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Effectiveness of insecticide-incorporated bags to control stored-product beetles

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Abstract

Adults of seven stored-product beetle species were exposed on the inside and outside surfaces of polypropylene polymer bags incorporated with the insecticide deltamethrin (approx. concentration of 3,000 ppm; ZeroFly[®] Storage Bags (3g/kg). Beetles were exposed for 60, 120, and 180 min, and 1, 3 and 5 days on the same treatment arenas, and after the 5 d interval the insects were removed and placed in untreated arenas for 5 more days. All *Trogoderma variable* (Ballion), the warehouse beetle, *Prostephanus truncatus* (Horn), the larger grain borer, *Rhyzopertha dominica* (F.), the lesser grain borer, and *Tribolium castaneum* (Herbst), the red flour beetle, were knocked down on the outside and inside surfaces of the bag after one hour of exposure. Mortality of *T. variable*, *P. truncatus*, and *R. dominica* increased during the exposure period, with generally lower mortality on the inside versus the outside of the bag after either 3 or 5 days of continual exposure. However, maximum mortality of *T. castaneum*, the red flour beetle, was only $5.6 \pm 3.4\%$ after 5 days of exposure. While it took longer for 100% knockdown of *Sitophilus oryzae* (L.), the rice weevil, compared to the above species, all *S. oryzae* were dead after 5 d of exposure on both surfaces. In contrast, after 5 days knockdown of *S. zeamais* (Motschlulsky), the maize weevil, did not exceed 30% and there was no mortality. After the *Sitophilus* species were transferred to untreated arenas, knockdown of all species decreased and mortality increased, indicating delayed mortality and no recovery from knockdown. Mortality of *Dermestes maculatus* (DeGeer), the hide beetle, did not exceed 5.6% at any time and there was no delayed mortality, indicating a potential tolerance of this particular strain of *D. maculatus* used in the study. Our results show that the ZeroFly[®] Storage Bags could effectively limit penetration of stored-product beetles through the bag into stored grains or milled grain products.

Keywords: Packaging, deltamethrin, stored-product beetles, toxicity

1. Introduction

Contact insecticides have been extensively used for decades in stored product protection, as direct treatments to grains going into storage, or as surface, spot, crack and crevice treatments in empty bins, mills and processing facilities, and food warehouses (Arthur and Subramanyam, 2012). The goal of these applications is to protect the commodity from insect infestations (Arthur, 1996; Arthur and Fontenot, 2012; Athanassiou et al., 2015; Kavallieratos et al., 2016). In general, contact insecticides give residual control, and in many cases are applied as a preventive measure (Towes et al., 2005; Arthur and Subramanyam, 2012). In contrast, fumigants are applied to eliminate an existing infestation (Reed, 2006; Phillips et al., 2012).

Many older organophosphate grain protectants have been withdrawn from the market world-wide in recent decades, due to concerns with residue accumulation and/or insecticide resistance, and have been replaced with newer reduced-risk products (Mohandass et al., 2006; Arthur and Subramanyam, 2012). Also, in many parts of the world, particularly in undeveloped countries, raw grains can be stored in bags instead of in bulk bins or elevator silos. Consequently, the use of insecticide-treated bag packaging received early interest as a possible alternative to direct treatment of grains. Highland and Cline (1986) tested polypropylene plus polybutylene packaging films that were treated with the pyrethroid permethrin, and found that film penetration varied according to the tested insects. The authors reported that *Cadra cautella* (Walker), the almond moth, was able to penetrate the film only after 24 months, by which time the insecticide could have dissipated so that larvae were able to penetrate the bag. Moreover, *Lasioderma serricorne* (F.), the cigarette beetle, and *Tribolium castaneum* (Herbst), the red flour beetle, could not penetrate the film, while *Rhyzopertha dominica* (F.), the lesser grain borer, was able to penetrate 19% of the treated

72 films. However, investigation of treated packaging lapsed and little recent research has been
73 conducted in this area.

