cyhalothrin only or when the synergist PBO was added. The RR and SR and their respective 95% confidence intervals (CI) were calculated and considered significant when the CI did not include the value 1.0, following the method of Robertson and Preisler [37].

Autosomal or sex-linked inheritance of resistance in *H. convergens* to λ-cyhalothrin was tested using the KD and LD determined for $F_1$ adults from reciprocal crosses between Hc-GA and Hc-CA populations, $F_1$ RS and $F_1$ SR progenies. The degree of dominance ($D$) was estimated using the method of Stone [38], which is based on the KD or LD values. The standard error (SE) of the degree of dominance was calculated following the method of Lehmann [39], and interpreted after Preisler et al. [40]. The dominance ($h$) was estimated based on a single dose, following Hartl [41].

The minimum number of genes controlling resistance was investigated using the method of Lande [42] based on $KD_{50}$ and $LD_{50}$ responses. The minimum number of genes driving resistance was calculated separately for $F_1$ progeny of *H. convergens* and the respective backcrosses.

To evaluate genetic variation of parental populations, observed knockdown and mortality were initially corrected for the number of males and females of *H. convergens* tested. Thus, the testable hypothesis for genetic homozygosity is that the proportion of observed knockdown or mortality would be equal to the proportion of expected knockdown or mortality based on the sex-linked inheritance for *H. convergens*, assuming the recessive inheritance of resistance found with the discriminatory dose (0.5 g a.i. of λ-cyhalothrin/L). Thus, using the G-statistic goodness of fit test for heterogeneity [43], homogeneity was tested among families and the hypothesis of absence of genetic variation was tested within and among families. The goodness of fit test was carried out only on the results for $F_1$ RS and for the backcross BC2 (♀ Hc-GA × ♂ $F_1$ SR). The test was not conducted for families of the susceptible population (Hc-CA), the $F_1$ SR progeny or their respective backcrosses (BC3 and BC4) because the knockdown and mortality responses observed were as expected for all families (1.00). Furthermore, for the resistant population (Hc-GA) and the backcross BC1 (♀ Hc-GA × ♂ $F_1$ RS), the expected mortality is null (0.00) and, therefore, a $G$-statistic could not be calculated.

## 3. Results

### 3.1. Dose–response curves

The knockdown results fit the Probit model ($P > 0.05$). In contrast, the dose-mortality curves differed in parallelism and equality ($P < 0.05$); thus the $KD_{50s}$ and $KD_{90s}$ were calculated (Table 1). Based on $KD_{50}$ and $KD_{90}$ from evaluations 2 h post-treatment the Hc-GA population was over 286 and 461-fold more resistant by knockdown effect to λ-cyhalothrin than Hc-CA adults (Table 1). The $LD_{50}$ and $LD_{90}$ of the Hc-CA population were, respectively, 0.004 and 0.816 g a.i. of λ-cyhalothrin/L, compared to 0.015 and 4.595, respectively, for the Hc-CA and Hc-GA populations. Based on these values, the Hc-GA population was over 220 ($LD_{50}$) and 308.0-fold ($LD_{90}$) more resistant to λ-cyhalothrin than the Hc-CA population (Table 1).

### 3.2. Dose-mortality curves with the synergist PBO

Adults from both populations exhibited similar patterns of response for knockdown and mortality when treated with λ-cyhalothrin plus the synergist PBO, but differed when using λ-cyhalothrin alone (Table 2). The $KD_{50}$ and $LD_{50}$, however, were lower than when only λ-cyhalothrin was applied. The $KD_{50}$ and $LD_{50}$ synergism ratios were 1.62 and 6.94 (KD); and 5.53 and 17.24 (LD) for Hc-CA and Hc-GA populations, respectively. The resistance ratio (RR) of λ-cyhalothrin based on the $KD_{50}$ or $LD_{50}$

**Table 1**
Knockdown and mortality responses of *Hippodamia convergens* susceptible (Hc-CA) and resistant (Hc-GA) populations, F1 progeny from reciprocal crosses and from backcrosses to λ-cyhalothrin during 2 h and 24 h evaluation intervals post-treatment, respectively. *n*, number of tested individuals; df, degrees of freedom; SE, standard error of the slope; CI, confidential intervals at 95% probability; DD, degree of dominance; and $\chi^2$, Chi-square test.

