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Responses of *Corcyra cephalonica* (Stainton) to pirimiphos-methyl, spinosad, and combinations of pirimiphos-methyl and synergized pyrethrins†

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Abstract: Field control failures with pirimiphos-methyl against the rice moth, *Corcyra cephalonica* (Stainton), in Weslaco, Texas, USA, led us to investigate the susceptibility of this particular strain to pirimiphos-methyl, spinosad, pyrethrins synergized with piperonyl butoxide, and pirimiphos-methyl combined with synergized pyrethrins. In laboratory bioassays, 50 eggs of *C cephalonica* were exposed to untreated and insecticide-treated corn and sunflower seeds to determine larval survival after 21 days, egg-to-adult emergence after 49 days, and larval damage to seeds at both exposure periods. Pirimiphos-methyl at both 4 and 8 mg kg^{-1} did not prevent larval survival or egg-to-adult emergence of *C cephalonica* on either corn or sunflower seeds, and seed damage was evident at both rates. The *C cephalonica* strain was highly susceptible to spinosad at 0.5 and 1 mg kg^{-1}. At both spinosad rates, reduction in larval survival, egg-to-adult emergence, and seed damage relative to the control treatment was ≥93% on both corn and sunflower seeds. Pirimiphos-methyl and spinosad were generally more effective against *C cephalonica* on corn than sunflower seeds. The *C cephalonica* strain was completely controlled on corn treated with 1.5 mg kg^{-1} of pyrethrins synergized with 15 mg kg^{-1} of piperonyl butoxide. Many larvae survived and became adults on corn treated with synergized pyrethrins at ≤0.75 mg kg^{-1}. Corn treated with pirimiphos-methyl at 4, 6 or 8 mg kg^{-1} in combination with 0.38 to 1.5 mg kg^{-1} of synergized pyrethrins reduced larval survival by ≥95%, egg-to-adult emergence by ≥97%, and seed damage by ≥94%. Our results suggest that the *C cephalonica* strain can be controlled on corn by combining pirimiphos-methyl with synergized pyrethrins or with synergized pyrethrins at the labeled rate. Although spinosad is not currently labeled for use on stored corn and sunflower seeds, it appears to be effective against *C cephalonica* on both commodities at very low rates.

Keywords: rice moth; *Corcyra cephalonica*; pirimiphos-methyl tolerance; grain protectants; efficacy assessment

1 INTRODUCTION

The rice moth, *Corcyra cephalonica* (Stainton) (Lepidoptera: Pyralidae), is an important stored-product pest in Asia and South America.[1] The larvae feed on rice, corn, cocoa, chocolate, dried fruit, biscuits, coffee and other seeds.[2–4] In addition to consumption, as they become fully grown, larvae contaminate the grain by producing dense webbing containing their fecal material and cast skins.

The organophosphate grain protectant, pirimiphos-methyl (Actellic®; Agriliance, St Paul, Minnesota, USA), has been registered in the USA since 1986 for treating stored corn and sorghum at 8 mg AI kg^{-1} to control insects.[5,6] Several stored-product insects have been reported to be resistant to pirimiphos-methyl.[7–10] Therefore, new pesticides with novel modes of action should be explored for managing insects resistant to traditionally used pesticides. At present, all organophosphates, including pirimiphos-methyl, are undergoing a rigorous risk assessment by the United States Environmental Protection Agency (US-EPA) under the 1996 Food Quality Protection Act. Although the initial review on the tolerance reassessment of pirimiphos-methyl by the US-EPA

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was favorable,[11] additional restrictions on its use may be expected in the future. A significant reduction in risks with organophosphate pesticides may include use of reduced rates alone or in combination with other environmentally benign pesticides.

Spinosad is a commercial pesticide based on the fermentation product of the soil bacterium, *Saccharopolyspora spinosa* Mertz and Yao.[12] This bacterial pesticide has a broad spectrum of activity against insect pests in the orders Lepidoptera, Diptera and Thysanoptera, and against some species of Coleoptera and Orthoptera. It is labeled for use on more than 100 crops in over 24 countries, including the USA.[13–16] Spinosad is not registered for treating stored grains or products. However, laboratory and field trials have shown spinosad to be effective on wheat against several stored-product insects.[17,18]

Dow AgroSciences (Indianapolis, Indiana, USA), the manufacturer of spinosad, were granted an experimental use permit (No 62719-EUP-50) at 1 mg AI kg^{-1} by the US-EPA in May, 2002, for conducting efficacy trials in farm-stored grain.

