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Acute lethal and behavioral sublethal responses of two stored-product psocids to surface insecticides

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Abstract

BACKGROUND: The psocids *Liposcelis bostrychophila* Badonnel and *L. entomophila* (Enderlein) (Liposceli-didae) are emerging pests of stored products. Although their behavior, particularly their high mobility, may contribute to the reported relatively low efficacy of insecticides against them, studies to investigate this have not been conducted. The present study aimed to assess the label rate efficacy of three commercial insecticides (β-cyfluthrin, chlorfenapyr and pyrethrins) applied on concrete surfaces against *L. bostrychophila* and *L. entomophila*, and also their sublethal effect on the mobility of these species.

RESULTS: The synthetic insecticides β-cyfluthrin and chlorfenapyr showed high short-term efficacy ($LT_{95} \leq 15$ h) against both psocid species, unlike the natural pyrethrins ($LT_{95} \geq 4$ days). *Liposcelis bostrychophila* was slightly more tolerant ($\geq 1.2\times$) than *L. entomophila* to all three insecticides. Behavioral assays with fully sprayed and half-sprayed concrete arenas indicated that the insecticides reduced the mobility of both species. Pyrethrins seem to elicit weak repellence in *L. bostrychophila*.

CONCLUSION: β-Cyfluthrin and chlorfenapyr were effective against both psocid species, but not pyrethrins. The mobility of both species does not seem to play a major role in the differential selectivity observed, but the lower mobility of *L. bostrychophila* may be a contributing factor to its higher insecticide tolerance.
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Keywords: Psocoptera; differential selectivity; mobility; repellence; β-cyfluthrin; chlorfenapyr; pyrethrins

1 INTRODUCTION

Historically, psocids (Psocoptera) have been considered to be scavengers and mold feeders of negligible importance. However, they have emerged as pests of stored products over the last decade in tropical countries, particularly Australia, Singapore, India, Indonesia, China and Zimbabwe.[1–5] Subsequent studies indicated that the status of psocids had changed from nuisance pests to that of worldwide pests of stored products.[6–9] The genus *Liposcelis* (Liposcelididae) contains the species of psocids that are the major cause of concern in stored products, and *L. bostrychophila* Badonnel and *L. entomophila* (Enderlein) are the most prevalent worldwide in stored commodities.[5,6,9]

Insecticides are frequently used for pest management, particularly in the tropics where alternatives are often not feasible.[10] However, control with insecticides has proven to be elusive owing to behavioral and physiological traits of some insect pest species,

such as stored-product psocids. The rapid life cycle of stored-product psocids allows rapid colonization of new habitats and potential recovery after insecticide applications.[5,6,11] In addition, their high mobility can reduce their level of exposure to insecticides, which reduces efficacy. For example, movement of psocids from dry products undergoing fumigation to absorb ambient atmospheric moisture impairs fumigation efficacy in open-top silos.[12] Delayed egg hatching in the presence of the fumigant phosphine, as well as phosphine resistance, further compromise psocid control with fumigants.[12]

A series of studies exploring residual application of conventional insecticides for use as both grain admixtures and structural treatments showed overall poor efficacy against the main liposcelidid species, including *L. bostrychophila* and particularly *L. entomophila*, which is usually the species most difficult to control.[13–19] Several organophosphates frequently used in stored-product protection worldwide, in

addition to the carbamate carbaryl and the pyrethroids bifenthrin, deltamethrin and permethrin, have been tested against stored-product psocids, particularly as surface treatments.[13,14,16,18] They all showed only low to moderate efficacy against *Liposcelis* species, as was also demonstrated for the microorganism-derived insecticide spinosad (used in grain treatment), hence requiring the use of insecticide mixtures for effective control.[13–19] Concrete flooring, which is common in food processing plants, warehouses and grain storage facilities, is probably one factor that compromises the efficacy of stored-product insecticides, in addition to the peculiarities of the insect pest targeted.[13,14,18,20] The concrete surface is porous and alkaline, favoring insecticide loss from the surface by absorption, and rapid hydrolysis and breakdown of the insecticide.[20] Organophosphates were preferred for concrete-surface applications until the recognition of their reduced efficacy on this surface by the 1990s.[20,21] Later studies indicated the superior performance of pyrethroids for concrete-surface treatments, leading to their current prevalence in the USA.[20,21]

Deltamethrin and permethrin applied as surface treatments provided poor protection against stored-product psocids, particularly *L. entomophila*, in studies conducted in Australia.[13] These were the only pyrethroid insecticides previously tested against psocids on concrete surfaces, whereas the use of another pyrethroid, cyfluthrin, prevails in the USA and the use of pyrethrins is also common.[20,22] Pyrethrins, particularly pyrethrins I and II, are the main insecticidal esters of the oleoresin extracted from dried flowers of the pyrethrum daisy *Tanacetum cinerariaefolium* (Trev.) Schultz-Bip (Asteraceae).[23,24] Pyrethrins interfere with the gating kinetics of sodium channels in nerve axons, the same qualitative mechanism of action as DDT and synthetic pyrethroids.[24] Pyrethroid insecticides are synthetic analogues of pyrethrins, with higher potency against insects and photostability, and their development shifted from the synthesis of new compounds to the development of enriched active isomers in the late 1980s.[24–26] This trend in pyrethroid development led to the eventual replacement of isomeric mixtures with the enriched isomers, as illustrated in the field of stored-product protection by the replacement of cyfluthrin with β-cyfluthrin.

