Efficacy of insecticides for control of stored-product psocids

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Abstract

A series of experiments were carried out between 2007 and 2009 to test the efficacy of selected insecticides against several stored-product psocids. Three series of experiments were conducted against *Liposcelis* spp. (Psocoptera: Liposcelididae) and *Lepinotus reticulatus* (Psocoptera: Trogiidae). In the first series of tests, contact insecticides were evaluated in the laboratory as grain protectants. Among these insecticides, diatomaceous earth (DE), natural pyrethrum, and the insect growth regulator methoprene were unable to control psocid populations on wheat, rice, and maize. For the same commodities, spinosad was effective against *L. reticulatus*, but was effective for *Liposcelis entomophila* only on maize; spinosad was not effective against *Liposcelis bostrychophila* and *Liposcelis paeta*. Chlorpyriphos-methyl + deltamethin and pirimiphos-methyl were very effective for all species tested. In the second series of tests, sulfuryl fluoride (SF) was tested against *L. paeta* eggs, nymphs, and adults, and *Liposcelis decolor* eggs and adults. Nymphs and adults were very susceptible; for most species mortality was 100%, after 48 h of exposure to SF doses ranging between 4 and 8 g of SF/m^3. In contrast, eggs were less susceptible to SF, and 100% mortality after 48 h of exposure was recorded only at doses ranging between 24 and 96 g of SF/m^3. In the third series of experiments, several contact insecticides were evaluated as surface treatments on concrete. In these tests, pyriproxifen and esfenvalerate provided poor control of psocids. The results of the above tests indicate that *Liposcelis* spp. and *L. reticulatus* were generally less susceptible than other major stored-product insect species to several insecticides, and susceptibility level is determined by the target species, the insecticide, and the commodity.

Keywords: Psocoptera, Stored grains, Grain protectants, Sulfuryl fluoride

1. Introduction

Currently, stored-product psocids are emerging pests in stored grains and related amylaceous products (Throne et al., 2006; Nayak, 2006). Psocids are generally considered as secondary pests, unable to infest sound grains. However, recent studies indicate that psocids can infest sound kernels (Nayak et al., 2005; Athanassiou et al., 2009b), and can develop resident populations (Kučerová, 2002; Athanassiou et al., 2010). Throne et al. (2006) recorded several psocid species in steel bins containing wheat and in empty bins. Opit et al. (2009) found that the peak of psocid presence was during autumn, especially in the center of the grain mass, where temperature and moisture content were higher in comparison with the peripheral layers of the grain bulks. In the laboratory, Kučerová (2002) found that *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae) could cause about 10% grain loss after three months of infestation. Apart from the quantitative losses, several psocid species are responsible for the development of allergies (Turner and Ali, 1996), the transfer of fungal spores and other microorganisms, and qualitative degradations (Obr, 1978).

Fumigants and grain protectants are used to control psocids, however, several psocid species are resistant. For example, *L. bostrychophila* is resistant to phosphine, especially in the egg stage (Nayak et al., 1998, 2002; Dou et al., 2006). Nayak et al. (1998) found that *Liposcelis entomophila* (Enderlein) and *Liposcelis paeta* Pearman were tolerant to the organophosphate (OP) chlorpyriphos-methyl. Similarly, *L. bostrychophila*, *L. entomophila*, and *L. paeta* were tolerant to the pyrethoids deltamethrin and bioresmethrin (Nayak et al., 1998) and the carbamate carbaryl (Nayak et al., 2002), while *L. bostrychophila* was resistant to the OP dichlorvos (Dou et al., 2006). In the case of insect growth regulators (IGRs), *L. bostrychophila* was tolerant to fenoxycarb (Bucci, 1994), while *L. entomophila*, *L. paeta*, and *L. bostrychophila* were tolerant to methoprene (Nayak et al., 1998). Spinosad, which is a bacterial-based insecticide, provided moderate control against *L. bostrychophila*, *L. paeta*, and *Liposcelis decolor* (Pearman) (Psocoptera: Liposcelididae) (Nayak et al., 2005). Hence, it is evident that psocid control in stored-product facilities is problematic and requires additional investigation. Between 2007 and 2009, an extensive series of laboratory bioassays were done at the USDA-ARS Center for Grain and Animal Health Research (CGAHR), and Department of Entomology at Kansas State University, both in Manhattan, KS, USA, to evaluate several insecticides against the most common stored-product psocid species. An extensive summary of these results is presented in this paper.

