Pest Manag Sci 61:356–362 (2005)
DOI: 10.1002/ps.968

Management of five stored-product insects in wheat with pirimiphos-methyl and pirimiphos-methyl plus synergized pyrethrins[†]

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Abstract: Hard red winter wheat was treated with pirimiphos-methyl at 4, 6 and 8 mg kg^{-1}, synergized pyrethrins at 0.38, 0.75, 1.13 and 1.5 mg kg^{-1}, and combinations of the two insecticides, to conduct laboratory bioassays against four beetle pests of stored grain, red flour beetle *Tribolium castaneum* (Herbst), rusty grain beetle *Cryptolestes ferrugineus* (Stephens), lesser grain borer *Rhyzopertha dominica* (F), and rice weevil *Sitophilus oryzae* (L), and one moth pest, Indianmeal moth *Plodia interpunctella* (Hübner). Beetle adults and *P interpunctella* larvae survived well on control wheat, producing a large number of progeny (65–1037 insects per container). Kernel damage in control wheat among the insect species ranged from 9 to 99%. On pirimiphos-methyl-treated wheat, mortality of *R dominica* adults was ≥72%, but that of the other beetle species and *P interpunctella* larvae was 100%. Progeny were not produced on pirimiphos-methyl-treated wheat, and the kernel damage was negligible (≤1%). Synergized pyrethrins were ineffective against the five insect pests. Pirimiphos-methyl combined with synergized pyrethrins was not superior to pirimiphos-methyl alone against the five insect pests. Pirimiphos-methyl is not registered in the USA for use on wheat, but our results suggest that it could be a viable grain protectant at rates of 4–8 mg kg^{-1}.

Keywords: stored-product insects; grain protectants; pirimiphos-methyl; synergized pyrethrins; efficacy assessment

1 INTRODUCTION

Malathion and chlorpyrifos-methyl (Reldan®) are the two most widely used organophosphate (OP) grain protectants in the USA for treating stored wheat.[1] However, the US Environmental Protection Agency (US-EPA) has begun tolerance reassessment for these grain protectants under the 1996 Food Quality Protection Act (FQPA).[2] Because malathion applied to grain breaks down rapidly and many stored-grain insects are resistant to the insecticide,[3–6] it is no longer recommended as a grain protectant by the Cooperative Extension Service specialists/educators and post-harvest researchers. Thus, malathion re-registration seems unlikely. Similarly, resistance to chlorpyrifos-methyl in some key stored-wheat insects, such as the lesser grain borer *Rhyzopertha dominica* (F), also has diminished the effectiveness of chlorpyrifos-methyl.[4–7] In addition, Dow AgroSciences has recently submitted a proposal to US-EPA to voluntarily cancel production and sale of chlorpyrifos-methyl by 31 December 2003, and use all existing stocks by 31 December 2004. There are several formulations with diatomaceous earth dusts approved for treating stored wheat, but these dusts are not commonly used because they adversely affect the physical properties of the grain such as test weight and flowability.[8] Therefore, it is necessary to look for other effective grain protectants for management of stored-product insects in stored wheat.[9]

Pirimiphos-methyl (Actellic®), an OP currently registered in the USA for treating stored corn and sorghum,[10,11] could be a potential chlorpyrifos-methyl alternative for treating stored wheat to control insects. Pirimiphos-methyl has lower mammalian toxicity than chlorpyrifos-methyl.[12] Laboratory and field data from past studies in the USA[13–15] and other countries[12–23] showed pirimiphos-methyl to

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[†]This paper reports research results only. Mention of a proprietary product name does not constitute an endorsement for its use by Kansas State University or Louisiana State University
Contract/grant sponsor: Agriliance, LLC
Contract/grant sponsor: USDA/CSREES-RAMP; contract/grant number: 00-51101-9674
(*Received 3 November 2003; revised version received 7 July 2004; accepted 17 August 2004*)
Published online 22 October 2004

