Efficacy of grain protectants against four psocid species onmaize, rice and wheat

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Efficacy of grain protectants against four psocid species on maize, rice and wheat

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Abstract

BACKGROUND: Psocids are emerging pests in stored products, particularly in amylaceous commodities such as grains. Currently, their control is based on the use of fumigants and contact insecticides; however, newer data indicate that psocids are tolerant to insecticides used to control other stored-grain species. This study evaluated the insecticides registered in the USA for use on stored maize, rice and wheat for control of the psocid species *Lepinotus reticulatus, Liposcelis entomophila, L. bostrychophila* and *L. paeta*. Mortality of exposed adult females was recorded after 7 and 14 days of exposure, while progeny production was assessed after 30 days of exposure.

RESULTS: On wheat and rice, chlorpyriphos-methyl + deltamethrin was generally more effective against exposed parental adults than spinosad or pyrethrin, while pirimiphos-methyl was more effective on maize than spinosad or pyrethrin. In most cases, progeny production was suppressed in the treated grains. Progeny production was consistently lowest on wheat and rice treated with chlorpyriphos-methyl + deltamethrin and maize treated with pirimiphos-methyl.

CONCLUSIONS: Chlorpyriphos-methyl + deltamethrin and pirimiphos-methyl were the most effective insecticides for all species and commodities. Conversely, efficacy of spinosad or pyrethrum was highly dependent on the psocid species and commodity. Published 2009 by John Wiley & Sons, Ltd.

Keywords: *Lepinotus reticulatus*; *Liposcelis bostrychophila*; *Liposcelis entomophila*; *Liposcelis paeta*; maize; rice; wheat

1 INTRODUCTION

Psocoptera, known as booklice or psocids, are frequently found in stored-product grains, often in extremely high numbers, in amylaceous products.[1] Recent studies indicate that their development is possible in whole grains.[2] Currently, psocids are perhaps the most important category of emerging pests in stored grains and related commodities.[1–3]

It has generally been considered that insecticides used to control other stored-product pests are also effective against psocids. However, recent studies document that the most common psocid species found in stored grains appear to be tolerant to traditional fumigants and contact insecticides at rates lethal to major beetle and moth species. For example, *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae) is one of the most resistant stored-product species to the fumigant phosphine, especially in the egg stage.[4–6] In the case of contact insecticides, the use of the carbamate carbaryl failed to control *L. bostrychophila, L. entomophila* (Enderlein) and *L. paeta* Pearman, while a survey of populations from the first two species indicated that this tolerance is a natural phenomenon and is not related to resistance.[4,7] Similarly, *L. paeta* and *L. entomophila* were tolerant to the organophosphate (OP) chlorpyriphos-methyl,[4] while the latter species was tolerant also to the combined use of chlorpyriphos-methyl with the pyrethroid bifenthrin.[8] Moreover, Nayak *et al*.[4] showed that the three species noted above were tolerant to the pyrethroid deltamethrin applied either alone or with piperonyl butoxide, while the OP pirimiphos-methyl was able to control *L. bostrychophila*. However, *L. bostrychophila* was found to be very resistant to dichlorvos.[9] Nayak *et al*.[4] also found that the three species above were extremely tolerant to the juvenile hormone analogue (JHA) methoprene. In contrast, Bucci[10] reported that fenoxycarb was effective against *L. bostrychophila*. Thus, efficacy of insecticides for beetles and moths or even other psocid species is not necessarily a good predictor of efficacy for control of a particular psocid species.

Most studies evaluating efficacy of grain protectants on psocids have been done on wheat. However, psocid development is highly affected by diet. Opit and Throne[3] found that *Lepinotus reticulatus* Enderlein (Psocoptera: Trogiidae) was able to achieve greater population levels on wheat and rice than on maize. Previous studies show that contact insecticides may have different levels of efficacy among different commodities, even though most grain protectants are labeled with one dose rate regardless of the target commodity. Moreover, Athanassiou *et al*.[11] reported that spinosad was less effective on maize than on wheat against adults of the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae). Similar results have been reported with plant extracts such as azadirachtin.[12]

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So far, there has been no published information on the effectiveness of grain protectants that are registered in the USA against some of the most common psocid species. Therefore, the objectives of the present study were (1) to evaluate the efficacy of grain protectants registered in the USA against four psocid species, and (2) to examine variations in efficacy among three commodities – maize, rice and wheat.