Another potential candidate for surface treatments against stored-product psocids that has not yet been considered is the novel pyrrole compound chlorfenapyr, discovered in 1988 and commercialized in 1995 as a broad-spectrum insecticide.[27–29] Chlorfenapyr is a pro-pesticide activated by the oxidative removal of the *N*-ethoxymethyl group generating a potent uncoupler of the mitochondrial oxidative phosphorylation.[27–29] This insecticide received recent use-amendment in all US states, extending its use for surface treatments to control nuisance and stored-product pests.

Although pyrethrins, β-cyfluthrin and chlorfenapyr are recommended for surface treatments against stored-product insects, their efficacy has not yet

been tested against stored-product psocids on concrete surfaces, therefore justifying the present study. Furthermore, the fast mobility of *Liposcelis*, which contributes to the impairment of the efficacy of fumigants, may also compromise insecticide treatments on concrete surfaces, which has not yet been considered in studies with the main species of stored-product psocid pests – *L. bostrychophila* and *L. entomophila*. These were the objectives of the present study, in which the neurotoxic activity of pyrethrins and pyrethroids in general are expected to increase the mobility of both psocid species, increasing their exposure and insecticide efficacy, unless significant repellence is elicited by these compounds, which was also assessed. The potency of pyrethrins was expected to be lower than that of the more active pyrethroid β-cyfluthrin, and the broad spectrum of high activity of chlorfenapyr is also suggestive of high potency against psocids, although with slower effect. The respiratory impairment caused by chlorfenapyr was expected to lead to reduced psocid mobility, consequently leading to their lower exposure to this compound, compromising even more its short-term efficacy, although this outcome will also depend on the spatial distribution of the insecticide.

2 MATERIAL AND METHODS
2.1 Insects and insecticides
Two species of stored-product psocids were used in the study – *L. bostrychophila* and *L. entomophila*. Cultures of both species were maintained on a cracked wheat diet: 97% (wt/wt) cracked hard red winter wheat, 2% Rice Krispies breakfast cereal (Kellogg USA Inc., Battle Creek, MI) and 1% brewer's yeast (MP Biomedicals Inc., Solon, OH) in 0.473 L glass canning jars covered with mite-proof lids; cultures were maintained at 30 °C, 70% RH and 24 h scotophase.[30] *Liposcelis bostrychophila* is parthenogenetic (females only), while *L. entomophila* is not, so only adult females were used in the experiments. *Liposcelis entomophila* shows sexual dimorphism, with females much larger than the males, easily allowing their recognition. Voucher specimens of *L. bostrychophila* and *L. entomophila* used in this study were deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research under lot numbers 202 and 182, respectively.

Commercial formulations of three insecticides available in the USA for surface treatments in storage facilities and food processing plants were used at their recommended label rates: β-cyfluthrin 120 g L^{-1} SC (Tempo® SC Ultra; Bayer CropScience, Kansas City, MO) diluted at 0.05% (v/v) was sprayed at 0.04 L m^{-2} to give a deposit of 0.24 µg AI cm^{-2}; chlorfenapyr 214.5 g L^{-1} SC (Phantom® SC; BASF Chemical Corporation, Research Triangle Park, NC) diluted at 0.5% (v/v) was sprayed at 0.23 L m^{-2} (24.7 µg AI cm^{-2}); pyrethrins 50 g L^{-1} SC (PyGanic Pro® SC; MGK Co., Minneapolis, MN) diluted at

2.35% (v/v) was sprayed at 0.21 L m^{-2} (24.7 µg AI cm^{-2}).

The insecticides were sprayed over concrete surfaces prepared in individual petri dishes (1.5 cm high × 13 cm diameter). The concrete-filled petri dishes were prepared by mixing 3200 g of concrete (Rockite, Hartline Prod. Co., Cleveland, OH) in 1600 mL of water to a thick running consistency, which was subsequently poured into individual petri dishes.[31] Insecticides were applied to the concrete surfaces by spraying with an artist's airbrush (No. 100 LG, Badger Air Brush Co., Franklin Park, IL).[20,31] The bioassays were carried out 24 h after spraying the concrete surface to allow sufficient time for the sprays to dry. The inside walls of the petri dishes were covered with Teflon® PTFE (DuPont, Wilmington, DE) to prevent insect escape.

2.2 Time–mortality bioassays
Adult female psocids of each species were subjected to time–mortality bioassays for each insecticide. Fifty insects were released on the concrete surface in each petri dish. Three independent replicates were used for each combination of insect species, insecticide (or control where only water was sprayed over the concrete surface) and length of exposure. The petri dishes containing insects were closed and placed on plastic waffle-type grids in the bottom of dark plastic boxes (26 × 36.5 × 15 cm) containing a layer of saturated aqueous sodium chloride solution to maintain 70% RH and 24 h scotophase.[32] The dark boxes containing the petri dishes with insects were placed in incubators at 30 °C. Temperature and humidity inside the chambers were monitored with HOBO data recorders (Onset Computer, Bourne, MA). Mortality assessments were conducted at regular and independent exposure intervals (i.e. with separate replicates at each time interval) pre-established after preliminary tests.