be effective on wheat against several stored-product insects. The reasons for not considering pirimiphos-methyl as a stored-wheat protectant in the USA, despite favorable field results, are unclear. The manufacturer of pirimiphos-methyl (Agriliance, LLC, St Paul, Minnesota, USA) is interested in re-evaluating pirimiphos-methyl as a stored-wheat protectant in light of the uncertain future of malathion and chlorpyrifos-methyl. Pirimiphos-methyl received a positive initial tolerance reassessment review under the 1996 FQPA,[10,11] but additional restrictions on the insecticide may be expected, such as the use of reduced label rates to minimize food safety risks. The objectives of this study were to determine the efficacy of pirimiphos-methyl at labeled and below labeled rates, alone and in combination with a botanical insecticide (synergized pyrethrins), on wheat against five economically important stored-product insects. Synergized pyrethrins and pirimiphos-methyl combinations were evaluated in the present investigation, because Agriliance, LLC, was interested in knowing whether the combination product had greater insecticidal activity than pirimiphos-methyl alone.

2 MATERIALS AND METHODS

2.1 Insecticides

Pirimiphos-methyl, 570 g liter^{-1} EC, (Actellic 5E®) was provided by Agriliance, LLC, and the synergized pyrethrins (Evergreen 60-6 ES®) containing 60 g liter^{-1} pyrethrins synergized with 600 g liter^{-1} piperonyl butoxide were supplied by McLaughlin Gormley King (Minneapolis, Minnesota, USA).

2.2 Insects

Insect species tested were the red flour beetle *Tribolium castaneum* (Herbst), rusty grain beetle *Cryptolestes ferrugineus* (Stephens), *R dominica*, rice weevil *Sitophilus oryzae* (L) and Indianmeal moth *Plodia interpunctella* (Hübner). Insects were reared at 28 °C, 65% RH and 14:10 h light:dark cycle in a walk-in growth chamber in the Department of Grain Science and Industry, Kansas State University, Manhattan, Kansas, USA. *Tribolium castaneum* was reared on a mixture of 95% wheat flour fortified with 5% (by weight) brewer's yeast, *C ferrugineus* was cultured on a mixture of 95% rolled oats and 5% (by weight) brewer's yeast, while *R dominica* and *S oryzae* were reared on whole, hard red winter wheat. *Plodia interpunctella* was reared on a poultry-mash diet.[24] Unsexed beetle adults of mixed ages and *P interpunctella* eggs laid within 24 h were used in bioassays. Egg hatchability of *P interpunctella* was determined by placing 200 eggs in glass Petri dishes (25 mm diameter × 10 mm high). These dishes were placed on the surface of 100 grams of control wheat (treated with distilled water only) held in 0.45-liter glass jars, so that larvae hatching from eggs could infest the wheat. These jars were held in a growth chamber maintained at the conditions described above. After 7 days, dishes were checked for eggs that failed to hatch. Egg hatchability in each dish was determined from the number of eggs that hatched out of the total in each dish. This experiment was replicated three times.

2.3 Bioassays

Hard red winter wheat was cleaned of dockage and broken kernels by sieving it over a 0.21-mm round-holed aluminum sieve. Cleaned wheat was frozen for 1 week at −13 °C before use, after which it was tempered and equilibrated to 13% moisture in an environmental growth chamber maintained at 28 °C and 65% RH. Insecticides were diluted in distilled water. Wheat was treated with pirimiphos-methyl at 4, 6 or 8 (the labeled rate for treating corn) mg kg^{-1}, with synergized pyrethrins at 0.38, 0.75, 1.13 and 1.5 (the labeled rate) mg kg^{-1}, and with combinations of pirimiphos-methyl and synergized pyrethrins. In the combination treatments, pirimiphos-methyl at each of the three rates was combined with the four rates of synergized pyrethrins. Wheat treated with distilled water served as the control treatment. For each combination of insect species and exposure period, there were a total of 20 treatment combinations.

In the treatments, 500 grams of wheat were placed in separate 0.95-liter glass jars. The 500-g lot (replicate) in each jar was treated with 0.5 ml of appropriate concentration of insecticide dispersion or aliquots of distilled water. The jars, holding control or insecticide-treated wheat, were closed with metal lids and then were placed in a plastic drum (*ca* 38 liter capacity) that was tumbled for 10 min on a ball-mill roller. After tumbling, 100-g of wheat from each jar was placed in four separate 150-ml plastic containers and a 0.45-liter glass jar. The four 150-ml containers were used for the four beetle pests and the 0.45-liter glass jars for *P interpunctella* eggs. In the bioassay, 25 adults of a beetle pest were introduced into each plastic container and 50 eggs of *P interpunctella* were introduced into each glass jar. After insect introduction, the plastic containers or glass jars were covered with lids fitted with filter papers and wire mesh screens, and incubated at 28 °C, 65% RH with a 14:10 h light:dark cycle.