2 MATERIALS AND METHODS

2.1 Commodities

Untreated, clean and infestation-free wheat (a mixture of var. Fuller and var. Santa Fe), rice (Francis) and maize (hybrid Asgrow RX899) were used in the tests. Before the beginning of the experiments, the moisture content of the three commodities was adjusted to 13.5%.

2.2 Insecticides

Four commercially available insecticides were evaluated for efficacy against psocids at the labeled rates for their use in specific grain commodities in the USA. These insecticides were: (a) chlorpyriphos-methyl + deltamethrin (Storicide II, 216 mg active ingredient [AI] mL^{-1} of chlorpyrifos-methyl and 37 mg AI mL^{-1} of deltamethrin; Bayer Crop Science, Research Triangle Park, NC), which is registered on wheat and rice at the rates of 3 ppm of chlorpyriphos-methyl and 0.5 ppm deltamethrin; (b) spinosad (NAF 313, 84 mg AI mL^{-1}; Dow Agrosciences, Indianapolis, IN), which has a label rate of 1 ppm for wheat, maize and rice; (c) pyrethrin (PyGanic Pro SC, 50 mg AI mL^{-1}; MGK, Minneapolis, MN), which is registered at 1.6 ppm for wheat and maize and 2.2 ppm for rice; and (d) pirimiphos-methyl (Actellic 5E, 480 mg AI mL^{-1}; Agriliance, St Paul, MN), which is registered on maize at 8 ppm. The above insecticides were evaluated only on the commodities for which they are registered.

2.3 Insects

The psocid species used in the tests were *L. reticulatus* (voucher specimen #181 placed in the Kansas State University Museum of Entomological and Prairie Arthropod Research), *L. entomophila* (#182), *L. bostrychophila* (#202) and *L. paeta* (#207). All species were reared on a mixture of 97% cracked wheat kernels, 2% rice krispies and 1% wheat germ at 30 °C and 75% RH. Adult females (<4 weeks old) for use in the tests were obtained by placing females to oviposit in dishes containing colored diet, as described by Opit and Throne.[3]

2.4 Bioassays

Lots of 0.5 kg of each grain were sprayed with the respective doses of the aforementioned insecticides by using a Badger 100 artists' airbrush (Badger Air-Brush Company, Franklin Park, IL) to dispense the insecticides at a volume that was proportional to the label rate, which depended on the specific insecticide and commodity to be treated. Another series of lots were sprayed with equivalent volumes of tap water to serve as the untreated controls. Each individual treatment–commodity combination, including untreated controls, was placed in a 0.48 L glass jar. Then, for each species, nine aliquots of 10 g each were taken from each jar and placed in cylindrical plastic vials (3 cm in diameter, 8 cm in height, 1296 vials for all grains). Ten adult females of a single species were placed in each vial. The vials had a plastic lid with a hole in the centre that was covered with fine-mesh brass screen. The internal 'neck' of the vials was covered with Fluon® (Northern Products, Woonsocket, RI) to prevent psocids from escaping. All vials were then placed in black boxes (30 × 23 × 9 cm) on false floors below, with saturated NaCl solution to maintain 75% RH.[13] The boxes were then placed in an incubator maintained at 30 °C. Three of the nine vials were examined for mortality after 7 days, and three were examined for mortality after 14 days, while progeny production was recorded 30 days after the introduction of the parental individuals in the remaining three vials. Tests were repeated 3 times by preparing different lots of treated and untreated grains each time.