| Population or progeny[a] | *n* | df | Slope ± SE | $KD_{50}$ ($CI_{95\%}$)[b] | $RR_{50}$ ($CI_{95\%}$)[c] | $DD_{50}$ ± SE | $KD_{90}$ ($CI_{95\%}$)[b] | $RR_{90}$ ($CI_{95\%}$)[c] | $DD_{90}$ ± SE | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Knockdown – 2 h evaluation* | | | | | | | | | | |
| Hc-CA | 191 | 4 | 2.39 ± 0.42 | 0.001 (0.0004–0.002) | – | | 0.004 (0.002–0.011) | – | | 6.76 |
| Hc-GA | 221 | 4 | 1.73 ± 0.28 | 0.297 (0.156–0.439) | 286.75 (86.59–949.64) | | 1.636 (0.955–6.219) | 461.16 (133.26–1595.93) | | 4.76 |
| $F_1$ RS | 214 | 5 | 1.10 ± 0.20 | 0.012 (0.005–0.021) | 11.91 (5.43–26.11) | −0.13 ± 0.15 | 0.182 (0.105–0.474) | 51.11 (24.04–108.68) | 0.27 ± 0.17 | 4.50 |
| $F_1$ SR | 220 | 4 | 1.52 ± 0.19 | 0.003 (0.0002–0.007) | 2.62 (0.57–12.02) | −0.66 ± 0.27 | 0.019 (0.009–0.038) | 5.35 (2.81–10.16) | −0.48 ± 0.11 | 0.50 |
| BC1 | 198 | 6 | 1.32 ± 0.19 | 0.271 (0.162–1.14) | 211.33 (111.96–398.90) | | 2.254 (1.02–15.43) | 835.24 (252.59–2761.92) | | 6.35 |
| BC2 | 167 | 4 | 0.72 ± 0.20 | 0.073 (0.026–0.144) | 70.47 (31.19–159.24) | | 4.480 (1.100–396.1) | 1259.04 (143.76–11026.3) | | 6.33 |
| BC3 | 267 | 8 | 2.27 ± 0.33 | 0.003 (0.002–0.004) | 2.81 (1.71–4.63) | | 0.011 (0.008–0.017) | 3.00 (1.85–4.89) | | 4.78 |
| BC4 | 268 | 8 | 2.63 ± 0.40 | 0.003 (0.002–0.004) | 2.91 (1.80–4.71) | | 0.009 (0.007–0.014) | 2.61 (1.64–4.14) | | 1.78 |
| *Mortality – 24 h evaluation* | | | | $LD_{50}$ | | | $LD_{90}$ | | | |
| Hc-CA | 191 | 4 | 2.12 ± 0.33 | 0.004 (0.003–0.005) | – | | 0.015 (0.010–0.028) | – | | 1.24 |
| Hc-GA | 221 | 4 | 1.71 ± 0.32 | 0.816 (0.631–1.167) | 220.03 (76.89–629.65) | | 4.595 (2.54–15.53) | 308.00 (79.62–1191.39) | | 1.54 |
| $F_1$ RS | 214 | 5 | 1.17 ± 0.17 | 0.194 (0.059–1.745) | 52.33 (32.30–84.80) | 0.47 ± 0.16 | 2.423 (0.545–14490) | 162.29 (56.64–465.02) | 0.78 ± 0.26 | 19.63* |
| $F_1$ SR | 220 | 4 | 2.19 ± 0.33 | 0.026 (0.019–0.034) | 7.03 (4.89–10.11) | −0.28 ± 0.09 | 0.100 (0.072–0.173) | 6.73 (3.62–12.52) | −0.34 ± 0.12 | 1.46 |
| BC1 | 198 | 6 | 2.03 ± 0.39 | 0.804 (0.548–1.441) | 216.95 (131.14–358.92) | | 3.431 (1.793–12.971) | 230.03 (85.46–619.16) | | 1.03 |
| BC2 | 167 | 4 | 1.45 ± 0.22 | 0.364 (0.245–0.621) | 98.08 (59.26–162.32) | | 2.754 (1.346–9.637) | 184.56 (65.92–516.78) | | 4.58 |
| BC3 | 267 | 8 | 2.17 ± 0.25 | 0.015 (0.012–0.019) | 4.07 (2.90–5.71) | | 0.059 (0.043–0.091) | 3.93 (2.19–7.08) | | 4.78 |
| BC4 | 268 | 8 | 2.24 ± 0.27 | 0.011 (0.009–0.014) | 3.05 (2.17–4.27) | | 0.042 (0.031–0.065) | 2.83 (1.58–5.08) | | 4.20 |

[a] $F_1$ RS and $F_1$ SR stand for reciprocal crosses between ♀ Hc-GA × ♂ Hc-CA and ♀ Hc-CA × ♂ Hc-GA, respectively; BC1, BC2, BC3, and BC4 are the backcrosses of ♀ Hc-GA × ♂ $F_1$ RS, ♀ Hc-GA × ♂ $F_1$ SR, ♀ Hc-CA × ♂ $F_1$ RS; and ♀ Hc-CA × ♂ $F_1$ SR, respectively.
[b] g a.i./L of λ-cyhalothrin at technical grade producing 50% or 90% knockdown effect in the population 2 h after treatment.
[c] RR, resistance ratio estimated by the relationship of KDs or LDs between resistant and susceptible populations following the method of Robertson and Preisler [37].
* *P*-value (<0.05).

was reduced approximately 3–4-fold to ~70 for Hc-GA relative to Hc-CA when PBO was added (Table 2). These results further demonstrate that the Hc-GA population is more resistant to λ-cyhalothrin than the Hc-CA population. Furthermore, the $LD_{90}$ calculated for the Hc-GA population is 10.44 times greater than the highest field rate of λ-cyhalothrin recommended to spray cotton (0.44 g a.i./L).