2. Materials and methods

2. 1. Insects

The psocid species used in the bioassays were *L. bostrychophila*, *L. entomophila*, *L. paeta*, *L. decolor*, and *Lepinotus reticulatus* Enderlein (Psocoptera: Trogiidae). All insects were reared on a mixture of 97% cracked wheat kernels, 2% rice krispies (Kellogg Company, Battle Creek, MI), and 1% wheat germ at 30°C and 75% r.h. Adults used in bioassays were <4 wk-old and obtained following procedures described by Opit and Throne (2008b).

2.2. Efficacy of neurotoxic grain protectants

Four insecticides were applied at the US labeled rates: pirimiphos-methyl (Actellic 5E, Agriliance, USA), chlorpyriphos-methyl + deltamethrin (Storicide II, Bayer Crop Science, USA), spinosad (NAF 313, Dow Agrosciences, USA), and natural pyrethrum (PyGanic Pro SC, MGK Co, USA) to untreated, clean, and infestation-free wheat, rice, or maize (13.5% mc). Pirimiphos-methyl was used only on maize at 8 ppm, Storicide II was used only on wheat and rice at 3 ppm chlorpyriphos-methyl and 0.5 ppm deltamethrin, spinosad was used at 1 ppm in all three grains, and pyrethrum was used at 1.6 ppm on wheat and maize and 2.2 ppm on rice. The psocid species used in these tests were *L. reticulatus*, *L. entomophila*, *L. bostrychophila*, and *L. paeta*, and the bioassays were carried out at 30°C, 70% r.h. and continuous darkness. Ten g samples were taken from treated lots of grain and placed in a small cylindrical plastic vials (3 cm diameter by 8 cm in height). For each psocid species, grain, and pesticide combination, ten adult females were placed in a vial. There were three replications. Mortality was checked after 14 d of exposure, while progeny production was checked after 30 d (Athanassiou et al., 2009a). For each species and commodity, data were submitted to one-way ANOVA and means separated using Tukey-Kramer (HSD) test (alpha = 0.05).

2.3. Efficacy of diatomaceous earths (DEs)

DE formulations Insecto (Insecto Natural Products Inc., USA), Protect-It (Hedley Technologies Ltd., Canada), and Dryacide (Entosol Ltd., Australia) were tested at 500, 400 and 1000 ppm, respectively on wheat, rice, and maize against *L. entomophila*, *L. reticulatus*, and *L. decolor*. Psocids obtained and tested as described above, and grains treated as described in Athanassiou et al. (2009b). Mortality was corrected for control mortality by using Abbott's formula (Abbott, 1925). Mortality and progeny production were analysed by species using two-way ANOVA, commodity and DE as main effects, and HSD test.

2.4. Efficacy of methoprene

Efficacy of methoprene (Diacon II, Wellmark International, USA) against *L. bostrychophila*, *L. entomophila*, and *L. reticulatus* on wheat, rice, and maize was evaluated as described above except three dose rates (1, 5, and 10 ppm) were tested, grain was held at 27.5°C and 75% r.h., and adult progeny production was evaluated after 40 d. The data were analyzed by species using two-way ANOVA, commodity and application rate as main effects, and HSD test.

2.5. Efficacy of pyriproxifen and esfenvalerate

Pyriproxifen (Archer, Syngenta, USA) efficacy against *L. bostrychophila, L. paeta,* and *L. decolor* was evaluated in Petri dishes with concrete bottoms (2.3 mg of active ingredient per m^2). Ten 10 young nymphs obtained as described above, were added to dishes and treated as follows: a) dishes sprayed before introduction of psocids, b) dishes sprayed after introduction of psocids, c) dishes containing ten cracked wheat kernels sprayed before introduction of psocids, and d) dishes containing ten cracked wheat kernels sprayed after introduction of psocids. Dishes were then held as described in previous experiment, and number of live adults recorded 28 d after spraying. Data were analyzed by species by using one-way ANOVA, and HSD test. Efficacy of aerosol applications of esfenvalerate (Conquer, Paragon Professional Pest Control Products, USA) against *L. bostrychophila, L. decolor,* and *L. paeta* was evaluated by exposed them on concrete dishes placed in sheds, and treated at a rate of 29.6 mL / 28.3 m^3 of airspace for a period of two hours. Control dishes were held in a separate untreated shed. Characteristics of the sheds can be found Toews et al. (2009). A replicate consisted of 20 adults in each of four dishes. The dishes containing the psocid species were examined immediately after treatment, and mortality recorded. Approximately 5 g of cracked wheat was then added to each dish, and then dishes were held at 27°C and 60% r.h. for 48 h and mortality assessed again. Data were analyzed using the General Linear Models (GLM) procedure of SAS (SAS Institute), with treatment and species as main effects.