2.5 Data analysis

Given that different insecticides were used on each commodity (Storicide II was used only on wheat and rice, Actellic was used only on maize), the entire dataset could not be analyzed for main effects and interactions (e.g. commodity × insecticide). Hence, the data were analyzed using a one-way ANOVA to determine differences among treatments (insecticides and controls) within each species, commodity and exposure interval, by using the JMP 6 software.[14] Means were separated by the Tukey–Kramer HSD test at 0.05.[15]

3 RESULTS

3.1 *Lepinotus reticulatus*

After 7 days of exposure, all adults were dead in vials containing wheat treated with chlorpyriphos-methyl + deltamethrin, and percentage mortality was not statistically different from 100% in wheat treated with spinosad (Tables 1 and 2). In contrast, mortality did not exceed 42% in the pyrethrin treatment. Seven days later, mortality in the spinosad treatments was only slightly higher, and mortality in the pyrethrin treatment (66%) was still lower than mortality in the other treatments. After 7 days, all adults were dead in rice treated with chlorpyriphos-methyl + deltamethrin, while mortality in the spinosad and pyrethrin treatments was lower compared with mortality on wheat. A similar trend occurred at the 14 day exposures, with no significant difference in mortality between the pyrethrin treatment and the controls. All adults were dead after 7 days of exposure on corn treated with pirimiphos-methyl. After 14 days of exposure, mortality was 100% on maize treated with spinosad, had increased to 87% in the pyrethrin treatment and was 61% in untreated controls.

All insecticides reduced progeny production in wheat compared with untreated controls (Tables 1 and 2), with more progeny in the pyrethrin treatment than the other insecticides. No progeny were found in the spinosad-treated wheat. Progeny production was higher in rice than in wheat or maize. The number of psocids produced in pyrethrin-treated rice did not differ significantly from that in the control vials, but was <4 individuals $vial^{-1}$ for the other two insecticides. Finally, progeny production was lower in maize than in wheat or rice. All insecticides significantly reduced progeny production compared with that in untreated maize, and no progeny were found in maize treated with pirimiphos-methyl.

3.2 *Liposcelis entomophila*

Complete mortality after 7 days of exposure occurred only on wheat treated with chlorpyriphos-methyl + deltamethrin, with no significant differences in mortality between spinosad and pyrethrum (Tables 1 and 3). Seven days later, mortality on wheat

Table 1. *F*-values from ANOVA for each commodity and species tested (in all cases, df = 3, 32)

		Species							
		L. reticulatus		*L. bostrychophila*		*L. entomophila*		*L. paeta*	
Exposure	Commodity	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
7 days	Wheat	30.2	<0.01	36.7	<0.01	16.1	<0.01	49.2	<0.01
	Rice	60.9	<0.01	18.9	<0.01	51.8	<0.01	123.9	<0.01
	Maize	14.4	<0.01	36.8	<0.01	66.2	<0.01	186.9	<0.01
14 days	Wheat	22.0	<0.01	26.7	<0.01	26.3	<0.01	47.9	<0.01
	Rice	27.8	<0.01	35.4	<0.01	88.2	<0.01	36.6	<0.01
	Maize	7.6	<0.01	22.0	<0.01	37.7	<0.01	29.8	<0.01
30 days	Wheat	19.2	<0.01	15.5	<0.01	10.0	<0.01	17.9	<0.01
	Rice	37.2	<0.01	5.0	<0.01	20.6	<0.01	24.4	<0.01
	Maize	13.0	<0.01	20.5	<0.01	19.7	<0.01	5.7	<0.01

Table 2. Mean mortality (% ± SE) of *Lepinotus reticulatus* adults after 7 and 14 days of exposure, and mean progeny production (live individuals vial^{-1} ± SE) after 30 days of exposure in the treated and untreated commodities (within each column and commodity, means followed by the same letter are not significantly different; HSD test at 0.05)

		Exposure (days)		
Commodity	Treatment[a]	7 (mortality)	14 (mortality)	30 (progeny)
Wheat	Chlorpyriphos-methyl + deltamethrin	100.0 ± 0.0 a	100.0 ± 0.0 a	0.2 ± 0.2 a
	Spinosad	94.4 ± 4.5 a	96.7 ± 2.4 a	0.0 ± 0.0 a
	Pyrethrum	41.1 ± 14.2 b	65.7 ± 13.5 b	11.6 ± 6.3 b
	Control	10.0 ± 5.3 c	21.1 ± 7.4 c	60.8 ± 11.7 c
Rice	Chlorpyriphos-methyl + deltamethrin	100.0 ± 0.0 a	100.0 ± 0.0 a	1.6 ± 1.0 a
	Spinosad	80.0 ± 9.4 b	71.1 ± 13.0 b	3.3 ± 1.0 a
	Pyrethrum	23.4 ± 6.0 c	14.3 ± 8.8 c	91.1 ± 13.9 b
	Control	6.8 ± 2.4 d	15.5 ± 4.1 c	115.6 ± 13.5 b
Maize	Pirimiphos-methyl	100.0 ± 0.0 a	100.0 ± 0.0 a	0.0 ± 0.0 a
	Spinosad	94.5 ± 3.8 a	100.0 ± 0.0 a	0.1 ± 0.1 a
	Pyrethrum	57.8 ± 11.2 b	86.7 ± 5.8 b	0.2 ± 0.2 a
	Control	34.4 ± 11.4 b	61.1 ± 11.9 c	29.7 ± 8.3 b