### 3.3. Dominance and role of sex linkage in resistance

The RR for the $F_1$ RS beetles was greater than that of the $F_1$ SR beetles when calculated using the $KD_{50}$, $KD_{90}$, $LD_{50}$, and $LD_{90}$ values, suggesting that resistance is X-linked (Table 1). Further the degree of dominance varied from −0.66 to −0.13 based on $KD_{50}$, and from −0.48 to 0.27 based on $KD_{90}$ (Table 1). The resistance ratios of the $KD_{50}$ for BC1 and BC2, both of which were offspring of Hc-GA mothers, were 211.33 and 70.47-fold, respectively, whereas the $KD_{50}$ resistance ratios for BC3 and BC4, which were offspring of Hc-CA mothers, were 2.81 and 2.91, respectively. These results are consistent with X-linked resistance. Despite the low ratios for BC3 and BC4 they were significantly different from the parental Hc-CA population according to the method of Robertson and Preisler [37] (Table 1).

The mortality data for the progenies and backcrosses fit a Probit model ($P > 0.05$), except for the mortality of the $F_1$ RS progeny ($P < 0.05$). There were significant differences between the $F_1$ progenies (SR and RS) in both the $LD_{50}$ and $LD_{90}$ [$RR_{50(IC95\%)}$: 7.44 (4.48–12.35) and $TR_{90(IC95\%)}$: 24.11 (8.56–67.87)], which, taken with the backcross results, strongly suggests a maternal effect or X-linked. The degree of dominance varied from −0.28 to 0.47 for the $LD_{50}$, from −0.34 to 0.78 for the $LD_{90}$ (Table 1).

### 3.4. Dominance of resistance in H. convergens to λ-cyhalothrin based on a single dose

The results indicate recessive dominance in the $F_1$ progenies tests and variability in the resistance based on single dose results. The resistance was found to be functionally dominant ($h = 1.0$) for the Hc-GA population at the lowest tested dose (0.001) for both reciprocal crosses (RS and SR) (Table 3). For $F_1$ SR, however, resistance was functionally recessive ($h = 0.0$) at doses of 0.1 and 1.0 g a.i. of λ-cyhalothrin/L at 2 and 24 h evaluations, respectively; while for $F_1$ RS it was recessive only at the highest tested dose at knockdown 2 h post-treatment (Table 3). Based on mortality evaluated 24 h post-treatment the effective dominance ranged from 0.32 to 0.5 for doses greater than 0.1 g a.i. of λ-cyhalothrin/L for $F_1$ RS (Table 3).

### 3.5. Minimum number of loci

The number of loci coordinating resistance in *H. convergens* to λ-cyhalothrin was estimated at −4.39 and 0.74 genes for the $F_1$ RS and $F_1$ SR progenies, and for their respective backcrosses. On the other hand, when considering the mortality data, the number of genes coordinating resistance is estimated at −1.23 and 3.73 for the $F_1$ progenies SR and RS, and their backcrosses, respectively.

### 3.6. Genetic variation within susceptible and resistant populations of H. convergens

The paired females and males from Hc-GA and the $F_1$ RS progeny resulted in four pairs that produced viable offspring (families), out of the five pairs set up. Thus, only four families were utilized for the BC1 and BC3 backcrosses. The knockdown and mortality results indicated that Hc-GA male parents, used to form the ♀ Hc-GA × ♂ Hc-GA families, were not susceptible to λ-cyhalothrin (i.e. the males of Hc-GA were not $X^Sy$). The genetic variation in resistance observed in the Hc-GA population is likely related to the proportion of susceptible adults produced by pairings of heterozygous females ($X^RX^S$) and resistant males ($X^Ry$) (Tables 4 and 5). Families of the susceptible population (Hc-CA), the progeny of $F_1$ SR and the backcrosses BC3 and BC4 exhibited responses aligned with the expected frequency of susceptible offspring (1.00) (Tables 4 and 5). Families of $F_1$ RS were similar to one another in knockdown ($P = 0.6611$) and mortality ($P = 0.0948$). Furthermore, the proportion of individuals exhibiting knockdown and mortality was significantly different from the expected proportion in three

**Table 2**
Knockdown (2 h) and mortality (24 h) responses of *Hippodamia convergens* (Hc) populations from California (CA) and Georgia (GA) to λ-cyhalothrin (99.5% technical grade) only or with 10 ppm of piperonyl butoxide (PBO) added to the solution. *n*, number of tested adults; df = degree of freedom; SE = standard error for the slope; LDs = lethal doses in g of a.i./L; CI = 95% confidence intervals; and $\chi^2$ = chi-square test.