Wheat with beetles was checked after 7 days to count the number of live adults. The number of progeny produced by beetles and kernel damage to wheat were counted after 49 days. The number of progeny for beetles included the total number of insects observed minus the 25 beetle adults originally added to wheat. Progeny data for *T castaneum* and *C ferrugineus* included all live larvae, pupae and adults found in wheat, whereas that for *R dominica* and *S oryzae* included only adults, as the latter two species complete larval and pupal development inside kernels. Wheat with *P interpunctella* eggs was examined after 21 days to count the number of live larvae, and after 49 days to determine number of adults that emerged, number of live progeny (larvae) and kernel damage.

Kernel damage was assessed by examining 100 wheat kernels from each container or jar. Kernels without germs and those with irregular or round holes due to insect chewing or adult emergence were considered damaged.[25] Each combination of insect species, insecticide, rate and exposure period was replicated three times and each replication was treated separately.

2.4 Data analysis

Data on the number of live beetle adults, the number of live larvae and adults of *Plodia interpunctella*, progeny production and kernel damage were subjected to two-way analysis of variance (ANOVA) using the GLM procedure of SAS[26] to determine differences among the main and interactive treatment effects. All data for the ANOVA were transformed to a log $(x + 1)$ scale to normalize heteroscedastic treatment variances.[27] Treatment means were separated using the least squares means test at the $\alpha = 0.05$ level.[26]

3 RESULTS

3.1 Survival of beetle adults

Wheat treated with pirimiphos-methyl at 4, 6 and 8 mg kg^{-1} was extremely effective against *T castaneum*, *C ferrugineus*, and *S oryzae* adults. The main effect of pirimiphos-methyl on adult survival of the three species was significant (F, range among species = 872.65–1449.18; $df = 3$, 40; $P < 0.0001$). After 7 days, a mean (± SEM) of 25 (±0) *T castaneum*, 22.7 (±1.3) *C ferrugineus* and 23.7 (±0.7) *S oryzae* adults per container survived on control wheat, whereas all adults of the three species died on pirimiphos-methyl-treated wheat (Table 1). The main effect of pirimiphos-methyl on *R dominica* adult survival was also significant ($F = 57.09$; $df = 3$, 40; $P < 0.0001$). On control wheat, 22.3 (±0.3) *R dominica* adults per container survived after 7 days. Survival of adult *R dominica* decreased significantly ($P < 0.05$) as the rate of pirimiphos-methyl increased (Table 1). However, unlike the other three beetle species, a few *R dominica* adults [1.3 (±0.7) adults per container] survived even the 8 mg kg^{-1} rate.

In general, synergized pyrethrins at 0.38–1.5 mg kg^{-1} were not effective against the four beetle species. The main effect of synergized pyrethrins on *T castaneum* and *R dominica* adult survival was not significant ($F = 1.88$; $df = 4$, 40; $P = 0.133$ for *T castaneum* and $F = 1.74$; $df = 4$, 40; $P = 0.16$ for *R dominica*). However, survival of *C ferrugineus* and *S oryzae* adults was significant ($F = 13.19$; $df = 4$, 40; $P < 0.0001$ for *C ferrugineus* and $F = 40.06$; $df = 4$, 40; $P < 0.0001$ for *S oryzae*). Although adult survival tended to decrease with an increase in insecticide rate, the observed decrease was less than satisfactory because at the labeled rate of 1.5 mg kg^{-1} nearly 16% [4.3 (±1.5) *C ferrugineus* and 4 (±1) *S oryzae* out of 25 adults] of exposed *C ferrugineus* and *S oryzae* adults survived the treatment (Table 1).