2.6. Efficacy of sulfuryl fluoride (SF)

Efficacy of the fumigant SF (ProFume, Dow AgroSciences, USA) at doses of 2, 4, 6, 24, 48, 72, and 96 g/m^3, was evaluated against *L. paeta* eggs, nymphs, and adults and *L. decolor* eggs and adults. Large jars were used as the experimental chambers, 10 adults, nymphs, or eggs in small cylindrical glass vials were placed in each jar. Mortality of nymphs and adults was assessed 48 h later. In the case of eggs, vials were transferred to the laboratory at 30^{o}C and 75% r.h., and egg hatch observed daily.

3. Results

3.1. Efficacy of neurotoxic grain protectants

For all four psocid species, mortality was approximately 100% with little or no progeny production when exposed to chlorpyriphos-methyl + deltamethrin on wheat, and pirimiphos-methyl or spinosad on maize (Table 1). Conversely, pyrethrum efficacy and impact on progeny production was low on all commodities. Spinosad efficacy varied among insecticides, psocid species and commodity. Within a psocid species, progeny production in controls varied considerably among the different commodities.

3.2. Efficacy of Des

In general Des did nor provide the levels of mortality obtained with some of the protectants reported above; ranging from 37.5 to 92.6% mortality (Table 2). The three Des did not differ in psocid mortality, except for *L. entomophila* on treated wheat, where Dryacide had significantly higher mortality than Protect-It, and *L. reticulatus* on treated maize, where Dryacide had greater mortality than the other two Des. *L. reticulatus* was most susceptible to DE of the species tested, mortality exceeded 75% in all cases and *L. decolor* was the most tolerant, given that mortality did not reach 50% for any of the DE-commodity combinations tested. Generally, the presence of DEs significantly reduced progeny production in comparison with the control, for all species tested (Table 2). However, progeny production in the treated grains was still high, and no significant differences were noted among DEs.

3.3. Efficacy of methoprene

Generally, for *L. bostrychophila*, with the exception of rice at 1 ppm, no significant differences were noted in adult progeny among methoprene doses for the three grains examined (Table 3). For *L. entomophila*, with the exception of maize, an increase in dose significantly reduced progeny production. Progeny production was generally higher on rice than in the other two commodities. For *L. paeta*, methoprene dose significantly affected progeny production on treated rice, but there was no difference in progeny production between 5 and 10 ppm. In contrast, progeny production was not affected by methoprene application rate on wheat and maize.

Table 1 Mean ± SE mortality (%) of psocid adults after 14 d of exposure, and mean progeny production (live individuals/vial ± SE) after 30 d of exposure in the treated and untreated commodities (within each column and commodity, means followed by the same letter are not significantly different; Tukey-Kramer (HSD) at $P < 0.05$).