2.3 Behavioral bioassays
Two behavioral bioassays were carried out in concrete arenas either fully sprayed or half-sprayed with insecticides (control treatments were sprayed with water). Plexiglass (polymethyl methacrylate) rings (1.0 cm high × 2.5 cm inner diameter) were glued on the center of the concrete surface of each sprayed petri dish for use as arenas for the behavioral bioassays. The inner walls of each ring were covered with Teflon® PTFE (DuPont, Wilmington, DE) to prevent insects from escaping. A single insect was placed in each arena (always at the center of the insecticide-sprayed portion of the arena for both fully sprayed and half-sprayed arenas). Twenty arenas (i.e. independent replicates) with individual insects were used for each treatment in each behavioral bioassay (fully sprayed and half-sprayed bioassays), and no insect mortality was observed within the 10 min exposure (trial duration) used for the behavioral bioassays.

The movement of each insect within the arena during 10 min was recorded using a Canon® NTSC video camcorder (XL1 3CCD; Canon USA, Lake Success, NY) equipped with a 16× video lens (zoom XL 5.5–88 mm) and digitally transferred to a computer for subsequent analysis using the software Studio version 9 (Pinnacle Systems, Mountain View, CA). The movement of the insects was recorded for each arena using the software EthoVision Pro 3.0 (Noldus Information Technology, Sterling, VA). EthoVision detected the insect's position using the subtraction method after applying an erosion and dilation filter. The video images of the arenas were maintained either undivided, for the behavioral bioassay with fully sprayed arenas, or divided into two symmetrical zones – one unsprayed and the other sprayed with insecticide, for the behavioral bioassay with half-sprayed arenas.

Average movement parameters were calculated for the treatments in both bioassays to determine differences in psocid response to insecticide-sprayed concrete surfaces. The parameters calculated for the fully sprayed bioassay were total distance moved (cm), velocity (cm s^{-1}), heading (deg), turn angle (deg), angular velocity (deg s^{-1}) and meander (deg s^{-1}). For the half-sprayed bioassay, these same parameters were calculated for each arena zone (i.e. unsprayed and insecticide-sprayed halves of the arena), in addition to two additional parameters – the number of visits to the sprayed zone and the percentage of time spent in the sprayed zone.

2.4 Statistical analyses
Time–mortality bioassays were subjected to probit analysis (PROC PROBIT; SAS)[33] to obtain times for 50% (LT$_{50}$) and 95% (LT$_{95}$) mortality. The selectivity ratio for each insecticide was obtained by dividing the LT$_{50}$ or LT$_{95}$ of *L. bostrychophila* by the corresponding LT estimate for *L. entomophila*. The 95% confidence limits of these estimates were calculated, and the LT values were considered to be significantly different ($P < 0.05$) if the confidence limits on the selectivity ratio did not include the value 1.[34]

The results for fully-sprayed arenas were subjected to a two-way (insecticide × species) multivariate analysis of variance (PROC GLM with MANOVA statement; SAS).[33] Individual analyses of variance for each parameter assessed were eventually subjected to two-way analyses of variance and subsequent Fisher's LSD test, if appropriate ($P < 0.05$) (PROC GLM; SAS).[33] The results of half-sprayed arenas were subjected to two distinct sets of analyses. Firstly, the results of unsprayed × sprayed zones of each psocid species were contrasted using multivariate analysis of variance for each species and insecticide (PROC GLM with MANOVA statement; SAS).[33] Secondly, the results of the sprayed half of the arenas were subjected to a two-way (insecticide × species) multivariate analysis of variance (PROC GLM with MANOVA statement; SAS).[33] As with the results for

fully sprayed arenas, individual analyses of variance for each parameter assessed in the half-sprayed arenas were also eventually subjected to two-way analyses of variance and subsequent Fisher's LSD test, if appropriate ($P < 0.05$) (PROC GLM; SAS).[33]

3 RESULTS
3.1 Time–mortality responses: insecticide toxicity and selectivity
The time–mortality results from insecticide exposure of adult females of the two species of stored-product psocids under investigation showed low χ^2 and high P values (<9.0 and >0.06 respectively), indicating the suitability of the probit model for fitting the time–response curves and consequently obtaining estimates of the mortality parameters LT_{50} and LT_{95} (Table 1). The insecticides β-cyfluthrin and chlorfenapyr both caused more rapid mortality ($LT_{95} \leq 15\,h$) against the two psocid species than did pyrethrins ($LT_{95} \geq 4$ days). *Liposcelis bostrychophila* showed slightly greater tolerance to all three insecticides tested than *L. entomophila* (between 1.0 and $1.9\times$ at LT_{50} and 1.2 to $1.9\times$ at LT_{95}) (Table 1). The differential tolerance between the species was greatest for pyrethrins ($1.9\times$). In addition, the time–mortality response curves for *L. bostrychophila* had lower slopes than those for *L. entomophila*, indicating higher heterogeneity of response to insecticides among individuals of the former species (Table 1).