Combinations of pirimiphos-methyl and synergized pyrethrins were no better than pirimiphos-methyl alone against *T castaneum* and *R dominica* adults, because the interaction of the two insecticides on adult survival was not significant ($F = 1.88$; $df =$

Table 1. Survival of adults of four beetle species after 7 days on control wheat and wheat treated with pirimiphos-methyl, synergized pyrethrins, and pirimiphos-methyl plus synergized pyrethrins

Insecticide rate (mg kg^{-1})		Number of survivors[b] (±SEM)			
Pirimiphos-methyl	Synergized pyrethrins[a]	*T castaneum*	*C ferrugineus*	*R dominica*	*S oryzae*
0	0	25.0 (±0.0) a	22.7 (±1.3) a	22.3 (±0.3) a	23.7 (±0.7) a
	0.38	24.7 (±0.3) a	11.7 (±0.7) b	17.7 (±1.8) a	20.3 (±1.7) ab
	0.75	24.3 (±0.3) a	7.6 (±2.2) c	13.7 (±1.2) a	19.3 (±0.7) b
	1.13	24.7 (±0.3) a	5.3 (±0.3) d	10.7 (±1.5) a	9.3 (±1.3) c
	1.5	23.3 (±0.9) a	4.3 (±1.5) e	7.7 (±0.7) a	4.0 (±1.0) d
4	0	0.0 (±0.0) b	0.0 (±0.0) f	6.3 (±0.9) b	0.0 (±0.0) e
	0.38	0.0 (±0.0) b	0.0 (±0.0) f	7.0 (±1.5) b	0.0 (±0.0) e
	0.75	0.0 (±0.0) b	0.0 (±0.0) f	3.0 (±0.0) b	0.0 (±0.0) e
	1.13	0.0 (±0.0) b	0.0 (±0.0) f	3.6 (±1.3) b	0.0 (±0.0) e
	1.5	0.0 (±0.0) b	0.0 (±0.0) f	5.0 (±0.6) b	0.0 (±0.0) e
6	0	0.0 (±0.0) b	0.0 (±0.0) f	2.0 (±1.2) c	0.0 (±0.0) e
	0.38	0.0 (±0.0) b	0.0 (±0.0) f	2.3 (±0.3) c	0.0 (±0.0) e
	0.75	0.0 (±0.0) b	0.0 (±0.0) f	2.3 (±0.3) c	0.0 (±0.0) e
	1.13	0.0 (±0.0) b	0.0 (±0.0) f	3.0 (±0.6) c	0.0 (±0.0) e
	1.5	0.0 (±0.0) b	0.0 (±0.0) f	2.0 (±1.2) c	0.0 (±0.0) e
8	0	0.0 (±0.0) b	0.0 (±0.0) f	1.3 (±0.7) c	0.0 (±0.0) e
	0.38	0.0 (±0.0) b	0.0 (±0.0) f	1.7 (±1.2) c	0.0 (±0.0) e
	0.75	0.0 (±0.0) b	0.0 (±0.0) f	2.3 (±0.3) c	0.0 (±0.0) e
	1.13	0.0 (±0.0) b	0.0 (±0.0) f	1.7 (±0.3) c	0.0 (±0.0) e
	1.5	0.0 (±0.0) b	0.0 (±0.0) f	0.7 (±0.3) c	0.0 (±0.0) e

[a] Pyrethrins were synergized with piperonyl butoxide in 1:10 ratio.
[b] Means within a vertical column followed by different letters are significantly different ($P < 0.05$; by least-squares means test).

12, 40; $P = 0.067$ for *T castaneum* and $F = 1.49$; $df = 12, 40$; $P = 0.170$ for *R dominica*). *Tribolium castaneum* adults did not survive the combination treatments after 7 days, while a mean (±SEM) of 0.7 (±0.3) to 7 (±0.5) *R dominica* adults survived these treatment combinations (Table 1). The interaction of pirimiphos-methyl and synergized pyrethrins was significant for *C ferrugineus* and *S oryzae* ($F = 13.19$; $df = 12, 40$; $P < 0.0001$ for *C ferrugineus* and $F = 40.06$; $df = 12, 40$; $P < 0.0001$ for *S oryzae*) and combination treatments resulted in 100% mortality of both the species (Table 1).