| Population/progeny | *n* | df | Slope ± SE | $LD_{50}$ ($CI_{95\%}$)[a] | $SR_{50}$ ($CI_{95\%}$)[b] | $RR_{50}$ ($CI_{95\%}$)[c] | $LD_{90}$ ($CI_{95\%}$)[a] | $SR_{90}$ ($CI_{95\%}$)[b] | $RR_{90}$ ($CI_{95\%}$)[c] | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Knockdown – 2 h evaluation with λ-cyhalothrin* | | | | | | | | | | |
| Hc-CA | 191 | 4 | 2.39 ± 0.42 | 0.001 (0.0004–0.002) | – | – | 0.004 (0.002–0.011) | – | – | 6.76 |
| Hc-GA | 221 | 4 | 1.73 ± 0.28 | 0.297 (0.156–0.439) | – | 286.75 (86.59–949.64) | 1.636 (0.955–6.219) | – | 461.16 (133.26–1595.93) | 4.76 |
| *Knockdown – 2 h evaluation with λ-cyhalothrin + PBO* | | | | | | | | | | |
| Hc-CA | 278 | 4 | 2.64 ± 0.33 | 0.0006 (0.0005–0.0008) | 1.62 (1.07–2.45) | – | 0.002 (0.001–0.004) | 1.82 (1.16–2.86) | – | 3.87 |
| Hc-GA | 182 | 5 | 1.45 ± 0.23 | 0.043 (0.030–0.061) | 6.94 (4.40–10.93) | 67.05 (45.70–98.37) | 0.327 (0.186–0.881) | 5.00 (2.08–12.02) | 167.81 (75.53–372.82) | 0.69 |
| *Mortality – 24 h evaluation with λ-cyhalothrin* | | | | | | | | | | |
| Hc-CA | 191 | 4 | 2.12 ± 0.33 | 0.004 (0.003–0.005) | – | – | 0.015 (0.010–0.028) | – | – | 1.24 |
| Hc-GA | 221 | 4 | 1.71 ± 0.32 | 0.816 (0.631–1.167) | – | 220.03 (76.89–629.65) | 4.595 (2.54–15.53) | – | 308.00 (79.62–1191.39) | 1.54 |
| *Mortality – 24 h evaluation with λ-cyhalothrin + PBO* | | | | | | | | | | |
| Hc-CA | 278 | 4 | 3.30 ± 0.42 | 0.0007 (0.0006–0.0008) | 5.53 (4.23–7.22) | – | 0.002 (0.001–0.003) | 9.10 (5.34–15.49) | – | 4.38 |
| Hc-GA | 182 | 5 | 1.57 ± 0.24 | 0.047 (0.034–0.067) | 17.24 (11.24–26.70) | 70.55 (49.49–100.57) | 0.309 (0.182–0.762) | 14.84 (5.19–42.39) | 188.81 (91.57–389.27) | 3.43 |

[a] g a.i./L of λ-cyhalothrin at technical grade producing 50% or 90% knockdown or mortality effect in the population 2 and 24 h after treatment, respectively.
[b] SR, synergism ratio based on the relationship of $LD_{50}$ or $LD_{90}$ calculated from populations treated with λ-cyhalothrin and λ-cyhalothrin + PBO following the method of Robertson and Preisler [37].
[c] RR, resistance ratio based on the relationships of $LD_{50}$ or $LD_{90}$ calculated from populations treated with λ-cyhalothrin and λ-cyhalothrin synergized with PBO following the method of Robertson and Preisler [37].

**Table 3**
Dominance (*h*) of resistance in *Hippodamia convergens* adults based on knockdown and mortality responses evaluated 2 h and 24 h periods after treatment with different doses (g a.i. of λ-cyhalothrin) for susceptible (Hc-CA), resistant (Hc-GA), and $F_1$ reciprocal crosses $F_1$ SR (♀ Hc-CA × ♂ Hc-GA), and $F_1$ RS (♀ Hc-GA × ♂ Hc-CA).

| Doses | Population/progeny | *n* | Knockdown (%) | *h*[a] | Population/progeny | *n* | Mortality (%) | *h*[a] |
|---|---|---|---|---|---|---|---|---|
| 0.001 | Hc-CA | 24 | 33.33 | | Hc-CA | 24 | 16.67 | |
| | Hc-GA | 24 | 0.00 | | Hc-GA | 24 | 0.00 | |
| | $F_1$ SR | 24 | 0.00 | 1.00 | $F_1$ SR | 24 | 0.00 | 1.00 |
| | $F_1$ RS | 24 | 0.00 | 1.00 | $F_1$ RS | 24 | 0.00 | 1.00 |
| 0.01 | Hc-CA | 24 | 100.00 | | Hc-CA | 24 | 91.67 | |
| | Hc-GA | 24 | 0.00 | | Hc-GA | 24 | 0.00 | |
| | $F_1$ SR | 24 | 83.33 | 0.17 | $F_1$ SR | 24 | 16.67 | 0.82 |
| | $F_1$ RS | 24 | 41.67 | 0.58 | $F_1$ RS | 24 | 0.00 | 1.00 |
| 0.1 | Hc-CA | 24 | 100.00 | | Hc-CA | 24 | 100.00 | |
| | Hc-GA | 24 | 33.33 | | Hc-GA | 24 | 8.33 | |
| | $F_1$ SR | 24 | 100.00 | 0.00 | $F_1$ SR | 24 | 79.17 | 0.23 |
| | $F_1$ RS | 24 | 75.00 | 0.38 | $F_1$ RS | 24 | 54.17 | 0.50 |
| 0.5 | Hc-CA | 24 | 100.00 | | Hc-CA | 24 | 100.00 | |
| | Hc-GA | 24 | 79.17 | | Hc-GA | 24 | 20.83 | |
| | $F_1$ SR | 24 | 100.00 | 0.00 | $F_1$ SR | 24 | 95.83 | 0.05 |
| | $F_1$ RS | 24 | 95.83 | 0.20 | $F_1$ RS | 24 | 75.00 | 0.32 |
| 1.0 | Hc-CA | 24 | 100.00 | | Hc-CA | 24 | 100.00 | |
| | Hc-GA | 24 | 95.83 | | Hc-GA | 24 | 33.33 | |
| | $F_1$ SR | 24 | 100.00 | 0.00 | $F_1$ SR | 24 | 100.00 | 0.00 |
| | $F_1$ RS | 24 | 100.00 | 0.00 | $F_1$ RS | 24 | 70.83 | 0.44 |