3.2 Walking behavior in fully sprayed arenas
The overall mobility parameters of both psocid species on the concrete surface fully covered with dried insecticide residues differed with species ($df_{num/den} = 18/116.26$, Wilks' lambda $= 0.6402$, $F = 3.95$, $P < 0.0001$) and insecticide ($df_{num/den} = 6/147$, Wilks' lambda $= 0.6885$, $F = 11.09$, $P < 0.0001$), and the species–insecticide interaction was significant ($df_{num/den} = 18/116.26$, Wilks' lambda $= 0.8227$, $F = 1.65$, $P = 0.045$) when subjected to a multivariate analysis of variance. Univariate analyses of variance were therefore carried out for each parameter assessed to determine the main parameters affecting the overall mobility of both species. Among the path linearity parameters (i.e. heading, turn angle, angular velocity and meander), only turn angle showed significant differences ($F_{7,72} = 2.37$, $P = 0.02$), in addition to total distance moved ($F_{1,71} = 3.53$, $P = 0.001$) and velocity ($F_{7,71} = 5.84$, $P < 0.0001$). The species–insecticide interaction was not significant for any of these parameters, but the effect of insecticide was significant for all of them ($F_{3,72} > 3.76$, $P < 0.01$). Walking velocity on the sprayed concrete surface also differed with species ($F_{1,72} = 11.99$, $P = 0.0007$).

Tracks representative of the typical walking behavior of both psocid species on the concrete surface fully sprayed with insecticides are shown in Fig. 1. All three

Table 1. Susceptibilities of two psocid species, *Liposcelis bostrychophila* and *L. entomophila*, to three surface-treated insecticides

Insecticide	Psocid species	N	Slope (± SEM)	LT_{50} (h) (95% FL)	Differential selectivity ratio at LT_{50} (95% CL)[a]	LT_{95} (h) (95% FL)	Differential selectivity ratio at LT_{95} (95% CL)[a]	χ^2	p
β-Cyfluthrin	*L. entomophila*	973	0.35 (±0.03)	7.85 (7.41–8.27)	–	12.48 (11.70–13.56)	–	2.76	0.06
	L. bostrychophila	1599	0.26 (±0.01)	8.87 (8.52–9.24)	1.13 (1.05–1.21)	15.33 (14.61–16.20)	1.23 (1.12–1.34)	9.02	0.17
Chlorfenapyr	*L. entomophila*	1198	0.91 (±0.07)	3.31 (3.12–3.47)	–	5.12 (4.90–5.42)	–	0.63	0.96
	L. bostrychophila	1380	0.37 (±0.04)	3.32 (2.60–3.83)	1.00 (0.87–1.14)	7.73 (6.92–9.11)	1.51 (1.35–1.67)	8.93	0.06
Pyrethrins	*L. entomophila*	1449	0.030 (±0.002)	46.54 (43.35–49.38)	–	102.12 (94.56–112.53)	–	7.34	0.20
	L. bostrychophila	1278	0.015 (±0.002)	89.99 (77.56–110.62)	1.93 (1.68–2.19)	195.80 (158.26–280.10)	1.92 (1.52–2.31)	8.95	0.06

[a] The LT values for the two species were considered significantly different ($P < 0.05$) if the confidence limits on the selectivity ratio did not include the value 1.[34]
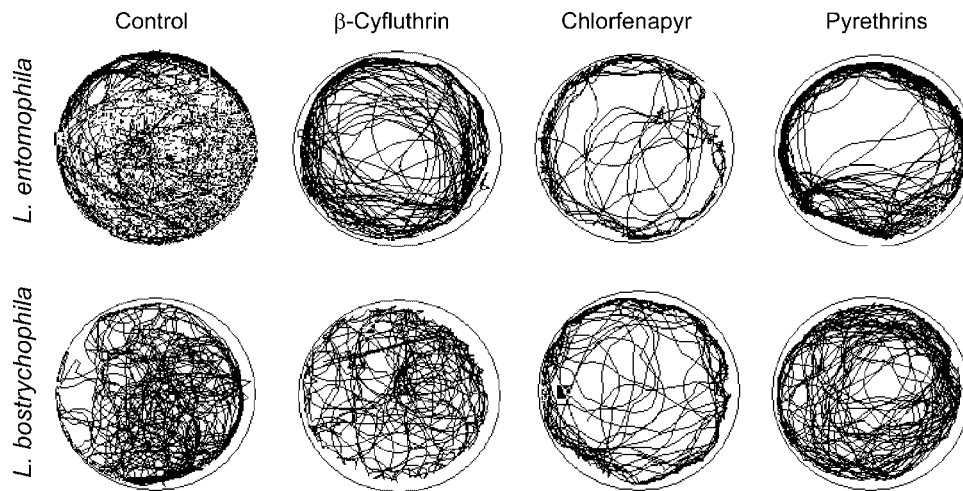
Figure 1. Representative tracks showing the movement of individual psocids from two species (*Liposcelis bostrychophila* and *L. entomophila*) over a 10 min period on concrete surface arenas (2.5 cm diameter) fully sprayed with water or insecticides.

insecticides reduced the velocity, but only β-cyfluthrin and chlorfenapyr reduced distance walked (Figs 2a and b). Chlorfenapyr led to the highest reduction in both distance moved and velocity of psocids on sprayed concrete surfaces (Figs 2a and b). Turn angle was increased by β-cyfluthrin and pyrethrins but not by chlofenapyr, reflected by a higher walking preference for the marginal outlines of the dishes in the case of the first two insecticides, which differed from the control (Fig. 2c). These trends were observed for both species of psocids. Insect velocity was the only mobility parameter that differed with psocid species, with *L. entomophila* moving at significantly higher velocity than *L. bostrychophila* ($0.49 \pm 0.03 \, \mathrm{cm \, s^{-1}}$ and $0.36 \pm 0.02 \, \mathrm{cm \, s^{-1}}$ respectively) regardless of the insecticide sprayed on the concrete surface.