In 2002, we received *C cephalonica* larvae collected from an infested stored-corn facility in Weslaco, Texas, USA, after reported field-control failures with pirimiphos-methyl. We were asked by the distributor of pirimiphos-methyl to evaluate the susceptibility of the *C cephalonica* strain from Texas in the laboratory to pirimiphos-methyl and other insecticides on both corn and sunflower seeds. Resistance to pirimiphos-methyl in the *C cephalonica* strain could not be confirmed because of unavailability of an insecticide-susceptible strain.

In this study, we evaluated the efficacy of pirimiphos-methyl at 4 and 8 mg kg^{-1} and spinosad at 0.5 and 1 mg kg^{-1} as well as at a series of rates against *C cephalonica* on corn and sunflower seeds. In further evaluations, we determined the susceptibility of *C cephalonica* to pirimiphos-methyl at 4, 6 and 8 mg kg^{-1} combined with different rates of pyrethrins synergized with piperonyl butoxide (1:10 ratio).

2 EXPERIMENTAL METHODS

2.1 Insects

The *C cephalonica* larvae were reared on a poultry-mash diet[19] at 28 °C, 65% RH with a 14:10 h light:dark cycle. Insects were reared for two generations before use in bioassays. Voucher specimens were placed in the Kansas State University Museum of Entomological and Prairie Arthropod Research under Lot Number 141.

2.2 Grains and insecticides

Organic, yellow dent corn seeds from Purdue University, Indiana, USA, and cleaned sunflower seeds from Northwest Grain, St Hilaire, Minnesota, USA, were frozen at −10 °C for 1 week to kill any residual infestation. Corn seeds were tempered by adding water and equilibrated to 13% moisture in an environmental growth chamber at 28 °C and 65% RH. The moisture content of the sunflower seeds used in the tests was 8.5%, as determined by the air oven method.[20]

Pirimiphos-methyl 570 gm $liter^{-1}$ EC (Actellic 5E) and spinosad 240 g $liter^{-1}$ SC (SpinTor® 2SC) were provided by Agriliance and Dow AgroSciences, respectively. Pyrethrin 60 g $liter^{-1}$ EC synergized by 600 g $liter^{-1}$ piperonyl butoxide (Evergreen 60-6® ES) was supplied by McLaughlin, Gormley and King (Minneapolis, Minnesota, USA).

2.3 Hatchability of *Corcyra cephalonica* eggs

Hatchability of *C cephalonica* eggs was determined by placing 500 eggs (≤24-h-old) each in three separate Petri dishes (25 mm diameter × 10 mm high). These dishes were placed on the surface of 100 g of untreated corn or sunflower seeds held in 0.45-liter glass jars so that larvae hatching from the eggs could infest the corn or sunflower seeds. All jars were held in a growth chamber at 28 °C, 65% RH with a 14:10 h light:dark cycle. After 1 week, dishes were checked for eggs that failed to hatch. Egg hatchability in each dish was determined from the number of eggs out of the total that hatched.

2.4 Efficacy of pirimiphos-methyl and spinosad against *Corcyra cephalonica*

Laboratory bioassays were conducted to evaluate the efficacy of pirimiphos-methyl and spinosad against *C cephalonica*. In tests with pirimiphos-methyl, corn and sunflower seeds were treated with 4 and 8 mg kg^{-1}. In tests with spinosad, corn and sunflower seeds were treated with 0.5 and 1.0 mg kg^{-1}. The appropriate dilutions were prepared by diluting the insecticide formulation in distilled water. One hundred grams of corn or sunflower seeds, placed in a 0.45-liter glass jar, were treated with 100 µl of insecticide dilution. Corn or sunflower seeds treated with 100 µl of distilled water served as the control treatment (0 mg kg^{-1}). Jars containing seeds treated with the insecticides or distilled water were tumbled on a ball-mill roller for 10 min to ensure uniform coverage of insecticides on seeds. After tumbling, 50 eggs (≤24-h-old) of *C cephalonica* were introduced into each jar. Infested jars were closed with lids fitted with wire mesh screens and filter papers. Jars were incubated at 28 °C, 65% RH with a 14:10 h light:dark cycle. Jars were examined after 21 days to count the number of live larvae and after 49 days to count the number of adults that emerged from the eggs. Seeds with damage to endosperm and/or germ or holes were also counted at these two observation times. There were five replications for each combination of commodity, insecticide, rate, and exposure period, and each replication was treated separately as explained above.