[a] *h* Varies between 0 and 1 (0 = survival is recessive and 1 = survival is dominant).

of the four families (Tables 4 and 5), evidencing genetic variation for knockdown ($\chi^2 = 30.23$, $P < 0.0001$, df = 4) and mortality ($\chi^2 = 25.35$, $P < 0.0001$, df = 4). Variation was observed among families of BC2 (♀ Hc-GA × ♂ $F_1$ SR) for knockdown ($\chi^2 = 26.55$, $P < 0.0001$, df = 5), but not for mortality ($\chi^2 = 0.55$, $P = 0.9932$, df = 5). Variation for the knockdown effect was observed for only two out of five families (Table 4). Regardless of individual family outcome, there was no difference among BC2 families based on knockdown ($P = 0.3277$) or mortality ($P = 0.9942$). For the backcross BC1 (♀ Hc-GA × ♂ $F_1$ RS), the high variability among families and variation from the expected response confirm the genetic variation of their parental resistant population (Hc-GA).

## 4. Discussion

Resistance in *H. convergens* to λ-cyhalothrin was confirmed in a Georgia population, and it appears to have multiple mechanisms that also may differ in inheritance. Based on knockdown response ($KD_{50}$), the resistance seems to be autosomally inherited and

**Table 4**
Knockdown response (2 h evaluation post-treatment) of resistant adults $X^RX^R$ and $X^Ry$ of *Hippodamia convergens* treated with a discriminatory dose (0.5 g a.i. of λ-cyhalothrin/L). Observed and expected proportions of knockdown are presented according to the progeny genotype and the null hypothesis: parental susceptible and homozygous resistant as function of inheritance of resistance linked to the $X^R$-chromosome with 1040 tested adults.

| Population/progeny[a] | Sex linkage | | | | | | |
|---|---|---|---|---|---|---|---|
| | Offspring genotype | | Expected proportion | | Observed proportion (SE) | $\chi^2$ | *P* |
| | ♂ | ♀ | Adults[b] | F/*n*[c] | Adults[b] | | |
| Hc-GA | $X^Ry$ | $X^RX^R$ | 0.00 | A/20 | 0.67 (0.05) | NC[d] | NC |
| | | | 0.00 | B/30 | 0.37 (0.03) | NC | NC |
| | | | 0.00 | C/30 | 0.15 (0.06) | NC | NC |
| | | | 0.00 | D/40 | 0.48 (0.12) | NC | NC |
| Hc-CA | $X^Sy$ | $X^SX^S$ | 1.00 | (A–E)/150 | 1.00 (0.00) | 0.00 | 1.00 |
| $F_1$ RS | $X^Ry$ | $X^RX^S$ | 0.50 | A/30 | 0.75 (0.00) | 7.50 | 0.01* |
| | | | 0.50 | B/30 | 0.65 (0.06) | 2.70 | 0.10 |
| | | | 0.50 | C/30 | 0.77 (0.07) | 8.53 | <0.00* |
| | | | 0.50 | D/30 | 0.80 (0.01) | 11.5 | <0.00* |
| $F_1$ SR | $X^Sy$ | $X^RX^S$ | 1.00 | (A–E)/150 | 1.00 (0.00) | 0.00 | 1.00 |
| BC1 | $X^Ry$ | $X^RX^R$ | 0.00 | A/30 | 0.00 (0.00) | NC[d] | NC |
| | | | 0.00 | B/30 | 0.18 (0.08) | NC | NC |
| | | | 0.00 | C/30 | 0.05 (0.03) | NC | NC |
| | | | 0.00 | D/30 | 0.53 (0.02) | NC | NC |
| BC2 | $X^Ry$ | $X^RX^S$ | 0.50 | A/30 | 0.63 (0.06) | 1.88 | 0.16 |
| | | | 0.50 | B/30 | 0.64 (0.02) | 2.41 | 0.12 |
| | | | 0.50 | C/30 | 0.63 (0.06) | 1.88 | 0.16 |
| | | | 0.50 | D/30 | 0.71 (0.12) | 5.21 | 0.02* |
| | | | 0.50 | E/30 | 0.86 (0.04) | 15.2 | <0.00* |
| BC3 | $X^Sy$ | $X^RX^S$ | 1.00 | (A–D)/110 | 1.00 (0.00) | 0.00 | 1.00 |
| BC4 | $X^Sy$ | $X^SX^S$ | 1.00 | (A–E)/150 | 1.00 (0.00) | 0.00 | 1.00 |