3.2 Larval survival and egg-to-adult emergence of *P interpunctella*

The mean (±SEM) hatchability of *P interpunctella* eggs was 97.2 (±1.2)%. On control wheat, 15.7 (±1.9) live larvae were found in each jar, whereas no live larvae were observed in pirimiphos-methyl-treated wheat (Table 2). The main effects of pirimiphos-methyl and synergized pyrethrins on larval survival were significant ($F = 488.20$; $df = 3, 40$; $P < 0.0001$ for pirimiphos-methyl and $F = 5.33$; $df = 4, 40$; $P = 0.0015$ for synergized pyrethrins). The number of live larvae on wheat treated with synergized pyrethrins at 0.75–1.5 mg kg^{-1} was significantly lower than on control wheat ($P < 0.05$) (Table 2). However, synergized pyrethrins alone did not provide sufficient control of larvae of *P interpunctella*, because 8% [4.3 (±1.5) larvae out of 50 eggs] of larvae survived the 1.5 mg kg^{-1} treatment. The interaction of pirimiphos-methyl and synergized pyrethrins also was significant ($F = 5.33$; $df = 12, 40$; $P < 0.0001$), and no live larvae were found in the combination treatments.

Pirimiphos-methyl at all three rates completely suppressed egg-to-adult emergence of *P interpunctella*, whereas on control wheat 12.3 (±0.7) adults per jar were observed (Table 2). The main treatment effects of pirimiphos-methyl and synergized pyrethrins on egg-to-adult emergence were significant ($F = 1138.82$; $df = 3, 40$; $P < 0.0001$ for pirimiphos-methyl and $F = 63.82$; $df = 4, 40$; $P < 0.0001$ for synergized pyrethrins). Synergized pyrethrins at 1.5 mg kg^{-1} provided good suppression against egg-to-adult emergence because only a total of one adult was found in wheat treated at this rate (Table 2). Combinations of pirimiphos-methyl and the synergized pyrethrins completely suppressed egg-to-adult emergence, and the interaction of the two insecticides also was significant ($F = 63.82$; $df = 12, 40$; $P < 0.0001$) (Table 2).

Table 2. Larval survival and egg-to-adult emergence of *Plodia interpunctella* on control wheat and on wheat treated with pirimiphos-methyl, synergized pyrethrins, and pirimiphos-methyl plus synergized pyrethrins

Insecticide rate (mg kg^{-1})		Number of live larvae after	Number of adults after
Pirimiphos-methyl	Synergized pyrethrins[a]	21 days[b] (±SEM)	49 days[b] (±SEM)
0	0	15.7 (±1.9) a	12.3 (±0.7) a
	0.38	12.7 (±1.3) a	12.3 (±0.7) a
	0.75	6.7 (±0.7) b	9.3 (±1.2) b
	1.13	6.3 (±2.8) b	4.3 (±0.3) c
	1.5	4.3 (±1.5) b	0.3 (±0.3) d
4, 6 or 8	0	0.0 (±0.0) c	0.0 (±0.0) d
	0.38	0.0 (±0.0) c	0.0 (±0.0) d
	0.75	0.0 (±0.0) c	0.0 (±0.0) d
	1.13	0.0 (±0.0) c	0.0 (±0.0) d
	1.5	0.0 (±0.0) c	0.0 (±0.0) d

[a] Pyrethrins were synergized with piperonyl butoxide in 1:10 ratio.
[b] Means within a vertical column followed by different letters are significantly different ($P < 0.05$; by least-squares means test).

3.3 Progeny production

Pirimiphos-methyl at all three rates effectively suppressed progeny production of the five insect species. The main effect of pirimiphos-methyl on progeny production was significant for all five insect species (F, range among species = 8.20–4990.36; $df = 3, 40$; $P < 0.0001$). A large number of progeny were observed on control wheat, and the numbers ranged from 64.7 (±4.8) larvae per jar (*P interpunctella*) to 1037 (±168) adults per container (*S oryza*e), whereas no progeny (larvae, pupae, or adults) were found on wheat treated with pirimiphos-methyl (Table 3).

The main effect of the synergized pyrethrins on progeny production of the five species also was significant (F, range among species = 6.11–35.01; $df = 4, 40$; $P < 0.0001$). In general, progeny production decreased with increasing rates of synergized pyrethrins. Synergized pyrethrins at 1.5 mg kg^{-1} satisfactorily suppressed progeny production of *C ferrugineus, R dominica*, and *P interpunctella* [0.3 (±0.3)—1 (±0.6) insect per replicate] (Table 3). However, synergized pyrethrins alone did not provide sufficient progeny suppression of *T castaneum* and *S oryzae* even at 1.5 mg kg^{-1} because 35 (±4) *T castaneum* and 209 (±61) *S oryzae* per container were produced on wheat at this rate.