2.5 *Corcyra cephalonica* responses at different pirimiphos-methyl and spinosad rates

Corn seeds were treated with pirimiphos-methyl at 0 (control, distilled water only), 0.625, 1.25, 2.5, 5, 8, 10 and 20 mg AI kg^{-1} or with spinosad at 0, 0.0015, 0.0023, 0.0035, 0.0053, 0.008, 0.012, 0.018 and 0.027 mg AI kg^{-1}. Sunflower seeds were treated with pirimiphos-methyl at 0, 8, 16, 32, 64, 128, 256 and 512 mg AI kg^{-1} or with spinosad at 0, 0.012, 0.021, 0.037, 0.064, 0.11, 0.19, 0.33 and 0.58 mg AI kg^{-1}. Insecticide applications to corn and sunflower seeds and handling of jars after insect infestation (50 eggs per jar) were similar to the procedures described above. There were five replications for each combination of commodity, insecticide and rate. The number of live larvae present in each jar was counted 21 days after egg introduction.

2.6 Efficacy of pirimiphos-methyl and synergized pyrethrin combinations

Corn seeds were treated with pirimiphos-methyl alone at 4, 6 or 8 mg kg^{-1}, synergized pyrethrins alone at 0.38, 0.75, 1.13 and 1.5 mg kg^{-1} (the labeled rate), and combinations of pirimiphos-methyl and synergized pyrethrins. Pirimiphos-methyl at each of the three rates was combined with the four different rates of synergized pyrethrins for the combination treatments. Corn treated with distilled water served as the control treatment. There was a total of 20 treatment combinations. The application of insecticides to corn, infestation with eggs of *C cephalonica*, and environmental conditions at which infested samples were held, were similar to those described above. Data on 21-day larval survival, 49-day egg-to-adult emergence, and seed damage were recorded using the procedures described above. Each combination of insecticide treatment, rate and exposure period was replicated three times.

2.7 Data analysis

Data on number of live *C cephalonica* larvae on corn or sunflower seeds, number of adults that emerged, and number of seeds that were damaged in tests with pirimiphos-methyl and spinosad were subjected to one-way analysis of variance (ANOVA) using the GLM procedure of SAS[21] to determine differences among main effects. Treatment means were separated using the Fisher's protected least significant difference test[21] at the $\alpha = 0.05$ level.

In tests with pirimiphos-methyl and spinosad on corn and sunflower seeds at a series of rates, percentage reduction of live larvae on treated seeds relative to those on untreated seeds was calculated as: $100 \times [1 - $(number of live larvae on treated grain/number of live larvae on untreated grain)]. Larval reduction data on treated seeds were subjected to probit analysis[21] to estimate the mean effective pirimiphos-methyl or spinosad rate that resulted in 50% (EC_{50}) or 99% (EC_{99}) reduction of live larvae.

Data on the number of live *C cephalonica* larvae on corn, number of adults that emerged, and number of kernels that were damaged in pirimiphos-methyl and synergized pyrethrins combination treatments were analyzed by two-way ANOVA using the GLM procedure.[21] Treatment means were separated using the least squares means test at the $\alpha = 0.05$ level.[21]

All data for ANOVA analysis were transformed using log $(x + 1)$ scale to normalize heteroscedastic treatment variances.[22] However, untransformed means and standard errors are presented in the tables.

3 RESULTS

3.1 Hatchability of *Corcyra cephalonica* eggs on corn and sunflower seeds

The mean (±SE) hatchability of eggs in Petri dishes placed above corn and sunflower seeds was 98.7 (±0.4)% and 98.0 (±0.2)%, respectively.