74 Long-lasting insecticide treated nets (LLINs) have been widely used in several parts
75 of the world as means of protection against mosquito species that transmit malaria, and
76 several case studies describe beneficial results of using them to limit disease transmission.
77 Gimnig et al. (2003) showed that the resting densities of *Anopheles gambiae* (Giles),
78 *Anopheles funestus* (Giles), both identified by the common name of African malaria
79 mosquito, were 38.8% and 94.5% less in houses with permethrin-treated bed nets than in
80 control treatments in Kenya. In the same study, the authors found that the transmission of the
81 *Plasmodium falciparum* (William H. Welch), which causes malaria in humans, was 90% less
82 in areas where the insecticide-treated nets were used than in controls. Killeen et al. (2007)
83 reported that the use of insecticide-treated nets would potentially protect 15-20% of children
84 and women who were pregnant in Africa. The utilization of insecticide-treated nets can also
85 change the population density and structure of certain mosquito species (Bayoh et al. 2010,
86 Russell et al. 2011).

87 There are limited data regarding the potential of long-lasting incorporated materials to
88 control stored product insects. One recent example is the use of impregnated nets for the
89 protection of stored tobacco (Msango and Longwe, 2013). In that study, the authors examined
90 the long-term effects of a net which was impregnated with the pyrethroid alpha-cypermethrin,
91 for control of *L. serricorne* in Malawi. They showed that during a 13-week interval, the
92 number of *L. serricorne* adults on the tobacco that was covered with the net was continuously
93 lower than that on uncovered tobacco. Kim et al. (2013) developed insect resistant packaging
94 films that contained microcapsule powder of cinnamon oil and whey protein
95 isolate/maltodextrine or microcapsule emulsion of cinnamon oil and polyvinyl alcohol. These
96 films repelled larvae of *Plodia interpunctella* (Hübner), the Indianmeal moth.

Vestergaard S.A. (Lausanne, Switzerland), has developed bed nets impregnated with the pyrethroid deltamethrin to control mosquitoes (PermaNet® 2.0) and also a long lasting insecticide-incorporated screen for outdoor use to protect livestock from biting insects (D-Terrence®/ ZeroFly® Screen). This incorporation technology has been adapted as a packaging treatment to potentially protect stored grains from insect damage (ZeroFly® Storage Bags). The objective of this study was to determine times required for knockdown and/or mortality of adult stored-product beetles when exposed to the fabric comprising these bags. The delayed mortality of these beetles was also evaluated after their removal from the bags.

2. Materials and Methods

2.1. Insects

Species used as test insects in this study were adults of *Trogoderma variabile* (Ballion), the warehouse beetle, *Prostephanus truncatus* (Horn) the larger grain borer, *R. dominica*, *T. castaneum*, *Sitophilus oryzae* (L.), the rice weevil, *Sitophilus zeamais* (Motschulsky), the maize weevil, and *Dermestes maculatus* (De Geer), the hide beetle. All insects were maintained at the USDA-ARS-Center for Grain and Animal Health Research (CGAHR), Manhattan, KS, USA. The *D. maculatus* colony originated from a field collection in 2009, and all other species had been maintained in culture at CGAHR for more than 30 years. *D. maculatus* was reared on ground dog food (Purina Lamb and Rice Dog Food, Purina®, St. Louis, MO, USA), inside a chamber set at 30 °C and 70% relative humidity (r.h.) in continual darkness. A Bunn Coffee Mill Model G3 HD set to extra fine ground (Bunn-O-Matic Corporation, Springfield, IL, USA) was used to grind the dog food. The *T. variabile* were reared on a diet of 1/3 organic protein shake mixed with 2/3 of the commercial dog food ground as described above, and reared inside the chamber with *D. maculatus*. The *S. oryzae* and *R. dominica* were reared on a mixture of 95% whole wheat and 5% cracked wheat, *S.*

zeamais and *P. truncatus* were reared on whole maize, and *T. castaneum* was reared on wheat flour plus 5% brewer's yeast (by weight). All these species were reared in incubators set at 27 °C and 60% r.h. Adults of *T. variable* used in the study were <1 week old, while adults of all other species were 1-2 weeks old.