Commodity	Treatment	*L. reticulatus* 14 d	*L. reticulatus* 30 d	*L. entomophila* 14 d	*L. entomophila* 30 d	*L. bostrychophila* 14 d	*L. bostrychophila* 30 d	*L. paeta* 14 d	*L. paeta* 30 d
Wheat	Chlorpyriphos-methyl + deltamethrin	100.0 ± 0.0a	0.2 ± 0.2a	100.0 ± 0.0a	0.2 ± 0.1a	98.9 ± 1.1a	0.7 ± 0.6a	100.0 ± 0.0a	0.2 ± 0.1a
	Spinosad	96.7 ± 2.4a	0.0 ± 0.0a	84.4 ± 7.8b	7.7 ± 5.9ab	75.6 ± 10.2b	42.3 ± 18.0b	55.6 ± 11.5b	40.1 ± 12.2b
	Pyrethrum	65.7 ± 13.5b	11.6 ± 6.3b	55.6 ± 11.8c	26.4 ± 9.0b	30.0 ± 11.1c	52.0 ± 21.0b	14.4 ± 4.7c	11.6 ± 2.1c
	Control	21.1 ± 7.4c	60.8 ± 11.7c	13.3 ± 4.7d	84.0 ± 21.5c	6.8 ± 3.3d	161.8 ± 21.1c	5.6 ± 1.8c	93.1 ± 15.2d
Rice	Chlorpyriphos-methyl + deltamethrin	100.0 ± 0.0a	1.6 ± 1.0a	100.0 ± 0.0a	0.0 ± 0.0a	100.0 ± 0.0a	0.3 ± 0.3a	100.0 ± 0.0a	0.8 ± 0.6a
	Spinosad	71.1 ± 13.0b	3.3 ± 1.0a	52.3 ± 4.6b	6.1 ± 1.9b	45.7 ± 10.1b	106.9 ± 14.3b	18.8 ± 6.4b	35.0 ± 4.4b
	Pyrethrum	14.3 ± 8.8c	91.1 ± 13.9b	16.7 ± 5.8c	82.1 ± 17.6c	26.5 ± 9.6bc	134.5 ± 19.3b	31.1 ± 12.5b	41.3 ± 7.2b
	Control	15.5 ± 4.1c	115.6 ± 13.5b	10.0 ± 4.7c	81.9 ± 9.5c	9.7 ± 2.4c	298.5 ± 49.0c	3.4 ± 1.6c	93.7 ± 12.9c
Maize	Pirimiphos-methyl	100.0 ± 0.0a	0.0 ± 0.0a	100.0 ± 0.0a	0.0 ± 0.0a	100.0 ± 0.0a	0.0 ± 0.0a	100.0 ± 0.0a	0.0 ± 0.0a
	Spinosad	100.0 ± 0.0a	0.1 ± 0.1a	98.9 ± 1.1a	0.3 ± 0.2a	76.4 ± 7.7b	10.9 ± 6.8b	37.8 ± 11.4bc	8.2 ± 1.8bc
	Pyrethrum	86.7 ± 5.8b	0.2 ± 0.2a	60.0 ± 12.5b	8.5 ± 1.6b	23.3 ± 7.8c	1.9 ± 0.4ab	18.9 ± 5.9cd	2.7 ± 1.8ab
	Control	61.1 ± 11.9c	29.7 ± 8.3b	14.4 ± 4.1c	65.5 ± 14.1c	13.5 ± 5.3c	82.7 ± 16.0c	14.1 ± 4.1d	18.1 ± 6.4c

Table 2 Mean ± SE mortality (%) after 14 d of exposure and mean progeny production (number of individuals/vial ± SE) for three psocid species on three commodities treated with three DE formulations (means for a species within each column followed by the same letter are not significantly different; where no letters exist, no significant differences were noted; Tukey-Kramer (HSD) at $P < 0.05$).

Species	Treatment	Wheat Mortality	Wheat Progeny	Rice Mortality	Rice Progeny	Maize Mortality	Maize Progeny
L. entomophila	Control	-	153.7 ± 36.3a	-	201.1 ± 28.4a	-	117.2 ± 20.2a
	Protect-It	63.6 ± 4.8b	37.3 ± 4.6b	73.5 ± 4.0	54.4 ± 12.8b	60.5 ± 7.5	40.0 ± 5.2b
	Dryacide	79.0 ± 3.6a	43.5 ± 6.9b	69.8 ± 6.9	42.6 ± 7.4b	70.4 ± 5.7	32.3 ± 4.1b
	Insecto	71.6 ± 5.7ab	49.1 ± 9.0b	64.8 ± 5.3	38.8 ± 7.7b	74.1 ± 4.9	29.4 ± 4.4b
L. reticulatus	Control	-	128.0 ± 21.2a	-	172.4 ± 39.0a	-	92.9 ± 17.7a
	Protect-It	85.2 ± 3.8	34.9 ± 4.1b	80.6 ± 6.2	28.0 ± 6.3b	76.0 ± 5.8b	27.7 ± 3.3b
	Dryacide	89.4 ± 4.1	30.1 ± 3.9b	89.4 ± 3.7	37.4 ± 6.8b	92.6 ± 2.1a	36.3 ± 4.5b
	Insecto	84.0 ± 5.0	41.9 ± 8.8b	82.9 ± 4.9	34.6 ± 5.6b	84.3 ± 3.0ab	32.4 ± 4.0b
L. decolor	Control	-	194.9 ± 41.5a	-	217.5 ± 34.7a	-	181.0 ± 28.5a
	Protect-It	37.7 ± 6.7	60.3 ± 12.3b	38.4 ± 6.3	79.3 ± 18.4b	37.5 ± 5.0	53.4 ± 9.5b
	Dryacide	49.5 ± 4.7	76.2 ± 17.3b	38.9 ± 4.5	49.2 ± 13.2b	43.1 ± 4.3	59.4 ± 12.4b
	Insecto	46.3 ± 4.5	61.3 ± 10.2b	47.2 ± 6.1	64.3 ± 16.7b	46.3 ± 5.9	42.0 ± 8.7b