3.2 Efficacy of pirimiphos-methyl and spinosad against *Corcyra cephalonica*

After 21 days, about 18 and 23 live larvae were found in each jar of untreated corn and sunflower seeds, respectively (Table 1). Fewer live larvae and adults were present at the 8 mg kg^{-1} of pirimiphos-methyl than at 4 mg kg^{-1} on both commodities. At each rate, pirimiphos-methyl was more effective on corn than on sunflower seeds. About 2 to 24 live larvae were found on corn and sunflower seeds treated with pirimiphos-methyl, respectively. Larval survival was significantly different among treatments in tests with corn ($F = 203.83$; $df = 4, 20$; $P < 0.0001$) and sunflower seeds ($F = 115.64$; $df = 4, 20$; $P < 0.0001$). After 49 days, about 12 and 17 adults of *C cephalonica* emerged from the untreated corn and sunflower seeds, respectively. About 4 to 18 adults emerged on pirimiphos-methyl treated corn and sunflower seeds, respectively. Adult emergence was also significantly different among the treatments in test with corn ($F = 53.07$; $df = 4, 20$; $P < 0.0001$) and sunflower seeds ($F = 260.92$; $df = 4, 20$; $P < 0.0001$). Spinosad at 0.5 and 1 mg kg^{-1} was very effective on both corn and sunflower seeds, because very few or no live larvae or moths were found (Table 1).

Larvae of *C cephalonica* damaged about 31 and 125 untreated corn seeds after 21 and 49 days of exposure, respectively. Seed damage was significantly different among the treatments after 21 days ($F = 53.16$; $df = 4, 20$; $P < 0.0001$) or 49 days ($F = 220.33$; $df = 4, 20$; $P < 0.0001$) (Table 1). *Corcyra cephalonica* larvae caused significantly ($P < 0.05$) less damage to spinosad treated corn than to pirimiphos-methyl treated corn. Damage to spinosad-treated corn seeds was reduced by >98% compared with damage to untreated seeds.

Larvae of *C cephalonica* damaged about 37 untreated sunflower seeds in 21-day tests and 197 seeds in 49-day tests. Seed damage observed after 21 days was significantly different among treatments

Table 1. Efficacy of pirimiphos-methyl and spinosad against *Corcyra cephalonica* on corn and sunflower seeds

Insecticide	Rate ($mg\,kg^{-1}$)	Number of live larvae after 21 days[a]	Number of adults after 49 days[a]	Number of damaged seeds at 21 days[a]	Number of damaged seeds at 49 days[a]
		Corn			
Control	0	17.8 (±1.5) a	12.0 (±1.9) a	31.2 (±2.7) a	125.4 (±12.1) a
Pirimiphos-methyl	4	7.2 (±1.1) b	6.2 (±1.7) b	10.8 (±0.6) b	59.4 (±4.5) b
	8	1.6 (±0.4) c	3.6 (±0.9) b	2.8 (±1.0) c	37.2 (±8.4) c
Spinosad	0.5	0.0 d	0.0 c	0.6 (±0.4) d	0.4 (±0.2) d
	1	0.0 d	0.0 c	0.6 (±0.4) d	0.2 (±0.2) d
		Sunflower			
Control	0	23.4 (±1.8) a	17.0 (±0.7) a	36.8 (±2.9) a	197.2 (±5.1) a
Pirimiphos-methyl	4	23.8 (±2.0) a	18.0 (±1.1) a	34.4 (±2.7) a	198.4 (±4.6) a
	8	18.0 (±1.3) a	10.0 (±0.9) b	28.0 (±1.8) a	116.4 (±20.5) a
Spinosad	0.5	1.0 (±0.4) b	0.4 (±0.2) c	2.6 (±0.8) b	8.8 (±3.3) b
	1	0.2 (±0.2) c	0.0 c	1.6 (±0.8) b	4.6 (±2.0) b

[a] For corn and sunflower, means within a vertical column followed by different letters are significantly different ($P < 0.05$; Fisher's protected least significant difference test).

($F = 51.96$; $df = 4, 20$; $P < 0.0001$). Significant differences in seed damage among treatments were also observed after 49 days ($F = 32.43$; $df = 4, 20$; $P < 0.0001$). Damage to spinosad-treated sunflower seeds was reduced by ≥93% when compared with damage to untreated seeds and by ≥90% compared with damage to pirimiphos-methyl treated seeds.