Combinations of pirimiphos-methyl and synergized pyrethrins significantly suppressed progeny of all five species (F, range among species = 6.11–63.82; $df = 12, 40$; $P < 0.0001$). For all species, pirimiphos-methyl alone and combination treatments provided 100% suppression of the progeny (Table 3).

3.4 Kernel damage

Pirimiphos-methyl alone at 4–8 mg kg^{-1} effectively prevented kernel damage by the five insect species. Damage to control wheat ranged from 9.3 (±0.6)% in tests with *C ferrugineus* to 99 (±1)% in tests with *S oryzae*, while damage to pirimiphos-methyl treated wheat was <1% (Table 4). The main effect of pirimiphos-methyl on kernel damage was significant for all five species (F, range among species = 32.16–423.90; $df = 3, 40$; $P < 0.0001$).

Synergized pyrethrins were ineffective in preventing kernel damage by *T castaneum*, because the main effect of the synergized pyrethrins and the interaction of the

Table 3. Progeny production of five insect species after 49 days on control wheat and on wheat treated with pirimiphos-methyl, synergized pyrethrins, and pirimiphos-methyl plus synergized pyrethrins

Insecticide rate (mg kg^{-1})		Progeny[a,b] (±SEM)				
Pirimiphos-methyl	Synergized pyrethrins[c]	*T castaneum*	*C ferrugineus*	*R dominica*	*S oryzae*	*P interpunctella*
0	0	103.7 (±9.0) a	100.3 (±11.7) a	154.0 (±10.1)a	1037.0 (±168.4) a	64.7 (±4.8) a
	0.38	68.7 (±1.8) b	40.7 (±3.5) b	34.7 (±10.2) b	620.0 (±155.8) b	47.3 (±6.4) a
	0.75	64.0 (±10.0) b	20.3 (±5.9) c	19.7 (±3.4) b	629.0 (±115.7) b	21.0 (±4.6) b
	1.13	63.3 (±12.9) b	6.7 (±3.7) d	5.0 (±5.0) c	569.7 (±135.3) b	9.7 (±5.7) b
	1.5	35.0 (±4.0) c	1.0 (±0.6) e	0.3 (±0.3) d	209.3 (±61.2) c	0.3 (±0.3) d
4, 6 or 8	0	0.0 (±0.0) d	0.0 (±0.0) e	0.0 (±0.0) d	0.0 (±0.0) d	0.0 (±0.0) d
	0.38	0.0 (±0.0) d	0.0 (±0.0) e	0.0 (±0.0) d	0.0 (±0.0) d	0.0 (±0.0) d
	0.75	0.0 (±0.0) d	0.0 (±0.0) e	0.0 (±0.0) d	0.0 (±0.0) d	0.0 (±0.0) d
	1.13	0.0 (±0.0) d	0.0 (±0.0) e	0.0 (±0.0) d	0.0 (±0.0) d	0.0 (±0.0) d
	1.5	0.0 (±0.0) d	0.0 (±0.0) e	0.0 (±0.0) d	0.0 (±0.0) d	0.0 (±0.0) d

[a] The number of progeny for the four beetle species was the total number of insects observed minus the 25 beetle adults, which were originally released to infest the wheat. No live beetle adults were found from any treatment containing pirimiphos-methyl. Progeny data for *T castaneum* and *C ferrugineus* include that of larvae, pupae and adults. The data for *R dominica* and *S oryzae* are based on adults only and the data for *P interpunctella* are based on the number of live larvae found 49 days after egg introduction.
[b] Means within a vertical column followed by different letters are significantly different ($P < 0.05$; by least-squares means test).
[c] Pyrethrins were synergized with piperonyl butoxide in 1:10 ratio.