[a] Susceptible (Hc-CA) and resistant (Hc-GA) populations; $F_1$ RS, cross of ♀ Hc-GA × ♂ Hc-CA, and $F_1$ SR cross of ♀ Hc-CA × ♂ Hc-GA. The backcrosses BC1 (♀ Hc-GA × ♂ $F_1$ RS), BC2 (♀ Hc-GA × ♂ $F_1$ SR), BC3 (♀ Hc-CA × ♂ $F_1$ RS), and BC4 (♀ Hc-CA × ♂ $F_1$ SR).
[b] Proportion of adults (mean pooled for males and females).
[c] F stands for families, and *n* stands for number of insects tested per family for each population, progeny, and backcrosses.
[d] NC stands for chi-square and *p*-values not determined; while *stands for significant deviation from the null hypotheses.

incompletely recessive, but based on $KD_{90}$ the inheritance also appears to be sex-linked. Sex-linked inheritance of resistance is also indicated based on lethal dose (LD) results calculated for $F_1$ progenies 24 h post-treatment. Several factors might contribute to the variability observed in types of responses, including presence of heterozygotes in the parental population causing unexpected genetic variation in reciprocal crosses (see below) and resulting in dose-mortality curve slopes approaching 1.0 [44]. In addition, we cannot disregard genetic differences of the two studied populations that probably also affect our results.

The metabolism of λ-cyhalothrin has at least one resistance mechanism in *H. convergens,* as indicated by the action of the synergist PBO in significantly decreasing resistance in the GA population. The estimated KDs and LDs were reduced by adding PBO to λ-cyhalothrin for the resistant population. Recovery from knockdown by 24 h post-treatment was reduced by approximately 2/3 with addition of PBO, and a similar reduction was observed in the LD responses (Table 2). However, resistance in the Hc-GA population was not fully suppressed by PBO – resistance in this population was still approximately 70 times that of Hc-CA after PBO was added. Thus, considering that the resistance was not fully inhibited with PBO, further studies are needed to identify the other mechanism(s) present.

The hypothesis of sex-linked inheritance should be accepted if the KD and LD calculated for backcrosses BC1 and BC2 are similar to the resistant Hc-GA population and $F_1$ RS, respectively, and if the KDs and LDs of backcrosses BC3 and BC4 are similar to those of the $F_1$ SR progenies and the susceptible population (Hc-CA), respectively. Only the KDs and LDs of BC2 and BC4 differed from the expected result. However, the limited differences observed also suggest presence of genetic variation [45] or possible natural variation [46] (Table 1). Furthermore, bioassays of single-paired crosses with the discriminating dose of λ-cyhalothrin clearly indicated sex-linked inheritance for both knockdown (KDs) and mortality (LDs) (Table 5). Additionally, the resistance phenotype of males carrying $X^R$-chromosome yielded responses similar to those of females that were $X^RX^R$. Finally, estimates of the minimum number of genes responsible for λ-cyhalothrin resistance in *H. convergens* based on KDs and LDs also support sex linkage as the model of inheritance. Sex linkage inheritance patterns tend to inflate phenotypic variances that are critical for estimating the number of genes governing the trait [42]. This inflated variance confounds accurately estimating the number of genes underlying the response, yielding results such as the negative gene estimated values for the $F_1$ progenies obtained in this study.

The knockdown responses indicate that λ-cyhalothrin resistance in *H. convergens* is inherited as a recessive trait. Thus, the difference in degree of dominance for the sex-linked response is independent of the survival of the heterozygotes in $F_1$ RS progeny (dominant) and mortality in the $F_1$ SR progeny (recessive) [47]. The difference is a result of varying mortality patterns between the offspring of the $F_1$ SR reciprocal cross compared to $F_1$ SR. Male $F_1$ RS progeny would be resistant ($X^Ry$), while female progeny would be susceptible ($X^RX^S$). In contrast, both male ($X^Sy$) and female ($X^RX^S$) $F_1$ SR progeny would be susceptible. In this way, the presence of resistant males in $F_1$ RS population inflates the KD and LD values, affecting degree of dominance for each reciprocal cross depending on the magnitude of the response for resistant individuals.

The mortality data for $F_1$ RS progeny did not fit the Probit model, indicating that the Hc-GA population was not homozygous for resistance. Assaying for homozygosity revealed presence of $X^RX^S$ females in the Hc-GA population. Despite the heterozygosity in the Hc-GA population, it was not the only influencing factor because the KD for $F_1$ RS progeny fit the Probit model. Some

**Table 5**
Mortality response 24 h post-treatment of resistant adults $X^RX^R$ and $X^Ry$ of *Hippodamia convergens* treated with a discriminatory dose (0.5 g a.i. of λ-cyhalothrin/L). Observed and expected proportions of mortality are presented according to the progeny genotype considering the null hypothesis: parental susceptible and homozygote resistant as function of inheritance of resistance linked to the $X^R$-chromosome with 1040 tested adults.