3.3 *Corcyra cephalonica* responses at different pirimiphos-methyl and spinosad rates

Dose-response data demonstrated that the *C cephalonica* larvae used in the tests were highly tolerant to pirimiphos-methyl on both corn and sunflower. Larval survival was observed on corn treated with pirimiphos-methyl at 10 and 20 $mg\,kg^{-1}$ (Fig 1). Live *C cephalonica* larvae were also observed on sunflower seeds treated with pirimiphos-methyl at all rates tested. Four *C cephalonica* larvae survived on sunflower seeds treated with 512 $mg\,kg^{-1}$ (Fig 1).

The pirimiphos-methyl-tolerant *C cephalonica* larvae were extremely susceptible to spinosad. About 18 larvae per jar were observed in the control treatment, but no live larvae were observed on corn treated with spinosad at 0.027 $mg\,kg^{-1}$ (Fig 1). The *C cephalonica* strain also was very susceptible to spinosad on sunflower seeds. No larvae were observed on sunflower seeds treated with spinosad at 0.58 $mg\,kg^{-1}$ (Fig 1).

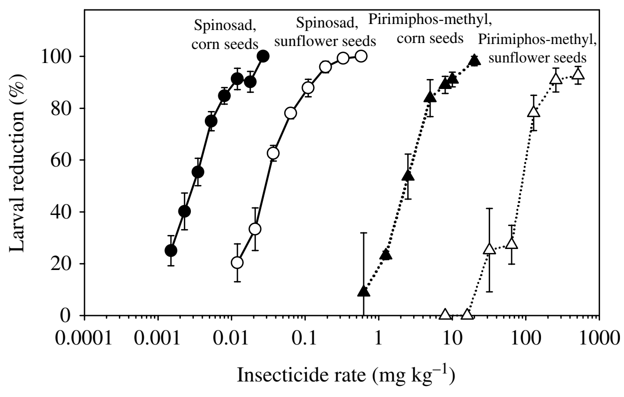

Figure 1. Percentage reduction (mean ± SE) in live larvae of *Corcyra cephalonica* relative to that in the control treatment on corn and sunflower seeds treated with different rates of pirimiphos-methyl and spinosad.

The dose-response data on both corn and sunflower seeds showed that spinosad was much more potent than pirimiphos-methyl against the *C cephalonica* strain (Table 2). The EC_{50} values of spinosad were 776 and 2755 times lower than those of pirimiphos-methyl on corn and sunflower seeds, respectively. Pirimiphos-methyl and spinosad were more effective against *C cephalonica* larvae on corn than on sunflower seeds (Table 2). The EC_{50} and EC_{99} values of pirimiphos-methyl on corn were about 35 times lower than those on sunflower seeds. The EC_{50} and EC_{99} values of spinosad on corn were about 10 times lower than on sunflower seeds.

3.4 Efficacy of pirimiphos-methyl and synergized pyrethrin combinations

The 21-day survival of *C cephalonica* larvae was highly significant for pirimiphos-methyl ($F = 32.74$; $df = 3, 40$; $P < 0.0001$) and synergized pyrethrins ($F = 137.98$; $df = 4, 40$; $P < 0.0001$). About 15 live larvae were found on untreated corn. Larval survival significantly decreased with an increase in the rate of synergized pyrethrins and no larvae survived at 1.5 $mg\,kg^{-1}$ (Table 3). However, larval survival on pirimiphos-methyl treated corn was not significantly different ($P > 0.05$) among the three rates. The interaction effect of pirimiphos-methyl and synergized pyrethrins on larval survival was significant ($F = 3.38$; $df = 12, 40$; $P = 0.0018$).