Table 3 Number of adults of three psocid species per vial (mean ± SE) 40 days after the introduction of 10 parental individuals on untreated commodities (0 ppm) or commodities treated with methoprene at three dose rates (within each row, means followed by the same uppercase letter are not significantly different; within each column, means followed by the same lowercase letter are not significantly different; where no letters exist, no significant differences were noted; in all cases for rows df=2,24, for columns df = 3, 32; Tukey-Kramer (HSD) at P < 0.05).

Dose (ppm)	*L. bostrychophila* Wheat	*L. bostrychophila* Rice	*L. bostrychophila* Maize	*L. entomophila* Wheat	*L. entomophila* Rice	*L. entomophila* Maize	*L. paeta* Wheat	*L. paeta* Rice	*L. paeta* Maize
0	102.6 ± 18.0a	75.8 ± 13.0a	48.2 ± 14.6a	155.3 ± 10.8Aa	132.1 ± 10.0Aa	66.9 ± 14.6Ba	151.2 ± 7.2Aa	87.8 ± 15.4Ba	45.1 ± 5.7Ca
1	6.3 ± 1.4Ab	66.7 ± 15.3Ba	4.2 ± 0.9Ab	40.0 ± 15.8Ab	97.0 ± 15.4Ba	17.8 ± 9.6Ab	14.7 ± 5.0Ab	93.1 ± 11.5Ba	12.3 ± 5.5Ab
5	4.2 ± 0.7b	5.8 ± 1.4b	3.1 ± 0.8b	8.3 ± 0.8Ac	15.2 ± 2.7Bb	6.1 ± 0.6Ab	6.9 ± 1.8b	11.0 ± 1.8b	5.8 ± 0.9b
10	4.5 ± 0.5b	5.8 ± 0.9b	2.8 ± 0.7b	7.5 ± 1.1c	8.8 ± 0.5b	7.2 ± 0.5b	6.1 ± 0.8b	6.0 ± 1.3b	6.1 ± 1.2b

3.4. Efficacy of pyriproxifen and esfenvalerate

Pyriproxifen efficacy was affected by the presence of psocids before spraying, as well as by the presence of food, but the pattern was not similar among psocid species (Table 4). In the case of *L. bostrychophila* and *L. paeta*, the placement of food and psocids after spraying generally increased adult emergence in comparison with the other treatments, but significant differences were not recorded in all combinations. The reverse was true for *L. decolor*. For the esfenvalerate experiments, survival in untreated controls ranged from 93 to 100% (data not included). Survival of psocids exposed directly to esfenvalerate aerosol ranged from 44 to 62%, with variation among species, and was generally less than the corresponding control survival. Moreover, psocid mortality did not increase 48 h after for any of the species tested (Table 5).

Table 4 Number of adults per dish, 28 d after spraying, for each species tested for efficacy of pyriproxifen as a surface treatment; Tukey-Kramer (HSD) test at $P < 0.05$).

Dish containment before spraying	*L. bostrychophila*	*L. decolor*	*L. paeta*
No psocids, no food	2.0 ± 0.8a	0.8 ± 0.3ab	4.1 ± 1.2a
Psocids and food	0.4 ± 0.4b	0.3 ± 0.2b	2.9 ± 0.6ab
Food but no psocids	0.0 ± 0.0b	2.1 ± 0.8a	1.1 ± 0.6bc
Psocids but no food	0.0 ± 0.0b	0.2 ± 0.1b	0.0 ± 0.0c

Table 5 Mean ± SE mortality (%) of L. bostrychophila, L. decolor, and L. paeta immediately after exposure to esfenvalerate application and mortality after 2 d.