3.3 Walking behavior in half-sprayed arenas

Tracks representative of the typical walking behavior of both psocid species on concrete surfaces half-sprayed with insecticides are shown in Fig. 3. The results obtained on both unsprayed and sprayed halves were contrasted for each species and for each insecticide within each species. Subsequently, the results obtained on the sprayed half were subjected to further analysis.

3.3.1 Unsprayed × sprayed halves

The walking behavior of *L. entomophila* was similar in both unsprayed and insecticide-sprayed halves of concrete arenas (multivariate ANOVA) regardless of the insecticide sprayed ($\mathrm{df_{num/den}} = 8/107$, Wilks' lambda $= 0.8756, F = 1.90, P = 0.07$). On the other hand, differences were observed in the walking behavior of *L. bostrychophila* ($\mathrm{df_{num/den}} = 8/88$, Wilks' lambda $= 0.8140, F = 2.51, P = 0.016$). There were differences in the walking behavior of *L. bostrychophila* on unsprayed and sprayed halves of the concrete-surface arenas sprayed with the insecticides chlorfenapyr ($\mathrm{df_{num/den}} = 8/31$, Wilks' lambda $= 0.5099$, $F = 3.72$, $P = 0.0037$) and pyrethrins ($\mathrm{df_{num/den}} = 8/31$, Wilks' lambda $= 0.6394, F = 2.19, P = 0.05$),

but not for β-cyfluthrin ($\mathrm{df_{num/den}} = 8/31$, Wilks' lambda $= 0.7371, F = 1.38, P = 0.24$). The individual mobility parameters of *L. bostrychophila* exposed to unsprayed and sprayed halves of concrete-surface arenas containing chlorfenapyr and pyrethrin residues were subsequently compared. Only path heading differed significantly between chlorfenapyr-sprayed and unsprayed halves of the arenas ($F_{1,38} = 18.63$, $P < 0.0001$), with higher values of heading for the unsprayed half of the arena (i.e. with less change in direction) ($249.80 \pm 25.30°$ and $115.82 \pm 17.99°$ respectively). The percentage of time spent on each half of the arena by *L. bostrychophila* was the only mobility parameter significantly different between pyrethrin-sprayed and unsprayed halves of the arenas ($F_{1,38} = 6.43, P = 0.015$), with significantly more time spent by the insects on the unsprayed half ($57.48 \pm 4.55\%$) than on the pyrethrin-sprayed half of the concrete arenas (41.58 ± 4.325).

3.3.2 Walking behavior in the insecticide-sprayed half of arenas

The overall mobility parameters of both psocid species on the insecticide-sprayed zone of half-sprayed concrete arenas differed with species ($\mathrm{df_{num/den}} = 8/107$, Wilks' lambda $= 0.7411$, $F = 4.67$, $P < 0.0001$) and insecticides ($\mathrm{df_{num/den}} = 16/214$, Wilks' lambda $= 0.7703$, $F = 1.86$, $P = 0.025$), but the species–insecticide interaction was not significant ($\mathrm{df_{num/den}} = 16/214$, Wilks' lambda $= 0.8433$, $F = 1.19, P = 0.28$) when subjected to multivariate analysis of variance. Univariate analyses of variance were therefore carried out for each parameter assessed to determine the main parameters affecting the overall mobility of both species over the insecticide-sprayed zone of the concrete arenas. There were no significant differences in the path linearity parameters nor in the percentage of time spent on the sprayed zone ($F_{5,114} \leq 1.33$, $P \geq 0.16$), but there were significant differences in total distance moved ($F_{5,114} = 5.95$, $P < 0.0001$), insect walking velocity ($F_{5,114} = 5.43$,
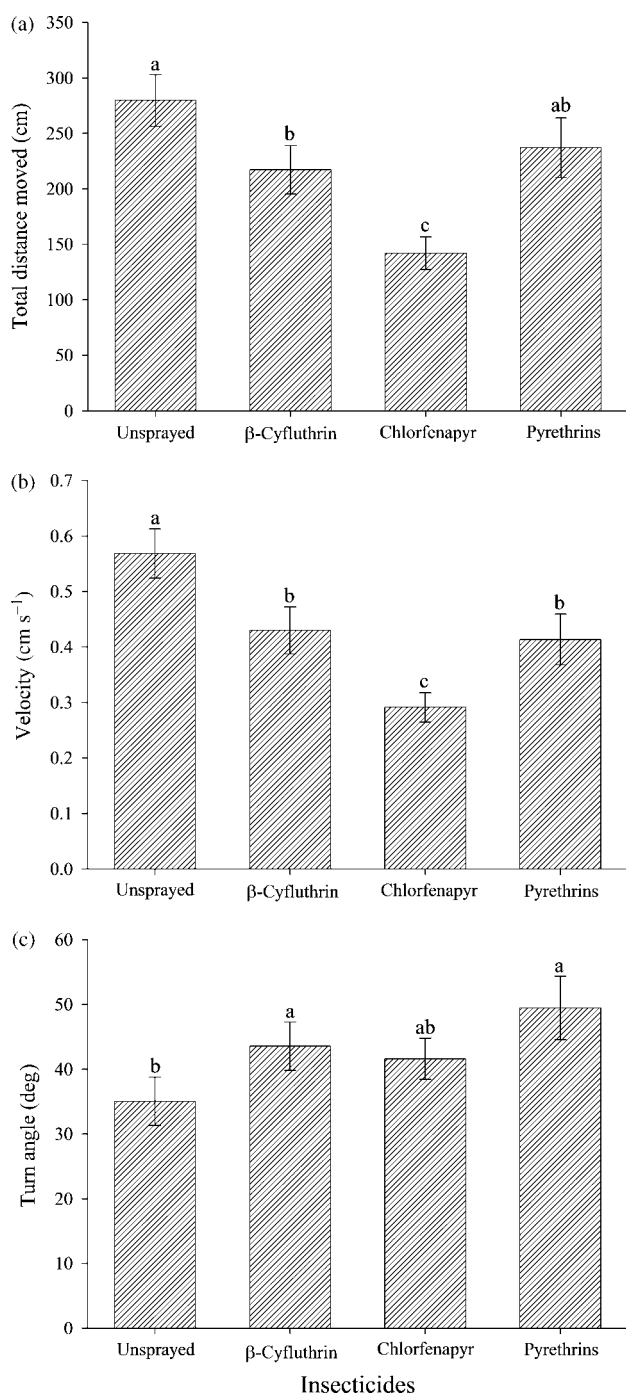
Figure 2. Total distance moved (a), velocity (b) and turn angle (c) (± standard error) of stored-product psocids exposed to concrete arenas fully sprayed with either water or insecticides over a 10 min period. Histogram bars with the same letter do not differ significantly by Fisher's LSD test ($P < 0.05$).