Larval survival was adversely and significantly affected when exposed to corn treated with pirimiphos-methyl and synergized pyrethrins mixtures. More than 95% of larvae were controlled when pirimiphos-methyl at ≥4 $mg\,kg^{-1}$ was combined with synergized pyrethrins at ≥0.38 $mg\,kg^{-1}$ (Table 3). No larvae

Table 2. EC_{50} and EC_{99} values for pirimiphos-methyl and spinosad against *Corcyra cephalonica* on corn and sunflower seeds

Commodity	Insecticide	Number of insects	Slope (SE)	Intercept (SE)	EC_{50} (mg kg^{-1}) Mean	EC_{50} 95% CL	EC_{99} (mg kg^{-1}) Mean	EC_{99} 95% CL	χ^2	*df*	*P*-value
Corn	Pirimiphos-methyl	392	2.40 (0.22)	−0.87 (0.13)	2.33	1.96–2.75	22.14	15.50–36.36	1.80	4	0.7724
	Spinosad	828	2.16 (0.16)	5.48 (0.38)	0.003	0.003–0.003	0.04	0.03–0.05	9.13	6	0.1666
Sunflower	Pirimiphos-methyl	385	2.40 (0.43)	−4.60 (0.85)	82.66	47.15–140.83	772.82	337.24–7,614	16.50	4	0.0024[a]
	Spinosad	1107	2.21 (0.14)	3.39 (0.20)	0.030	0.026–0.033	0.33	0.26–0.45	2.56	6	0.8616

[a] The χ^2 value for goodness-of-fit test of data to the probit model was significant ($P < 0.05$). A *t* value of 2.78 was used in computing the confidence limits.

survived on corn treated with pirimiphos-methyl at $\geq$4 mg kg^{-1} in combination with the synergized pyrethrins at $\geq$ 1.13 mg kg^{-1} or pirimiphos-methyl at 8 mg kg^{-1} in combination with the synergized pyrethrins at $\geq$0.38 mg kg^{-1}.

The egg-to-adult emergence of *C cephalonica* on corn was highly significant in tests with pirimiphos-methyl ($F = 33.23$; $df = 3, 40$; $P < 0.0001$) and synergized pyrethrins ($F = 97.23$; $df = 4, 40$; $P < 0.0001$). About 10 adults emerged on untreated corn. In general, the number of adults that emerged on corn decreased at increasing rates of pirimiphos-methyl and synergized pyrethrins (Table 3). Synergized pyrethrins provided excellent suppression of egg-to-adult emergence at 1.5 mg kg^{-1}. Pirimiphos-methyl alone did not greatly reduce egg-to-adult emergence, even at the labeled rate of 8 mg kg^{-1}. The interaction effect of the two insecticides on egg-to-adult emergence was significant ($F = 5.14$; $df = 12, 40$; $P < 0.0001$). Suppression of egg-to-adult emergence was significantly enhanced when corn was treated with the combinations of the two insecticides. No adults emerged on corn treated with pirimiphos-methyl at $\geq$4 mg kg^{-1} combined with the synergized pyrethrins at $\geq$0.75 mg kg^{-1}. Only one adult was found on corn treated with 4 mg kg^{-1} of pirimiphos-methyl mixed with 0.38 mg kg^{-1} of the synergized pyrethrins (Table 3).

Pirimiphos-methyl failed to prevent seed damage at 8 mg kg^{-1} (Table 3). Seed damage in the control treatment and pirimiphos-methyl treatments were similar ($P > 0.05$). Synergized pyrethrins generally protected corn from *C cephalonica* larval damage. There was no seed damage to corn treated with synergized pyrethrins at 1.5 mg kg^{-1}. Damage to corn by *C cephalonica* larvae was highly significant after 21 days of exposure ($F = 21.37$; $df = 3, 40$; $P < 0.0001$ for pirimiphos-methyl and $F = 82.43$; $df = 4, 40$; $P < 0.0001$ for pyrethrins). Similarly, significant differences among treatments were also evident after 49 days of exposure ($F = 16.84$; $df = 3, 40$; $P < 0.0001$ for pirimiphos-methyl and $F = 50.51$; $df = 4, 40$; $P < 0.0001$ for pyrethrins). The interaction effect of the two insecticides on seed damage was significant after 21 days ($F = 2.99$; $df = 12, 40$; $P = 0.0045$) or 49 days of exposure ($F = 2.69$; $df = 12, 40$; $P = 0.0094$).