| Population/progeny[a] | Sex linkage | | | | | | |
|---|---|---|---|---|---|---|---|
| | Offspring genotype | | Expected proportion | | Observed proportion (SE) | $\chi^2$ | *P* |
| | ♂ | ♀ | Adults[b] | F/*n*[c] | Adults[b] | | |
| Hc-GA | $X^Ry$ | $X^RX^R$ | 0.00 | A/20 | 0.54 (0.01) | NC[d] | NC |
| | | | 0.00 | B/30 | 0.37 (0.03) | NC | NC |
| | | | 0.00 | C/30 | 0.00 (0.00) | NC | NC |
| | | | 0.00 | D/40 | 0.40 (0.15) | NC | NC |
| Hc-CA | $X^Sy$ | $X^SX^S$ | 1.00 | (A–E)/150 | 1.00 (0.00) | 0.00 | 1.00 |
| $F_1$ RS | $X^Ry$ | $X^RX^S$ | 0.50 | A/30 | 0.75 (0.00) | 7.50 | 0.01* |
| | | | 0.50 | B/30 | 0.50 (0.00) | 0.00 | 1.00 |
| | | | 0.50 | C/30 | 0.77 (0.09) | 8.53 | <0.00* |
| | | | 0.50 | D/30 | 0.78 (0.01) | 9.31 | <0.00* |
| $F_1$ SR | $X^Sy$ | $X^RX^S$ | 1.00 | (A–E)/150 | 1.00 | 0.00 | 1.00 |
| BC1 | $X^Ry$ | $X^RX^R$ | 0.00 | A/30 | 0.00 (0.00) | NC | NC |
| | | | 0.00 | B/30 | 0.03 (0.03) | NC | NC |
| | | | 0.00 | C/30 | 0.00 (0.00) | NC | NC |
| | | | 0.00 | D/30 | 0.50 (0.00) | NC | NC |
| BC2 | $X^Ry$ | $X^RX^S$ | 0.50 | A/30 | 0.50 (0.00) | 0.00 | 1.00 |
| | | | 0.50 | B/30 | 0.53 (0.03) | 0.13 | 0.72 |
| | | | 0.50 | C/30 | 0.54 (0.04) | 0.21 | 0.65 |
| | | | 0.50 | D/30 | 0.50 (0.00) | 0.00 | 1.00 |
| | | | 0.50 | E/30 | 0.54 (0.04) | 0.21 | 0.65 |
| BC3 | $X^Sy$ | $X^RX^S$ | 1.00 | (A–D)/110 | 1.00 | 0.00 | 1.00 |
| BC4 | $X^Sy$ | $X^SX^S$ | 1.00 | (A–E)/150 | 1.00 | 0.00 | 1.00 |

[a] Susceptible (Hc-CA) and resistant (Hc-GA) populations; $F_1$ RS, cross of ♀ Hc-GA × ♂ Hc-CA, and $F_1$ SR cross of ♀ Hc-CA × ♂ Hc-GA. The backcrosses BC1 (♀ Hc-GA × ♂ $F_1$ RS), BC2 (♀ Hc-GA × ♂ $F_1$ SR), BC3 (♀ Hc-CA × ♂ $F_1$ RS), and BC4 (♀ Hc-CA × ♂ $F_1$ SR).
[b] Proportion of adults (pooled for males and females).
[c] F stands for families, and *n* stands for number of insects tested per family for each population, progeny, and backcrosses.
[d] NC stands for chi-square and *p*-values not determined; while *stands for significant deviation from the null hypotheses.

individuals of the $F_1$ SR progeny, as well as resistant individuals from Hc-GA, recovered from knockdown (2 h) during the 24 h post-treatment mortality evaluation in the bioassay of dose-mortality. The results from single-pair families demonstrated that the gene influencing recovery from treatment might be also sex-linked, as males and females of $F_1$ SR and females of $F_1$ RS did not recover 24 h after treatment. However, the degree of dominance was not conclusive because the discriminatory dose used in the single-pair cross bioassay was sufficiently high to yield functionally recessive inheritance. Thus, a sex linkage model can yield varying results for the resistance mechanisms.

Our results indicate that heterozygous Hc-GA females ($X^RX^S$) used in the $F_1$ RS reciprocal cross can produce susceptible males ($X^Sy$). The presence of susceptible males in such a cross would not be anticipated for the offspring of reciprocal crosses ($F_1$ RS) if the parental populations are homozygous susceptible ($X^SX^S$ and $X^Sy$) or resistant ($X^RX^R$ and $X^Ry$), based on an "Xyp" sex determination system. Presence of susceptible males might generate unusually low LDs and the conclusion that resistance is autosomally inherited. This occurred with a heterogeneous population of *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) tested for resistance to the CpGV (Baculoviridae), and resistance was originally characterized as autosomally inherited [48]. However, after selection in the laboratory, single-pair experiments with the selected homozygous-resistant *C. pomonella* population revealed that inheritance was sex-linked [33]. Results from single-pair experiments with a heterozygous population of *C. pomonella*, similar to our experiments, supported sex-linked inheritance for resistance [49]. Based on the slopes of the dose-mortality curves calculated for $F_1$ RS and $F_1$ SR, there is also support for sex-linked heritability of resistance in *H. convergens* similar to *C. pomonella* [49].