Species	Day	Mortality (%)
L. bostrychophila	0	58.7 ± 13.4
	2	61.7± 12.9
L. decolor	0	46.3 ± 13.1
	2	44.6 ± 13.0
L. paeta	0	45.8 ± 13.6
	2	45.4 ± 13.3

3.5. Efficacy of SF

Complete mortality of *L. paeta* adults and nymphs was recorded at 6 g/m^3 (Fig. 1). However, eggs were much more tolerant than the other life stages, given that mortality reached 100% only at the maximum dose tested (96 g/m^3). *Liposcelis decolor* adults were the most tolerant in comparison with the adults of the other species examined, but they were more susceptible than eggs, since 100% mortality was noted at 72 g/m^3 (Fig. 2).

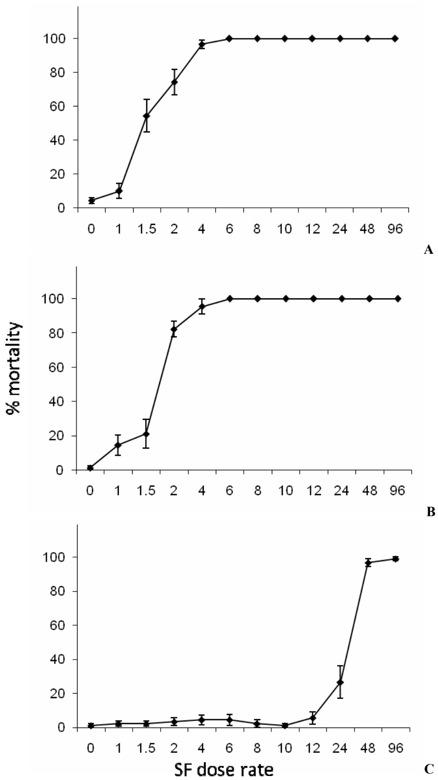

Figure 1 Mean (%) mortality (± SE) of *L. paeta* adults (A), nymphs (B), and eggs (C) after 48 h of exposure to various doses of SF (in g/m^3).

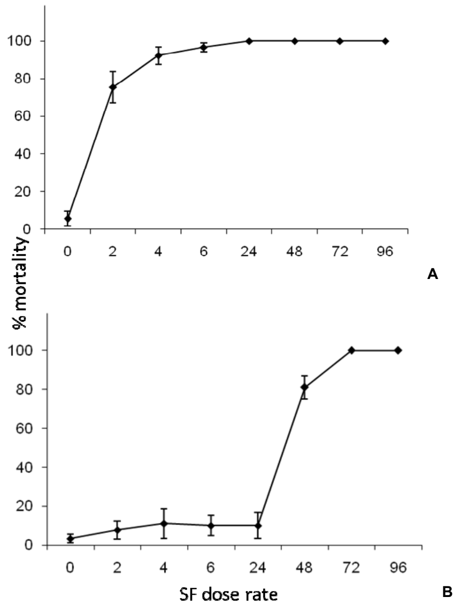

Figure 2 Mean (%) mortality (± SE) of *L. decolor* adults (A) and eggs (B) after 48 h of exposure on various doses of SF (in g/m^3).

4. Discussion

The four psocid species tested varied in their susceptibility among insecticides and commodities. Commodity is an important variable that affects insect development, as well as the insecticidal effect of grain protectants (Chanbang et al., 2008; Athanassiou et al., 2008b; 2009a). Opit and Throne (2008a) found that *L. reticulatus* and *L. entomophila* have different developmental rates on different diets. Based on the present results, rice may be the most suitable grain commodity for survival, development and reproduction of psocids, especially for *L. reticulatus* and *L. bostrychophila.* In light of our findings, OP insecticides result in higher mortality levels than spinosad or pyrethrum, despite variation among species and commodities. Hence, chlorpyriphos-methyl + deltamethrin was the most effective protectant on wheat and rice, and pirimiphos-methyl on maize, for all species tested. Nayak et al. (2003) found that chlorpyriphos-methyl on concrete was very effective against *L. bostrychophila*, but moderately effective against *L. entomophila* and *L. paeta*. Daglish et al. (2003) reported that chlorpyriphos-methyl with synergized bifenthrin was effective against *L. decolor*, *L. bostrychophila*, and *L. paeta* but not *L. entomophila.* The combination of OPs with pyrethroids are also effective against other stored-product insect species (Daglish, 1998; Nayak et al., 1998; Huang and Subramanyam, 2004). Generally, the current results clearly indicate that a single formulation that contains chlorpyriphos-methyl and deltamethrin is effective against all psocids species tested. However, Nayak et al. (1998) found that pirimiphos-methyl was unable to control *L. entomophila* and *L. paeta*, but it was effective against *L. bostrychophila*. Previously, there were no data available on protectant efficacy against psocids on maize; our results indicate that pirimiphos-methyl, at the label rate, can be used successfully, at least for the species range examined here.