Seed damage was significantly lower in treatments where pirimiphos-methyl was combined with synergized pyrethrins. There was no seed damage after 21 days of exposure in treatments where corn was treated with pirimiphos-methyl at $\geq$4 mg kg^{-1} in combination with the synergized pyrethrins at $\geq$1.13 mg kg^{-1} or in treatments with pirimiphos-methyl at 8 mg kg^{-1} in combination with the synergized pyrethrins at $\geq$0.75 mg kg^{-1}. Similarly seeds were not damaged after 49 days of exposure in treatments where corn was treated with pirimiphos-methyl at $\geq$6 mg kg^{-1} in combination with the synergized pyrethrins at $\geq$0.75 mg kg^{-1}. Overall, corn kernel damage was reduced by >94% when pirimiphos-methyl at

Table 3. Efficacy of pirimiphos-methyl in combination with synergized pyrethrins against *Corcyra cephalonica* on corn

Treatment				Number of damaged seeds	
Pirimiphos-methyl (mg kg^{-1})	Synergized pyrethrins (mg kg^{-1})	Number of live larvae after 21 days[a]	Number of adults after 49 days[a]	21 days[a]	49 days[a]
0	0	15.0 (±1.0) a	9.7 (±0.9) a	35.0 (±7.2) a	115.0 (±10.8) a
	0.38	3.0 (±1.0) c	3.7 (±0.9) c	9.3 (±3.5) b	48.7 (±13.0) ab
	0.75	2.7 (±0.9) c	3.7 (±1.7) c	8.7 (±3.0) b	37.0 (±16.9) b
	1.13	0.7 (±0.3) d	0.7 (±0.7) d	1.7 (±0.9) c	7.7 (±7.7) c
	1.50	0.0 e	0.0 d	0.0 d	0.0 c
4	0	6.0 (±1.5) b	7.0 (±1.2) b	13.7 (±4.3) b	75.7 (±4.1) ab
	0.38	0.7 (±0.3) d	0.3 (±0.3) d	2.0 (±1.0) c	3.7 (±3.7) c
	0.75	0.3 (±0.3) de	0.0 d	1.0 (±1.0) cd	3.3 (±2.4) c
	1.13	0.0 e	0.0 d	0.0 d	2.3 (±2.3) c
	1.5	0.0 e	0.0 d	0.0 d	0.0 c
6	0	5.7 (±0.3) b	4.3 (±0.9) bc	16.0(±2.1) ab	42.7 (±6.2) ab
	0.38	0.0 e	0.0 d	0.0 d	2.3 (±2.3) c
	0.75	0.3 (±0.3) de	0.0 d	1.0 (±1.0) cd	0.0 c
	1.13	0.0 e	0.0 d	0.0 d	0.0 c
	1.5	0.0 e	0.0 d	0.0 d	0.0 c
8	0	5.0 (±0.0) b	2.7 (±0.3) c	16.3 (±1.5) ab	31.7 (±2.9) b
	0.38	0.0 e	0.3 (±0.3) d	0.3 (±0.3) cd	2.0 (±2.0) c
	0.75	0.0 e	0.0 d	0.0 d	0.0 c
	1.13	0.0 e	0.0 d	0.0 d	0.0 c
	1.5	0.0 e	0.0 d	0.0 d	0.0 c

[a] Means within a vertical column followed by different letters are significantly different ($P < 0.05$; by least squares means test).

≥4 mg kg^{-1} was combined with synergized pyrethrins at ≥0.38 mg kg^{-1}.

4 DISCUSSION

Our data demonstrated that the *C cephalonica* field strain from Weslaco, Texas, exhibited high tolerance to pirimiphos-methyl on both corn and sunflower seeds. The reported control failures in Texas with pirimiphos-methyl at the labeled rate could be due to the high pirimiphos-methyl tolerance in this strain. *Corcyra cephalonica* is an important stored-product pest in subtropical areas of Asia and South America,[1] but it was not reported previously as a major stored-grain pest in the USA.[4] However, establishment and spread of pirimiphos-methyl tolerant *C cephalonica* strains within the USA should be of concern to grain managers. The Texas strain of *C cephalonica* may have been introduced from South America in corn shipments (Blake Murnan, Agriliance, St Paul, MN, USA, personal communication). We do not know whether the *C cephalonica* strain was naturally tolerant to pirimiphos-methyl or developed high resistance due to repeated pirimiphos-methyl applications in South America or the stored-corn facility in Texas.