$P = 0.0002$) and number of visits to the sprayed zone of the half-sprayed arenas ($F_{5,114} = 3.19$, $P = 0.01$). The species–insecticide interaction was not significant for any of these parameters, but the effect of insecticide was significant for total distance moved and velocity ($F_{2,114} \geq 3.10$, $P < 0.0001$) and the species significantly affected not only these two parameters but also the number of visits to the sprayed zone ($F_{1,114} \geq 6.26$, $P \leq 0.04$).

The total distance moved and the walking velocity in the insecticide-sprayed zone of half-treated arenas were significantly higher for β-cyfluthrin than for pyrethrins, with chlorfenapyr showing intermediate results, regardless of psocid species (Fig. 4). *Liposcelis entomophila* moved farther ($F_{1,114} = 17.20$, $P < 0.0001$) and faster ($F_{1,114} = 16.61$, $P < 0.0001$) and visited the insecticide-sprayed zone ($F_{1,114} = 6.26$, $P = 0.014$) more often than *L. bostrychophila*, regardless of the insecticide sprayed on the concrete surface (Fig. 5). *Liposcelis bostrychophila* was not as mobile and frequently remained static on the concrete surface with raised abdomen.

4 DISCUSSION

The low to moderate efficacy of insecticides applied in concrete surface treatments to control stored-product psocids led to the present study.[13,14] Among the insecticides tested so far, organophosphates and carbamates have reduced efficacy when applied over such a porous and alkaline surface, but pyrethroids usually perform better.[20,21] However, previous work with Australian populations of three species of stored-product psocids (*L. bostrychophila*, *L. entomophila* and *L. paeta* Pearman) demonstrated poor long-term protection (i.e. for long periods of time) with the pyrethroids deltamethrin and permethrin against psocids on concrete surfaces, suggesting a relatively high tolerance of these psocids to pyrethroids.[13] The insecticides β-cyfluthrin, chlorfenapyr and pyrethrins are currently available for surface treatments in the USA, but have not yet been evaluated for efficacy against psocids.