[a] For the insecticides used, the dose rates were (a) deltamethrin + chlorpyriphos-methyl at 3 + 0.5 ppm, respectively, for wheat and rice, (b) spinosad at 1 ppm for all commodities, (c) pyrethrum at 1.6 ppm for wheat and maize and at 2.2 ppm for rice and (d) pirimiphos-methyl at 8 ppm for maize.

treated with spinosad increased to 84%, but it did not exceed 56% on wheat treated with pyrethrin. Mortality was lower in rice than in wheat, with 96% mortality after 7 days in rice treated with chlorpyriphos-methyl + deltamethrin. Mortality on rice treated with pyrethrin was <9%, and did not differ from mortality in untreated controls. After the 14 day exposure, there was 100% mortality on rice treated wtih chlorpyriphos-methyl + deltamethrin, but the increase in mortality was negligible for the other treatments. All adults were dead after 7 days of exposure on maize treated with pirimiphos-methyl, with no differences in mortality between the pyrethrin treatment and the controls. After 14 days of exposure, 99% of the exposed adults in maize treated with spinosad were dead, and there was an increase in mortality on maize treated with pyrethrin such that there was a significant difference between this treatment and the controls.

Progeny production on wheat was significantly suppressed with all three insecticides in comparison with progeny production on the untreated wheat, but the greatest level of suppression occurred in wheat treated with chlorpyrifos-methyl + deltamethrin (Tables 1 and 3). Progeny production on rice treated with pyrethrin was similar to that in the controls, but no progeny were produced in rice treated with chlorpyriphos-methyl + deltamethrin. There were no progeny produced in the maize treated with pirimiphos-methyl, and progeny production was reduced in maize treated with spinosad and pyrethrin.

3.3 *Liposcelis bostrychophila*

As with the other psocid species, there were more dead adults in wheat treated with chlorpyrifos-methyl than in wheat treated with either spinosad or pyrethrin after 7 days of exposure (Tables 1 and 4). Mortality was extremely low for pyrethrum, but higher than that in the control vials. Mortality was only slightly increased at 14 days, and did not reach 100% in any of the treatments. Significantly more adults were dead in rice treated with chlorpyriphos-methyl + deltamethrin at the 7 day exposure interval. After 14 days of exposure, mortality was 100% for chlorpyriphos-methyl + deltamethrin, but it remained at low levels in the other insecticide treatments. All

Table 3. Mean mortality (% ± SE) of *Liposcelis entomophila* adults after 7 and 14 days of exposure, and mean progeny production (live individuals vial^{-1} ± SE) after 30 days of exposure in the treated and untreated commodities (within each column and commodity, means followed by the same letter are not significantly different; HSD test at 0.05)