2.3. Bioassays

ZeroFly[®] Storage Bags, a woven polypropylene bag designed for post-harvest storage of commodities, were used in the tests. The insecticide deltamethrin was incorporated into the individual yarns during the extrusion process of manufacturing at an approximate concentration of 3g/kg or 3,000 parts per million (ppm). An individual treatment arena (replicate) consisted of circular pieces of a bag cut to fit the bottom of a plastic Petri dish (9 cm diameter by 1.5 cm high), with a bottom surface area of 62 cm². Either the inside or the outside surface of a bag was affixed face up to the bottom of the arena with white adhesive caulk (DAP Kwik Seal[®], DAP Products Inc., Baltimore, MD, USA). The internal sides of an arena were coated with Fluon[®] (polytetrafluoroethylene, Northern Products, Woonsocket, RI, USA) to prevent escape of the insects.

The experiment was carried out in a completely randomized block design, with three blocks of three replicates each for a total of nine replicates per treatment combination for each of the seven species and for the outside and inside surfaces of the bags (7 species x 3 replicates x 3 sub-replicates x 2 surfaces = 126 arenas). Ten adults from each of the above species were exposed in an individual dish for 60, 120, 180 min, 1, 3 and 5 d, and at each of those times insects were classified as alive (active and running), knocked down (on their backs and unable to right themselves) or dead (unable to move when prodded). These assessments were made using a stereomicroscope, and all observation times (days) were conducted on the same arena (repeated measure). All arenas were initially placed in a chamber set at 27.5 °C and 65% r.h. and continuous darkness, then they were removed and

taken to the laboratory for the assessments. When the assessments were done they were returned to the incubators until the test was completed.

After the 5 d interval the insects were removed and placed in new arenas that had been prepared by using a driveway patching material (Rockkrite[®], Hartland Products, Cleveland, OH, USA). This material is mixed with water to create a liquid slurry, which was then poured into an individual arena to a depth of about 1.25 mm. The arenas were allowed to dry on a laboratory counter for several days before the transfer of insects after the 5-day assessments. The sides of these arenas were also coated with Fluon. After the transfer the insects were held for 5 d more, and then on termination of this interval the insects were classified again as alive, knocked down, or dead.

Untreated ZeroFly[®] Storage Bags are not manufactured, due to possible contamination issues, and thus were not available to use as controls. Hence, for untreated controls for the initial assessments from 1 hr to 5 d, a total of 63 untreated concrete arenas (7 species x 3 replicates x 3 sub-replicates) were used as controls for each species. These controls were held in the same chamber as the treatments, removed and assessed in the same manner as described above. After the termination of the 5 d interval the insects in the untreated controls were removed and placed in new untreated concrete arenas as described above for the treatments.

2.4. Data Analysis

There was negligible overall knockdown (0% for all seven species) or mortality (4.4, 4.4, 3.3, 4.4, 0.0, 0.0% for *T. variabile*, *P. truncatus*, *R. dominica*, *S. oryzae*, *T. castaneum*, *S. zeamais*, and *D. maculatus*, respectively) in untreated controls, hence the values for the controls were not included in the analyses. The results for the number of individuals that were knocked down, or dead was converted to a percentage value based on the original 10 in the arena, and these results were analyzed separately for each of the tested species according to

the repeated-measures model (Sall et al., 2001), with time (exposure) as the repeated factor while the percentage of knocked down, or dead were the response values. Surface of the storage bags was the main effect. All analyses were conducted using JMP 10 software (SAS Institute Inc., 2012). Means were separated by the Tukey-Kramer Honestly Significant Difference (HSD) at the 5% level (Sokal and Rohlf, 1995). Where possible, curves were fit to the data using Table Curve 2D software to determine the proper equations to use (Version 5.01, SPSS Inc., Chicago, IL, USA). Mean values and curve-fit lines were plotted using Sigma Plot (Version 11.0, SPSS Inc., Chicago, IL, USA).

3. Results

For immediate knockdown between exposure intervals, the surface of the bag (inside versus outside) was significant for all species except *T. castaneum* (Table 1). Within exposure intervals, exposure was significant for all species except *T. castaneum* and *D. maculates*, exposure x surface of the bags was significant for *P. truncatus*, *S. oryzae*, and *S. zeamais*. For immediate mortality, between exposure intervals, surface of the bags was significant for *D. maculatus*, *S. zeamais*, *R. dominica* and *P. truncatus* (Table 2). Within exposure intervals, exposure was significant for *S. oryzae*, *R. dominica*, *P. truncatus* and *T. variable*, and exposure x surface of the bags was significant for *P. truncatus* (Table 2).