Table 4. Number of kernels of control wheat and insecticide-treated wheat damaged by five insect species after 49 days

Insecticide rate (mg kg^{-1})		Number of damaged kernels[b] (±SEM)				
Pirimiphos-methyl	Synergized pyrethrins[a]	*T castaneum*	*C ferrugineus*	*R dominica*	*S oryzae*	*P interpunctella*
0	0	28.7 (±4.2) a	9.3 (±0.6) a	14.7 (±1.9) a	99.0 (±1.0) a	49.7 (±10.1) a
	0.38	17.7 (±4.7) a	4.0 (±0.6) b	8.3 (±2.7) ab	88.7 (±4.9) a	30.3 (±1.2) ab
	0.75	16.3 (±1.8) a	3.7 (±1.2) b	4.7 (±1.5) b	80.0 (±10.3) a	21.3 (±2.3) b
	1.13	16.7 (±1.3) a	3.0 (±0.6) b	1.3 (±0.7) c	65.0 (±13.0) a	11.0 (±4.2) c
	1.5	10.0 (±1.5) a	0.7 (±0.7) c	0.7 (±0.3) cd	27.3 (±6.8) b	2.3 (±0.3) d
4	0	1.0 (±0.6) b	0.3 (±0.3) c	0.7 (±0.7) cd	0.3 (±0.3) c	0.3 (±0.3) e
	0.38	0.7 (±0.7) b	0.7 (±0.7) c	0.7 (±0.7) cd	1.0 (±0.6) c	1.0 (±0.6) e
	0.75	0.3 (±0.3) b	0.7 (±0.3) c	0.3 (±0.3) cd	0.0 (±0.0) c	0.0 (±0.0) e
	1.13	0.7 (±0.7) b	0.7 (±0.3) c	0.3 (±0.3) cd	0.7 (±0.3) c	0.0 (±0.0) e
	1.5	0.3 (±0.3) b	0.0 (±0.0) c	0.0 (±0.0) d	0.3 (±0.3) c	0.0 (±0.0) e
6	0	0.3 (±0.3) b	0.7 (±0.7) c	0.0 (±0.0) d	0.7 (±0.3) c	1.0 (±0.6) e
	0.38	0.7 (±0.3) b	0.0 (±0.0) c	0.0 (±0.0) d	0.7 (±0.3) c	0.7 (±0.7) e
	0.75	0.0 (±0.0) b	0.3 (±0.3) c	0.7 (±0.7) cd	0.0 (±0.0) c	0.0 (±0.0) e
	1.13	0.3 (±0.3) b	0.0 (±0.0) c	0.0 (±0.0) d	0.7 (±0.7) c	0.3 (±0.3) e
	1.5	0.0 (±0.0) b	0.3 (±0.3) c	0.3 (±0.3) cd	0.0 (±0.0) c	0.7 (±0.7) e
8	0	0.0 (±0.0) b	0.0 (±0.0) c	0.0 (±0.0) d	0.3 (±0.3) c	0.3 (±0.3) e
	0.38	0.7 (±0.7) b	0.3 (±0.3) c	0.3 (±0.3) cd	0.3 (±0.3) c	0.0 (±0.0) e
	0.75	0.7 (±0.7) b	0.0 (±0.0) c	0.0 (±0.0) d	0.3 (±0.3) c	0.0 (±0.0) e
	1.13	0.0 (±0.0) b	0.7 (±0.7) c	0.0 (±0.0) d	0.0 (±0.0) c	0.7 (±0.7) e
	1.5	0.3 (±0.3) b	0.3 (±0.3) c	0.0 (±0.0) d	0.7 (±0.7) c	0.3 (±0.3) e

[a] Pyrethrins were synergized with piperonyl butoxide in 1:10 ratio.
[b] Means within a vertical column followed by different letters are significantly different ($P < 0.05$; by least-squares means test).

two insecticides were not significant ($F = 1.35$; $df = 4, 40$; $P = 0.2695$ for synergized pyrethrins and $F = 0.87$; $df = 12, 40$; $P = 0.5803$ for the interaction). However, for the remaining four insect species, the main effect of synergized pyrethrins was significant (F, range among species $= 2.81-17.85$; $df = 4, 40$; $P \leq 0.0380$). In general, kernel damage decreased with increasing rate of synergized pyrethrins. Wheat treated with synergized pyrethrins at 1.5 mg kg^{-1} provided good kernel protection because <2.3% of the kernels were damaged by *C ferrugineus*, *R dominica*, and *P interpunctella* (Table 4). However, synergized pyrethrins failed to prevent damage by *S oryzae*, because 27.3 (±6.8)% of the kernels were damaged at the highest rate of 1.5 mg kg^{-1}.