Commodity	Treatment[a]	Exposure (days) 7 (mortality)	14 (mortality)	30 (progeny)
Wheat	Chlorpyriphos-methyl + deltamethrin	100.0 ± 0.0 a	100.0 ± 0.0 a	0.2 ± 0.1 a
	Spinosad	61.2 ± 14.0 b	84.4 ± 7.8 b	7.7 ± 5.9 ab
	Pyrethrum	47.8 ± 13.1 b	55.6 ± 11.8 c	26.4 ± 9.0 b
	Control	5.6 ± 2.9 c	13.3 ± 4.7 d	84.0 ± 21.5 c
Rice	Chlorpyriphos-methyl + deltamethrin	95.6 ± 4.4 a	100.0 ± 0.0 a	0.0 ± 0.0 a
	Spinosad	52.2 ± 10.2 b	52.3 ± 4.6 b	6.1 ± 1.9 b
	Pyrethrum	8.9 ± 3.5 c	16.7 ± 5.8 c	82.1 ± 17.6 c
	Control	3.3 ± 2.6 c	10.0 ± 4.7 c	81.9 ± 9.5 c
Maize	Pirimiphos-methyl	100.0 ± 0.0 a	100.0 ± 0.0 a	0.0 ± 0.0 a
	Spinosad	90.0 ± 4.4 b	98.9 ± 1.1 a	0.3 ± 0.2 a
	Pyrethrum	17.8 ± 7.6 c	60.0 ± 12.5 b	8.5 ± 1.6 b
	Control	15.6 ± 6.9 c	14.4 ± 4.1 c	65.5 ± 14.1 c

[a] For the insecticides used, the dose rates were (a) deltamethrin + chlorpyriphos-methyl at 3 + 0.5 ppm, respectively, for wheat and rice, (b) spinosad at 1 ppm for all commodities, (c) pyrethrum at 1.6 ppm for wheat and maize and at 2.2 ppm for rice and (d) pirimiphos-methyl at 8 ppm for maize.

Table 4. Mean mortality (% ± SE) of *Liposcelis bostrychophila* adults after 7 and 14 days of exposure, and mean progeny production (live individuals vial^{-1} ± SE) after 30 days of exposure in the treated and untreated commodities (within each column and commodity, means followed by the same letter are not significantly different; HSD test at 0.05)

Commodity	Treatment[a]	Exposure (days) 7 (mortality)	14 (mortality)	30 (progeny)
Wheat	Chlorpyriphos-methyl + deltamethrin	97.8 ± 1.4 a	98.9 ± 1.1 a	0.7 ± 0.6 a
	Spinosad	74.5 ± 13.5 b	75.6 ± 10.2 b	42.3 ± 18.0 b
	Pyrethrum	17.8 ± 5.9 c	30.0 ± 11.1 c	52.0 ± 21.0 b
	Control	3.3 ± 1.7 d	6.8 ± 3.3 d	161.8 ± 21.1 c
Rice	Chlorpyriphos-methyl + deltamethrin	93.3 ± 6.7 a	100.0 ± 0.0 a	0.3 ± 0.3 a
	Spinosad	48.9 ± 11.6 b	45.7 ± 10.1 b	106.9 ± 14.3 b
	Pyrethrum	23.3 ± 9.7 bc	26.5 ± 9.6 bc	134.5 ± 19.3 b
	Control	8.9 ± 4.5 c	9.7 ± 2.4 c	298.5 ± 49.0 c
Maize	Pirimiphos-methyl	100.0 ± 0.0 a	100.0 ± 0.0 a	0.0 ± 0.0 a
	Spinosad	71.1 ± 12.6 b	76.4 ± 7.7 b	10.9 ± 6.8 b
	Pyrethrum	18.9 ± 5.1 c	23.3 ± 7.8 c	1.9 ± 0.4 ab
	Control	8.9 ± 2.6 c	13.5 ± 5.3 c	82.7 ± 16.0 c

[a] For the insecticides used, the dose rates were (a) deltamethrin + chlorpyriphos-methyl at 3 + 0.5 ppm, respectively, for wheat and rice, (b) spinosad at 1 ppm for all commodities, (c) pyrethrum at 1.6 ppm for wheat and maize and at 2.2 ppm for rice and (d) pirimiphos-methyl at 8 ppm for maize.

adults died after 7 days of exposure in maize treated with pirimiphos-methyl, while no significant differences were noted between pyrethrum and the control. At the 14 day exposure interval, similar trends were noted, with only a slight increase in mortality.

There were generally large numbers of progeny produced in wheat treated with either spinosad or pyrethrin, but negligible production in wheat treated with chlorpyriphos-methyl + deltamethrin (Tables 1 and 4). Progeny production of *L. bostrychophila* in rice was the highest among the species tested, and especially high in the rice treated with spinosad or pyrethrin. No progeny production occurred in maize treated with pirimiphos-methyl, and fewer progeny were produced in the pyrethin and spinosad treatments.