Species are arranged in order of susceptibility, as determined by a combination of knockdown and mortality during the 5-day exposure period. All *T. variable*, *P. truncatus*, *R. dominica*, and *T. castaneum* were knocked down after the 1-hr exposure interval, hence only the values for mortality are reported, as they are the inverse of knockdown. The most susceptible species of those tested appeared to be *T. variable* (Fig. 1A). Mortality on both the inside and outside bag surface gradually increased during the 5-day holding period, and non-linear equations were fit to the mortality data to show the relationship between the dependent variable, % mortality, and the independent variable, exposure time. After 3 and 5 days of

exposure >82% of adults were dead on both surfaces of the bags, with no significant differences in mortality between the two bag surfaces at any of the exposure intervals.

The next species in order of decreasing susceptibility was *P. truncatus*. Linear equations were fit to the data for mortality on the outside and inside surfaces, but mortality at 3 and 5 days on the outside surface was $27.4 \pm 6.4\%$ and $94.4 \pm 1.8\%$, respectively, and greater than the corresponding mortality on the inside surface, $33.3 \pm 4.4\%$ and $62.2 \pm 4.4\%$, respectively (Fig. 1B). Non-linear curves were fit to the mortality data for the next species, *R. dominica* (Fig. 1C), with greater mortality on the outside surface at 3 and 5 days, $26.7 \pm 6.0\%$ and $58.9 \pm 7.5\%$ and compared to $10.0 \pm 2.9\%$ and $38.9 \pm 4.6\%$, respectively, on the inner surface. In contrast to the above species, maximum mortality of *T. castaneum* on either bag surface during the 5-day exposure period was $5.6 \pm 3.4\%$ (Fig. 1D), even though there was 100% knockdown after the 1-hour-exposure interval.

Data % knockdown of *S. oryzae* and *S. zeamais* are plotted separately for the 1, 2, and 3 hour exposure periods, and the 1, 3, and 5-day exposure periods because the inverse of knockdown at the 1-3 hour exposures is % active, while the inverse of knockdown at 1-3 days is the % dead. About 12x more *S. oryzae* were knocked down after 1-hour on the outside versus the inside of the bag ($85.6 \pm 3.4\%$ versus $6.7 \pm 3.3\%$), but this was the only interval where there was a significant difference between the bag surfaces (Fig. 2A). By 5 days mortality was 100% on both surfaces (Fig. 5B). In contrast, there was little knockdown of *S. zeamais* on the inside compared to the outside of the bag at 1-3 hours, and was always less than knockdown on the outside surface (Fig. 2C). Even after 5 days, knockdown on the inside of the bag was only $30.0 \pm 5.8\%$ compared to $90.0 \pm 4.7\%$ on the outside of the bag, and all comparisons were significant (Fig. 2D). Most of the adults on the outside of the bag were still in the knockdown stage after 5 days, contrary to the 100% mortality of *S. oryzae* after 5 days on both surfaces.

The most tolerant species was *D. maculatus*, with no knockdown or mortality at any time on the inside surface, hence only data for exposures on the outside surface are reported. The percentage of active beetles at 1-3 hours was 97.7%, with a corresponding 2.3% knockdown, and no mortality (Fig. 3A). There was a slight decrease in percentage active after 5 days, with some knockdown and mortality (Fig. 3B).

The delayed mortality of all species, which was assessed 5 days after they were removed and transferred to untreated concrete arenas, is shown in Fig. 4. Since mortality of *S. oryzae* was 100% at the conclusion of the 5-day exposure interval, this species is not depicted. There was no additional knockdown of *T. variable*, while knockdown of all species except *D. maculatus* decreased because individuals that were knocked down after 5 days died sometime during the time after they were transferred to new untreated arenas (Fig. 4 AB). Nearly all *P. truncatus* and *R. dominica* had died. The primary reason that there were more dead *R. dominica* on the inside versus the outside of the bag is that more were dead on the outside versus the inside of the bag after the original 5-day exposure. Similarly, *T. castaneum* began to transition from being knocked down to dead, which meant there was no recovery from knockdown after they were moved to the new untreated arenas. The *S. zeamais* that were knocked down after the 5-day exposure also began dying after the transfer to the untreated arenas, again indicating delayed mortality and no recovery from knockdown. There was little delayed knockdown or mortality with *D. maculatus* (Fig. 4AB).