Combinations of pirimiphos-methyl and synergized pyrethrins were not better than either insecticide alone against *T castaneum* and *S oryzae*, because the interaction of the two insecticides was not significant ($F = 0.87$; $df = 12, 40$; $P = 0.5803$ for *T* *castaneum* and $F = 1.93$; $df = 12, 40$; $P = 0.0599$ for *S oryzae*). The interaction, however, was significant for the remaining three species ($F = 2.84$; $df = 12, 40$; $P = 0.0066$ for *C ferrugineus*, $F = 17.85$; $df = 12, 40$; $P < 0.0001$ for *R dominica*, and $F = 5.73$; $df = 12, 40$; $P = 0.0599$ for *P interpunctella*), as the combination treatments provided 100% protection from kernel damage by the three species (Table 4).

4 DISCUSSION

Although a few adults of *R dominica* adults survived the 7-day exposure to wheat treated with pirimiphos-methyl at 4–8 $mg\,kg^{-1}$, progeny production and kernel damage were completely suppressed at these rates. *Rhyzopertha dominica* adults lay eggs outside the kernels and larvae hatching from eggs enter the kernels and continue development within the kernels. The complete suppression of progeny production and kernel damage can be attributed to the high susceptibility of neonate larvae to pirimiphos-methyl. Reduced susceptibility of *R dominica* adults to pirimiphos-methyl, relative to other stored-product insects, has also been reported from the United Kingdom,[22,28] Australia[16–29] and the USA.[14,15]

Pyrethrins alone or in combination with synergists have been registered for treating empty storage facilities and direct grain treatment to manage stored-product insects.[30–32] However, our data indicate that synergized pyrethrins alone at the labeled rate (1.5 $mg\,kg^{-1}$) were only partially effective or ineffective against the five insects. Desmarchelier[29] reported pyrethrins at 1 $mg\,kg^{-1}$ synergized with piperonyl butoxide (in 1:10 ratio) were ineffective against *R dominica*. However, the synergized pyrethrins at 4 $mg\,kg^{-1}$ gave more than 99% adult and progeny control for more than 140 days at 20 and 30 °C.

Statistically, the interaction of pirimiphos-methyl and the synergized pyrethrins was significant ($P < 0.05$) in 12 out of the 16 two-way analyses. It is difficult to separate the interaction effect from the main effect of pirimiphos-methyl, because all treatments containing pirimiphos-methyl killed 100% of exposed adults of the beetles (except for *R dominica*), and completely suppressed progeny production and kernel damage. Similarly, all treatments containing pirimiphos-methyl killed all exposed eggs/larvae of *P interpunctella* and successfully prevented egg-to-adult emergence, progeny production and kernel damage. The interaction between pirimiphos-methyl and synergized pyrethrins therefore has little biological or practical significance and there are thus no advantages in combining pirimiphos-methyl with synergized pyrethrins. Our results suggest that pirimiphos-methyl could be used at half the labeled rate (4 $mg\,kg^{-1}$) on stored wheat to control *R dominica, S oryzae, T castaneum, C ferrugineus* and *P interpunctella*.

5 CONCLUSIONS

Pirimiphos-methyl at 4–8 $mg\,kg^{-1}$ on wheat provided excellent control of *R dominica, S oryzae, T castaneum, C ferrugineus* and *P interpunctella*. Synergized pyrethrins, even at the labeled rate of 1.5 $mg\,kg^{-1}$, were ineffective against the five insect species. Combination of pirimiphos-methyl at $\leq$4 $mg\,kg^{-1}$ with the synergized pyrethrins was not deemed necessary to achieve high control efficacy against the five insects. Pirimiphos-methyl appears to be a potential grain protectant for use on wheat at 4–8 $mg\,kg^{-1}$ to manage the five major stored-product insects.

ACKNOWLEDGEMENTS

We are grateful to Dr Frank Arthur (USDA Grain Marketing and Production Research Center, Manhattan, Kansas, USA) for reviewing the manuscript and Yuyu Wang, Muktinutalapati Laxminarayan, Carmelita Goossen and Brandi Kaufman for providing laboratory assistance. This article is Contribution No 04-121-J of the Kansas Agricultural Experiment Station, and represents work supported by Agriliance, LLC, and USDA/CSREES-RAMP under Agreement No 00-51101-9674.

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