3.4 *Liposcelis paeta*

All adults were dead after 7 days of exposure in the wheat treated with chlorpyriphos-methyl + deltamethrin, there was lower mortality in the spinosad treatment and there were no differences in mortality between the pyrethrin treatment and the controls (Tables 1 and 5). At the 14 day exposure, mortality was only slightly increased for the spinosad and pyrethrin treatments. Almost all of the exposed adults were dead after 7 days of exposure in rice treated with chlorpyriphos-methyl + deltamethrin, but mortality for the other two insecticides did not differ significantly from the control. At the 14 day exposure, mortality was 100% in the rice treated with chlorpyriphos-methyl + deltamethrin, but remained at low levels for the other two insecticides. Mortality was nearly 100% after 7 days of exposure in maize treated with

Table 5. Mean mortality (% ± SE) of *Liposcelis paeta* adults after 7 and 14 days of exposure, and mean progeny production (live individuals vial^{-1} ± SE) after 30 days of exposure in the treated and untreated commodities (within each column and commodity, means followed by the same letter are not significantly different; HSD test at 0.05)

Commodity	Treatment[a]	Exposure (days) 7 (mortality)	14 (mortality)	30 (progeny)
Wheat	Chlorpyriphos-methyl + deltamethrin	100.0 ± 0.0 a	100.0 ± 0.0 a	0.2 ± 0.1 a
	Spinosad	46.7 ± 7.7 b	55.6 ± 11.5 b	40.1 ± 12.2 c
	Pyrethrum	14.5 ± 6.3 c	14.4 ± 4.7 c	11.6 ± 2.1 b
	Control	7.8 ± 3.2 c	5.6 ± 1.8 c	93.1 ± 15.2 d
Rice	Chlorpyriphos-methyl + deltamethrin	98.9 ± 1.1 a	100.0 ± 0.0 a	0.8 ± 0.6 a
	Spinosad	10.0 ± 3.7 b	18.8 ± 6.4 b	35.0 ± 4.4 b
	Pyrethrum	15.7 ± 7.9 b	31.1 ± 12.5 b	41.3 ± 7.2 b
	Control	3.3 ± 1.7 b	3.4 ± 1.6 c	93.7 ± 12.9 c
Maize	Pirimiphos-methyl	97.8 ± 1.5 a	100.0 ± 0.0 a	0.0 ± 0.0 a
	Spinosad	16.7 ± 3.8 b	37.8 ± 11.4 bc	8.2 ± 1.8 bc
	Pyrethrum	10.0 ± 3.3 b	18.9 ± 5.9 cd	2.7 ± 1.8 ab
	Control	13.3 ± 3.3 b	14.1 ± 4.1 d	18.1 ± 6.4 c

[a] For the insecticides used, the dose rates were (a) deltamethrin + chlorpyriphos-methyl at 3 + 0.5 ppm, respectively, for wheat and rice, (b) spinosad at 1 ppm for all commodities, (c) pyrethrum at 1.6 ppm for wheat and maize and at 2.2 ppm for rice and (d) pirimiphos-methyl at 8 ppm for maize.

pirimiphos-methyl, but did not exceed 17% in any of the other treatments. After the 14 day exposure, mortality increased to about 38% in the spinosad treatment, with a negligible increase in the pyrethrin treatment.

Progeny production was significantly suppressed in wheat treated with chlorpyrifos-methyl, and there were more progeny in the spinosad treatment than in the pyrethrin treatment (Tables 1 and 5). Similar results occurred in rice, while for maize the number of progeny was low, even in the control vials, but there was still no difference between the spinosad treatments and the controls.