Diatomaceous earth was not effective against psocids, despite variations among species, commodities, and formulations. Generally, DEs are considered to be less effective on maize than on wheat or rice against stored-grain beetle species (Subramanyam and Roesli, 2000; Athanassiou et al., 2003), probably because of reduced retention of DE particles on maize kernels (Kavallieratos et al., 2005). The combination of DEs with other, reduced-risk insecticides may be a solution to this problem. Athanassiou et al. (2008a) found that adults of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrychidae), were very susceptible to an abamectin-enhanced DE. Similar combinations should be further evaluated for control of psocids (Athanassiou et al., 2009b).

Methoprene reduced the numbers of adult progeny in all commodities and application rates, with the exception of 1 ppm. Bucci (1994) noted that high application rates of methoprene (47.5-190 ppm) reduced population growth of *L. bostrychophila*. Nevertheless, methoprene, even at 10 ppm, did not suppress adult progeny, in any of the commodities evaluated. Consequently, >10 ppm are needed for complete progeny suppression. Nayak et al. (1998; 2002) also noted that methoprene was unable to control *L. bostrychophila*, *L. entomophila*, *L. paeta*, and *L. decolor*, while a survey of field populations of *L. bostrychophila* and *L. entomophila* indicated that this tolerance is a natural phenomenon and not due to methoprene resistance. Moreover, methoprene efficacy was different among commodities. Samson et al. (1990) found that the efficacy of three IGRs against *R. dominica* differed between paddy rice and maize. In our study, adult numbers were continuously higher on rice than on wheat and maize which is in accordance with the observations obtained from the previous experiments.

There are many studies available for the efficacy of contact insecticides on different surfaces against psocids. Guedes et al. (2008) in laboratory bioassays found that beta-cyfluthrin and chlorfenapyr were very effective against *L. bostrychophila* and *L. entomophila* on concrete. Collins et al. (2000) also reported that chlorpyriphos-methyl was not able to provide long-term protection on concrete against *L. entomophila* and *L. paeta*. However, there was no data available on the efficacy of pyriproxifen or esfenvalerate against psocids on concrete. The results of the present study indicate that pyriproxifen efficacy varied with psocid species, presence of psocids before or after the application, as well as the presence of food (kernels). Survival on esfenvalerate-treated surfaces was generally high for the tested psocid species, but, longer exposure intervals on the treated surfaces need to be evaluated in order to examine if, and to what extent, delayed mortality can gradually eliminate the population.

Sulfuryl fluoride is perhaps the most promising alternative fumigant to methyl bromide, as it combines high efficacy and good penetration characteristics (Bell and Savvidou, 1999; Small, 2007; Baltaci et al., 2009). Sulfuryl floride has been evaluated with success against a wide range of stored-product insect species, but there is still inadequate information on its efficacy against psocids. Our results show that psocids are generally susceptible as nymphs or adults to low doses of SF. In contrast, eggs are very tolerant to SF and can survive at doses that are usually lethal for the control of other major insect species. High egg tolerance to SF has been reported for some stored-product pests (e.g. Phillips et al. 2008), but there are exceptions (e.g. Baltaci et al., 2009). Additional experimentation is required with more psocid species, commodities, doses, and exposures, in order to evaluate the factors that could contribute to higher SF efficacy against psocid eggs.

In conclusion, this paper has briefly discussed the results of a series of experiments aimed at assessing the efficacy of registered pesticides against psocids. For the entire treatment of the grain mass, chlorpyriphos-methyl + deltamethrin and pirimiphos-methyl were more effective than spinosad, pyrethrum, DEs, or methoprene. For concrete surfaces, neither pyriproxifen nor esfenvalerate were able to completely control psocids, and based on previous publications, OPs may be more effective in this case as well. Finally, SF is effective against psocids, but higher doses and/or longer exposures are needed to obtain 100% egg kill. All the above observations underline the need for a more integrated approach for psocid management in storage facilities.

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