The pirimiphos-methyl-tolerant *C cephalonica* strain was very susceptible to spinosad. The high susceptibility of *C cephalonica* to spinosad may be due to its unique mode of action.[23,24] Spinosad is toxic to insects by action on the insect nervous system at the nicotinic acetylcholine receptor and GABA receptor sites. Several field-crop insects that are resistant to conventional insecticides do not show cross-resistance to spinosad because of its novel mode of action.[25–30]

Both pirimiphos-methyl and spinosad had significantly higher insecticidal potency on corn than on sunflower seeds. The shape, size, density and oil content of seeds may have influenced spinosad distribution on the seed coat and its penetration into underlying seed coats layers. For example, spinosad residues on sunflower seeds may be less than those on corn seeds, because of the larger surface area of sunflower seeds relative to corn seeds. The observed differences in potency at the same rate on two different commodities suggest that the labeled rates of spinosad should be adjusted based on the type of commodity being protected.

Pyrethrins combined with the synergist piperonyl butoxide are currently registered for treating empty storage facilities and direct treatment of stored cereal grains to manage insects.[31–34] The addition of piperonyl butoxide to pyrethrins is essential, as the synergist inhibits insect oxidative processes that detoxify pyrethrins.[32] Improved activity of pirimiphos-methyl when combined with synergized pyrethrins against *C cephalonica* larvae suggests the role of mixed function oxidases in conferring pirimiphos-methyl tolerance. The use of pirimiphos-methyl in combination with synergized pyrethrins appears to be a viable treatment until spinosad is registered for use on stored corn. Pirimiphos-methyl at ≥4 mg kg^{-1} in combination with the synergized pyrethrins at ≥0.38 mg kg^{-1} could be used to protect stored corn against the Texas *C cephalonica* strain.

Pirimiphos-methyl was ineffective against the *C cephalonica* strain, even at high rates, on sunflower seeds. Therefore, we did not evaluate the efficacy of pirimiphos-methyl in combination with synergized pyrethrins on this commodity. Pirimiphos-methyl is not registered for treating sunflower seeds in the USA, and there is very limited information about its use as a grain protectant on this commodity. Zabel *et al*[35] reported that pirimiphos-methyl could be a good insecticide on sunflower seeds against the rice weevil *Sitophilus oryzae* L. Our laboratory tests (F Huang and Bh Subramanyam, unpublished data) showed that pirimiphos-methyl at $\geq 4\,\text{mg kg}^{-1}$ on sunflower seeds was very effective against the red flour beetle *Tribolium castaneum* (Herbst), confused flour beetle *Tribolium confusum* Jacquelin du Val, Indianmeal moth *Plodia interpunctella* (Hübner) and almond moth *Cadra cautella* (Walker). Our present study indicated that pirimiphos-methyl applied to sunflower seeds was ineffective against the *C cephalonica* strain from Weslaco, Texas. However, spinosad appears to be a potential seed protectant for control of this pirimiphos-methyl-tolerant *C cephalonica* strain on sunflower seeds.

5 CONCLUSIONS

The poor field performance of pirimiphos-methyl against the *C cephalonica* strain was verified through laboratory bioassays. The pirimiphos-methyl-tolerant *C cephalonica* strain was extremely susceptible to spinosad on corn and sunflower seeds at 0.5 and $1\,\text{mg kg}^{-1}$ and also to pyrethrins on corn at $1.5\,\text{mg kg}^{-1}$ synergized with $15\,\text{mg kg}^{-1}$ of piperonyl butoxide. Combinations of pirimiphos-methyl and the synergized pyrethrins significantly enhanced the control efficacy of the two insecticides on corn. Spinosad alone at 0.5 to $1\,\text{mg kg}^{-1}$ on corn and sunflower seeds or the synergized pyrethrins alone at $1.5\,\text{mg kg}^{-1}$ or combination of pirimiphos-methyl at $\geq 4\,\text{mg kg}^{-1}$ and the synergized pyrethrins at $\geq 0.38\,\text{mg kg}^{-1}$ on corn could be used as grain protectants to manage the pirimiphos-methyl tolerant *C cephalonica* strain. Further studies are needed to evaluate the performance of spinosad, synergized pyrethrins, and combinations of pirimiphos-methyl and the synergized pyrethrins against *C cephalonica* under field conditions.

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