4 DISCUSSION

The four species tested varied remarkably in their susceptibility to the insecticides, and there was also variation in efficacy on the three commodities. The characteristics of a grain commodity are key elements that are often overlooked when planning a contact-insecticide-based strategy, in spite of evidence that shows insecticidal efficacy will often vary depending upon the specific insecticide and the commodity that is treated. This is often the case in trials with diatomaceous earth. For example, Kavallieratos *et al*.[16] found that certain diatomaceous earths (DEs) had different efficacy levels against adults of the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) on eight grain commodities. Also, Athanassiou *et al*.[11] noted that spinosad dust performance varied on wheat, rice and maize against adults of *S. oryzae*, while efficacy of this dust did not vary with commodity in tests with adults of *R. dominica*. Variations among cultivars of a specific commodity, as well as variations among commodities, will also affect the development of stored-grain insects, which may in turn indirectly affect the susceptibility to insecticides. Chanbang *et al*.[17] found that the hull characteristics of certain rice varieties may induce a higher infestation level by *R. dominica* through differences in oviposition and insect fecundity. For this reason, it is feasible to use varietal resistance as a control tool in conjunction with certain protectants such as DEs.[18] In the case of psocids, Opit and Throne[3] found that *L. reticulatus* and *L. entomophila* have different population growth rates on different types of amylaceous-based diet. In that study, population growth of *L. reticulatus* was higher on wheat and rice than on maize, while wheat was the best diet for *L. entomophila* and there were no significant differences in population growth of *L. entomophila* on rice and maize. The present results support previous studies showing that maize is a relatively poor diet for *L. reticulatus*, as mortality in untreated controls exceeded 60% after 14 days. Conversely, control mortality for the other three species was generally low on all three commodities. However, apart from control mortality, maize is likely to have a negative effect on psocid development, given that, for all species, progeny production was lower on maize than for the other three commodities, especially for *L. paeta*. While this effect is apparently influenced by the physical and chemical properties of the commodities used,[3] the present data are indicative only for the varieties/hybrids tested in this study, and hence generalizations should be avoided. Athanassiou *et al*.[19] reported that the rearing medium from which *S. oryzae* adults emerged before exposure to DEs affected their susceptibility. In that study, *S. oryzae* reared on maize were always more susceptible to DEs than those reared on wheat or barley, regardless of the DE-treated substrate. This characteristic may have some indirect effect on the efficacy of insecticides for the psocid species tested here. Taking into account the overall progeny production, rice was the most suitable commodity for *L. reticulatus* and *L. bostrychophila* for both treated and untreated substrates. In addition, mortality in most cases was lower on rice than on the other commodities, which may be directly related more with developmental parameters than with the insecticidal efficacy per se.

Newer insecticides, such as metabolite-based substances or plant extracts, are promising for wider use as grain protectants, as alternatives to traditionally used OPs which are very toxic to mammals.[12,20,21] Many of these insecticides have been evaluated with success against many stored-grain pests, and in some cases have proven more effective than OPs. Spinosad, for example, was more effective than pirimiphos-methyl on maize or on sunflower seeds against the rice moth, *Corcyra cephalonica* (Stainton) (Lepidoptera: Pyralidae).[22] However, the present results show that OPs are superior to spinosad and pyrethrum for the control of the four psocid species tested. Chlorpyriphos-methyl + deltamethrin was by far the most effective protectant on wheat and rice, with practically no variations in efficacy among species, given that 93–100% adult mortality was recorded after only 7 days of exposure. In a previous study, Nayak *et al*.[7] found that deltamethrin failed to provide long-term protection on concrete against *L. paeta* and especially *L. entomophila*, but controlled *L. bostrychophila* for 8 weeks. Similarly, Nayak *et al*.[23] reported that *L. bostrychophila* was sensitive to chlorpyriphos-methyl on concrete, while this insecticide had reduced efficacy against *L. entomophila* and *L. paeta*. However, the efficacy was notably increased with the combined use of chlorpyriphos-methyl and carbaryl. Moreover, on sorghum, Daglish *et al*.[8] reported that chlorpyriphos-methyl with synergized bifenthrin was very effective against *Liposcelis decolor* (Pearman) (Psocoptera: Liposcelididae), *L. bostrychophila* and *L. paeta*, but not against *L. entomophila*. The potential of the combined use of OPs with synergized pyrethrins has been evaluated in the case of other species as well.[7,23–26] For example, Huang and Subramanyam[26] noted that the simultaneous use of synergized pyrethrins increased the efficacy of pirimiphos-methyl against *C. cephalonica*. The present results indicate that the simultaneous use of chlorpyriphos-methyl and deltamethrin, in one single formulation, can protect wheat and rice against *L. reticulatus, L. entomophila, L. bostrychophila* and *L. paeta*. In spite of the fact that progeny production in the wheat and rice was not totally eliminated, the number of progeny in the treatment with chlorpyrifos-methyl + deltamethrin never reached a mean of two progeny. Similarly, pirimiphos-methyl was generally more effective on maize than the other two insecticides, with no progeny of any species being produced in maize treated with pirimiphos-methyl. Collins *et al*.[27] reported that pirimiphos-methyl with carbaryl provided long-term protection against *L. bostrychophila, L. entomophila* and *L. paeta* on steel surfaces, but not on concrete. However, Nayak *et al*.[7] found that pirimiphos-methyl was unable to control *L. entomophila* and *L. paeta* but was effective against *L. bostrychophila*. The mortality levels noted in the present study were higher than those obtained in previous studies; hence, based on the present results, pirimiphos-methyl is effective against the species tested on maize. There are no relative data so far for stored maize, and any differences could be attributed to differences in the commodity and the insect strains used.