Numerous studies have reported recessive inheritance for pyrethroid resistance in different groups of insects. However, sex-linked inheritance of resistance is not common compared to autosomal inheritance. These results add to the reported cases of sex-linked inheritance of resistance: *Sitophilus oryzae* L. (Col.: Curculionidae) [50], *Culex quinquefasciatus* Say [51], *Sitophilus zeamais* Mots. [52], *Spodoptera littoralis* Boisduval (Lepidoptera: Noctuidae) [53], *Helicoverpa armigera* Hübner [54], *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae) [55], *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) [56], and *C. pomonella* [33].

When λ-cyhalothrin is applied in high doses to resistant *H. convergens*, the effective dominance is best characterized as recessive, but at lower doses it is functionally dominant. This pattern of dominance has been reported in other insects [32,57–62]. Dominance is not an intrinsic trait of one allele [63], as its expression is dependent on the dose applied [47]. Thus, when a dose is sufficiently high to kill all heterozygotes in the population, the resistance can be functionally recessive, as described by Curtis et al. [64]. On the other hand, at low doses in which the heterozygotes survive, resistance would be characterized as functionally dominant. Numerically, we found no functionally recessive response for $F_1$ RS progeny at high doses of λ-cyhalothrin. This can be explained by inheritance driven by sex linkage due to the presence of $X^Ry$ males.

Resistance of *H. convergens* to λ-cyhalothrin was likely selected by historically widespread and intensive insecticide use in Georgia crop systems where the beetles regularly occurred. Using cotton as an example, DDT was widely used during the 1950s to control boll weevil and bollworms in cotton [65]. DDT was replaced with organophosphates (OPs) after DDT resistance was detected in boll weevil [66]. Detection of bollworms resistant to OPs [67] led, in turn, to

wide and frequent use of pyrethroid insecticides in Georgia to control this group of pests in the 1980s [68]. The persistence of boll weevil in cotton required repeated applications of broad-spectrum insecticides beginning as early as the appearance of the first flower bud and continuing until close to harvest, producing prolonged negative effects on natural enemy populations [69]. Thus, the historically intensive use of DDT, OPs, and pyrethroids in cotton fields, as well as other surrounding crops frequented by *H. convergens* (e.g., pecans, tobacco, corn), would have applied significant selection pressure to *H. convergens* populations for resistance. Even after pesticide use was dramatically reduced by widespread adoption of Bt-transgenic cotton resistant to lepidopteran pests and following eradication of the boll weevil in Georgia [69,70], pyrethroids and OPs continue to be applied for stink bugs and other pests [71]. The recently reduced application frequency of pyrethroids and OPs to cotton likely reduced the negative effect on *H. convergens* populations and, therefore, permitted resistance-conferring genes to be fixed in the population, affording the stability typical of pyrethroid resistance.

Unlike the case with autosomally inherited resistance, sex linkage allows males of *H. convergens* to exhibit resistance to λ-cyhalothrin even when the allele is present at low levels, because they need only a single resistant allele to confer complete resistance. This capacity may facilitate persistence and rapid spread of the resistant allele(s) in the population. Information on factors that usually influence resistance, such as initial allele frequency in the field population, population size, sex ratio in the field, adaptive costs of resistance, migration, and polyandry in *H. convergens* are needed to better understand evolution of the resistance in this important natural enemy species. However, initial results of resistance selection in Hc-GA under laboratory conditions suggest rapid evolution of resistance can occur, as described for recessive and sex-linked inherited resistance [54]. Variables, such as high frequency of the allele for resistance, heterozygote female $X^RX^S$ being susceptible to λ-cyhalothrin and being killed in the progeny, males requiring only one allele to survive the insecticide application, and the interaction of resistance mechanisms driving the survival of susceptible individuals to the insecticide application, can pace the evolution of resistance in *H. convergens*. Despite the likelihood of multiple genes governing resistance of *H. convergens* to λ-cyhalothrin, the nature of the interactions among these genes was not studied. The interaction among factors governing inheritance of resistance is complex to define [72], but studies focusing on the role of the multiple genes in resistance, the adaptive costs to maintain multiple resistance genes in the absence of insecticide pressure, and the benefits of different resistance mechanisms in the studied species are open avenues for investigation. For instance, we treated adults of Hc-GA and Hc-CA with 10-fold the field rate of the organophosphate dicrotophos and the results showed 100% and 0% survival for these two populations, respectively.

In conclusion, the inheritance of λ-cyhalothrin resistance in *H. convergens* is sex-linked and recessive. Likely, the major mechanism of the resistance involves insensitivity of a kdr-type target site, with participation of detoxifying enzymes, which were partially inhibited by PBO leading to greater susceptibility of the resistant population (Hc-GA). These results differ from those obtained for another lady beetle species, *E. connexa*, that exhibits resistance to the λ-cyhalothrin, but in which resistance is autosomally inherited and incompletely dominant, and which was fully inhibited with PBO with high activity of esterase (A.R.S.R. unpublished data). Further, the $LD_{50}$ and $LD_{90}$ for the Hc-GA population (0.816 and 4.595 g) are greater than the highest recommended field rate of λ-cyhalothrin for cotton (44 g of a.i/ha at 100 L/ha) Roberts et al. [73], indicating the possibility of effectively integrating these predators with pyrethroid insecticides.

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