Pyrethrins showed poor short-term performance against both psocid species at the recommended label rate, unlike β-cyfluthrin and particularly chlorfenapyr. In contrast, β-cyfluthrin showed high short-term performance against stored-product psocids at concentrations lower than for previously studied pyrethroids ($52\times$ lower than permethrin and about $6\times$ lower than deltamethrin).[3,13] This is most likely a consequence of the use of an enriched isomer (i.e. β-cyfluthrin) instead of an isomeric mixture (e.g. cyfluthrin, permethrin and deltamethrin).[26] Chlorfenapyr showed even higher short-term performace than β-cyfluthrin at its current label rate, which came as a surprise because slower action was expected for this insecticide owing to its primary mode of action of uncoupling mitochondrial oxidative phosphorylation,[27] with this occurring only after activation within the organism.[27–29] The causes of such quick performance of chlorfenapyr against psocids invites further investigation. In addition, the authors explored the short-term performance of the insecticides, and those showing high performance (i.e. β-cyfluthrin and chlorfenapyr) should be subjected to long-term assessment with the aim of extended protection against stored-product psocids on concrete surfaces.
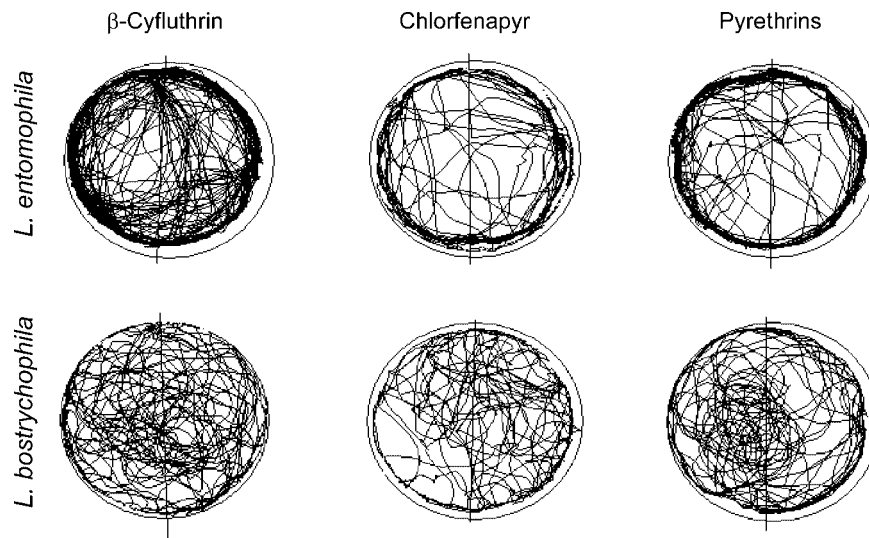
Figure 3. Representative tracks showing the movement of individual psocids from two species (*Liposcelis bostrychophila* and *L. entomophila*) over a 10 min period on concrete surface arenas (2.5 cm diameter) half-sprayed with insecticides (right half of each arena).
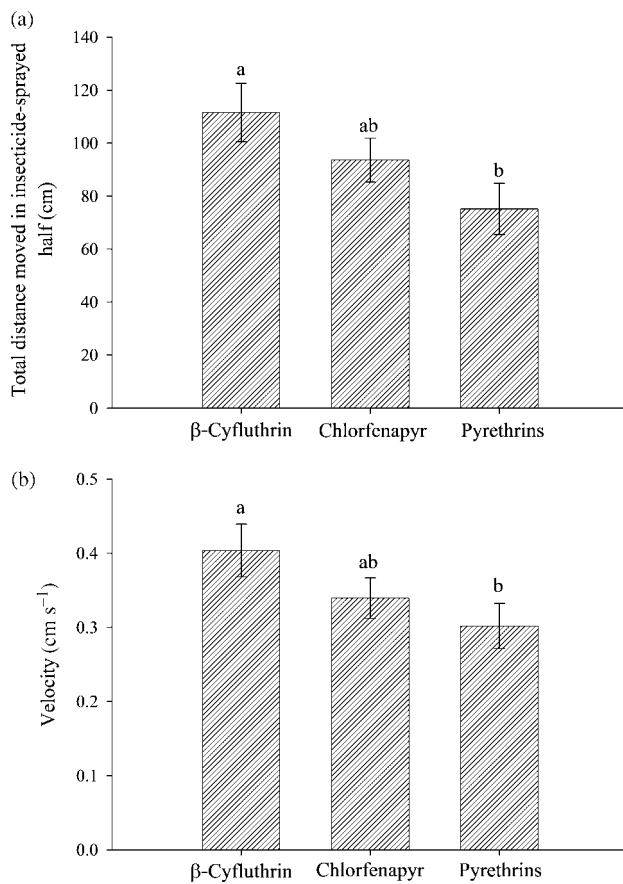

Figure 4. Total distance moved (a) and velocity (b) (± standard error) of stored-product psocids on the insecticide-sprayed half of concrete arenas half-sprayed with insecticides. Histogram bars with the same letter do not significantly differ by Fisher's LSD test ($P < 0.05$).

Both stored-product psocid species exhibited differential tolerance to all three insecticides investigated, although differences were low in magnitude. *Liposcelis bostrychophila* was slightly more tolerant ($\geq 1.2\times$) than *L. entomophila* to all three insecticides, which was not expected and is likely to become more apparent with long-term assessments. In addition, *L. bostrychophila* consistently exhibited higher heterogeneity of response to insecticides in the present study, suggesting a higher individual variability and therefore higher risk of selection for insecticide resistance than *L. entomophila*. The present results differ from those of Australian studies which showed *L. entomophila* to be the more tolerant species.[13–15,17] Although the insecticides used in the Australian studies differ from those used by the present authors, there was consistency in the results for all insecticides, suggesting that strain differences and past exposure to insecticides (in the case of Australian psocids) may be responsible for the differences observed in insecticide selectivity in Australia and in the USA (represented by the present study).

The sublethal behavioral effects of insecticides are also relevant for insect pest management because the target species are expected to remain exposed to sublethal concentrations of these compounds for longer periods than to lethal concentrations as a consequence of insecticide degradation. In addition, the high mobility of *Liposcelis* species seems further to impair the efficacy of fumigants,[5] and may also compromise the efficacy of insecticide treatments on concrete surfaces. The neurotoxic activity of pyrethrins and pyrethroids in general was expected to increase the activity of both psocid species, thus increasing their exposure and insecticide efficacy,[35–38] unless significant repellence is elicited by these compounds,[39–42] which was also assessed. In contrast, the respiratory impairment caused by chlorfenapyr was expected to lead to reduced psocid mobility, consequently leading to their lower exposure to this compound, and thereby compromising even more its short-term efficacy.