Spinosad was most effective for *L. reticulatus*, where results were similar to those obtained with chlorpyriphos-methyl + deltamethrin and pirimiphos-methyl. Spinosad was most effective against *L. entomophila* only on wheat and maize. In contrast, spinosad was ineffective against *L. bostrychophila* and *L. paeta*, with reduced adult mortality and progeny production. Nayak *et al*.[1] also found that 1 ppm of spinosad on wheat was effective against *L. entomophila* but ineffective against *L. bostrychophila* and *L. paeta*, given that progeny production for the last two species was high. Consequently, spinosad is not effective against a wide spectrum of stored-product psocid species. The combined use of spinosad with other contact insecticides might increase its efficacy against psocid species. However, Daglish[28] found no further increase in efficacy from the combined use of spinosad and chlorpyriphos-methyl or methoprene against several stored-grain beetle species. Moreover, Subramanyam *et al*.[29] also reported similar results for the combination of spinosad and chlorpyriphos-methyl on wheat. In contrast, Chintzoglou *et al*.[30] reported that the presence of DE increased the efficacy of spinosad dust against adults of *T. confusum* on wheat and maize. Nayak and Daglish[31] found that a combination of 1 ppm spinosad with 10 ppm chlorpyriphos-methyl was more effective than the application of spinosad or chlorpyriphos-methyl alone against *L. bostrychophila, L. entomophila, L. paeta* and *L. decolor* on wheat. However, the chlorpyriphos-methyl dose used in that study can be considered as high, and such an application may not be practically feasible owing to increased residues on the grain. Additional experimentation is needed to investigate spinosad-based combinations that could be more effective against psocid species.

There are no data available so far for the efficacy of pyrethrin on grains against psocids. In the light of the present findings, pyrethrin was not particularly effective against any of the psocid species, except on maize. Paradoxically, in this commodity, although survival of the parental individuals was high in most cases, progeny production was notably suppressed, and this suppression was often similar to that for pirimiphos-methyl. The most susceptible species to pyrethrin was *L. reticulatus*, where progeny production was extremely low. Guedes *et al*.[32] found that the same formulation of pyrethrum had a very poor performance on concrete against *L. bostrychophila* and *L. entomophila*, while beta-cyfluthrin and chlorfenapyr were highly effective. The present results confirm the reduced efficacy of pyrethrin; hence, in spite of the reduction in progeny, pyrethrum might not be effective as a grain protectant to control psocids in stored products.

In summary, the results of the present study clearly suggest that the efficacy of grain protectants differs among psocid species and among commodities. Chlorpyriphos-methyl + deltamethrin for wheat and rice and pirimiphos-methyl for maize were highly effective in terms of mortality from parental exposures and reduced progeny production, and this trend was consistent among species and commodities. In contrast, with the exception of *L. reticulatus* on all commodities and *L. entomophila* on maize, spinosad was only moderately effective. Finally, pyrethrum was generally ineffective on rice and moderately effective on wheat and maize. This knowledge of pesticide selectivity, in conjunction with the target species and commodity, will provide the knowledge necessary for judicious management of psocids in stored grains with registered protectants.

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