4. Discussion

Previous studies have shown the effectiveness of deltamethrin on various surfaces and on stored grains. Arthur (1997) reported that all adults of *R. dominica* were dead after 1 or 2 days of exposure on the same surfaces for 22 weeks. Athanassiou et al. (2004) showed that deltamethrin was able to provide sufficient control of *S. oryzae* on stored wheat for at least three months, with adult mortality of >80% at an application rate of 0.25 ppm. In a recent

residual study, Ghimire et al. (2016) found that deltamethin was very effective against the larger cabinet beetle, *Trogoderma inclusum* (LeConte), adults on a concrete surface, with mortality of >85% for a 3-month period at application rates of 16 or 24 mg of active ingredient (AI)/m². However, recently, Kavallieratos et al. (2015) reported that deltamethrin provided poor mortality after short exposures to a calculated application rate of 0.5 ppm on treated rice, against different stored-product insect species, while there was no residual effect. Our results show that, for the bags tested here, efficacy varied according to the target species, but also according to the exposure interval and the surface of the bags on which the insects were exposed.

This study is also the first in many years to report data for susceptibility of *D. maculatus* to insecticides. In an early study, Lloyd and Dyte (1965) and Wheatley (1971) reported that the organochloride dieldrin and the organophosphate phoxin were effective against this species as topical application and application on calf hide, respectively. Later, Macquillan and Shipp (1976) showed that the organophosphates chlorpyrifos and chlorpyrifos-methyl caused >90% mortality of *D. maculatus* adults and larvae for a 2-month post treatment on treated sheepskins. Golob et al. (1987) also found that a formulation which contained deltamethrin plus piperonyl butoxide (PBO) was able to protect dried fish from *D. maculatus* for at least 6 months after treatment, and that this insecticide was better than fenitrothion, pirimiphos-methyl, iodofenphos, pyrethrins and diflubenzuron. However, Athanassiou et al. (2013) found that the pyrethroid beta-cyfluthrin in combination with the neonicotinoid imidacloprid were unable to provide satisfactory control of *D. maculatus*, after 7 days of exposure on treated concrete. In the present study, the bags were not able to control this species, even after the highest exposure interval. Moreover, there was no delayed mortality after the removal of the exposed adults from the treated substrate. The same parent strain of *D. maculatus* was used in the current study and in Athanassiou et al. (2013). One

possible explanation for this result is that all other species used in this test were from colonies that had been reared in the laboratory for more than 30 years, while the *D. maculatus* strain was collected in 2009. We have no knowledge of the history of insecticide exposure of this particular population. Thus, it may be necessary to conduct additional tests with *D. maculatus* before forming strong conclusions regarding the efficacy of deltamethrin against this species.

In contrast, though mortality of *S. zeamais* was also low in comparison to other species, knockdown and mortality increased even after the adults were removed from the exposure arena and placed in untreated arenas. Athanassiou et al. (2010) examined short exposures of *R. dominica* to spinosad-treated maize or wheat and found that although immediate mortality was low at 120 or 240 min, all exposed individuals were dead after a week, indicating complete delayed mortality. However, in the current test, even though there was 100% knockdown of *T. castaneum* after 1 hour in the current test, more than one half of the exposed individuals were still alive at the post-exposure period. Thus, for this species longer exposure intervals may be needed, but the fact that no exposed adults recovered after they were removed from the treated arenas indicates that a longer post-exposure observation period may have yielded 100% delayed mortality. Arthur (1997) found that >90% *T. castaneum* adults knocked down or died after 1 d of exposure on concrete, plywood and tile that had been treated with 3.54 g/m² of a dust formulation of deltamethrin for a 20-weeks period, indicating that the type of deltamethrin formulation may play a role in efficacy (Giga and Canhão, 1991).