Behavioral assays with fully sprayed and half-sprayed concrete arenas indicate that the insecticides reduced the mobilities of both species. All three insecticides studied reduced not only the mobility but even the path of the insect movement in some
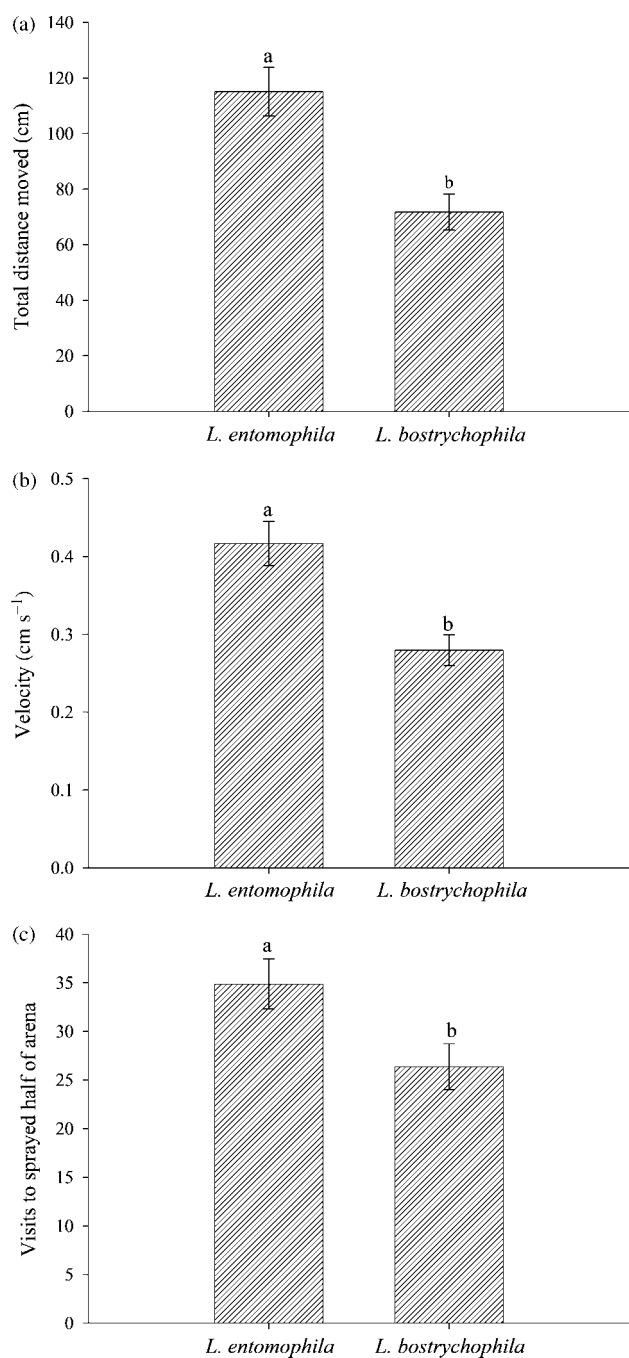
Figure 5. Total distance moved (a), velocity (b) and percentage of time spent (c) (± standard error) by two species of stored-product psocids on the insecticide-sprayed zone of concrete arenas half-sprayed with insecticides. Histogram bars with the same letter do not significantly differ by Fisher's F test ($P < 0.05$).

However, the authors did not expect pyrethrins and the pyrethroid β-cyfluthrin to reduce psocid mobility, as their neurotoxic activity is generally associated with increased mobility.[38–43] The reduced mobility observed with pyrethrins and β-cyfluthrin may be a reflex in response to high concentrations of these compounds which lead to paralysis instead of the hyperactivity expected under lower intoxication.[38,43] Alternatively, such reduced mobility may also result from a more peripheric movement on surfaces sprayed with these insecticides, either because the psocids tend to move more slowly along the walls in general or because the encounter with the walls slows them down. In addition, pyrethrins seem to elicit weak repellence in *L. bostrychophila*, which is likely to compromise even further the efficacy of this insecticide against this psocid species. *Liposcelis bostrychophila* proved to be a less mobile species than *L. entomophila* and frequently remained static on the concrete surface with raised abdomen, which potentially minimized insecticide exposure and body penetration and may explain its slightly higher insecticide tolerance reported here.

In summary, β-cyfluthrin and chlorfenapyr were efficient against both psocid species. The pyrethrin formulation was not effective and also seemed to elicit weak repellence in *L. bostrychophila*, compromising even further its efficacy against this species of stored-product psocid. Although the insecticides reduced the mobility of both psocid species, this does not seem to play a major role in the differential selectivity observed. However, the lower mobility of *L. bostrychophila* may be a contributing factor to its higher insecticide tolerance.

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instances. The high turn angle observed mainly with pyrethrins and β-cyfluthrin, regardless of the insect species, indicates walking preference for the marginal outlines of the arenas and suggests a potential preference for the edges of stored-product facilities. Therefore, the surface treatments in such facilities should consider these walking preferences and prevent the insects from using such edges as refuges from insecticide spraying.

Mobility reduction was particularly strong with chlorfenapyr, as expected from its mode of action.[27–29]

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