Sitophilus oryzae appears to be highly susceptible to deltamethrin. For example, Arthur (1994) reported that the mortality of *S. oryzae* adults ranged from 73.8 to 95.3% on wheat treated with 0.75 or 1 ppm deltamethrin respectively. Moreover, *T. variable* was also very susceptible to deltamethrin. Kavallieratos et al. (2015) noted that deltamethrin did not prevent progeny production of this species on rice at the current label rate of 0.5 ppm. Our

results indicate that deltamethrin is probably more effective against *T. variabile* adults on surfaces than as a grain protectant. Similarly, Ghimire et al. (2016) found all *T. variabile* adults were dead on concrete treated with 8 mg deltamethrin/m² at a 2-month post-treatment assay.

Deltamethrin is also an effective grain protectant for *P. truncatus*. Richter et al. (1998) found that deltamethrin (1 mg/kg) successfully controlled that species since only 2 live adults were found after 8 months on maize that had been treated with 50 g of dust insecticide/100 kg grain. Also, in a laboratory study, Pozidi Metaxa and Athanassiou (2013) reported that deltamethrin killed all exposed *P. truncatus* adults on maize treated with 0.5 ppm deltamethrin after 7 d at 25 and 30°C. Furthermore, no offspring production was recorded on the treated substratum at temperatures ranging from 20 to 30°C. According to Giga and Canhão (1991), deltamethrin was very effective against *P. truncatus* adults on different types of surfaces, i.e., glass, jute and wood for a period >18 months. *P. truncatus* along with *S. zeamais*, are major threats for stored maize in Africa (Holst et al., 2000), so the use of impregnated bags for storage purposes may provide a satisfactory level of control for both species. This is particularly important in the case of *P. truncatus*, as this species can easily bore holes in plastic (Ramirez Martinez and Silver, 1983; Hodges, 1986), which means that adults of *P. truncatus* may be able to penetrate untreated bags used to protect stored grains and infest the product. Although we did not take quantitative measurements, we observed that *P. truncatus* adults were able to create numerous holes in the plastic bags that were used as controls. But, given the delayed mortality observed in our study, even if *P. truncatus* were able to chew through the Zerofly[®] Storage bags, they could potentially absorb enough of the insecticide to eventually die. About 50% of *R. dominica* adults were dead during the exposure period in the current study, but mortality was high at the post-exposure period. This species is known to be susceptible to deltamethrin either as a grain protectant or

as surface treatment (Arthur, 1997; Daglish, 1998; Sehgal and Subramanyam, 2014). Also, as for *P. truncatus*, *R. dominica* is able to bore holes in plastic films (Riudavets et al., 2007).

One of the most interesting findings of the present study is the dissimilar performance of the two surfaces of the bags. This was unexpected because during the manufacturing process, the treated yarns are uniformly incorporated into the fabric matrix. Also, the texture of both surfaces is similar. This result has not been reported in other tests discussed above with treated fabrics. However, our results seem to indicate that the amount of insecticide may be greater on the outside compared to the inside surface. Given that the newly-harvested grains can be infested after storage (Hagstrum, 1989; Vela Coiffier et al., 1997; Hagstrum, 2001), the storage bags could serve as a barrier between the grain and stored-product insect pests (Sbardelotto Di Domenico et al., 2015). From a practical point of view, if there is a quantity of bulked grain that has been stored for longer period and is planned to be placed in insecticide-incorporated bags, the grain should be fumigated first to eliminate any internal infestation. This approach is also recommended on the label of the product by the manufacturer, and a disclaimer is printed on the bags, indicating for the best efficacy of the product grain/seed must be insect free prior to filling the bags.

Under the scenario tested here, for many species, the bags are effective, as they were toxic to adults, even after the termination of their contact with the plastic. After the contact with the treated plastic, knockdown was, for most species, fast, and in certain cases, knockdown resulted in delayed mortality. In a storage facility, knockdown often stops the contact of the insect with the toxic agent, and recovery can occur (Tyler and Binns, 1982; Arthur, 1999; Kavallieratos et al., 2016). However, in our study, we found that bags impregnated with deltamethrin did result in increased delayed mortality, instead of recovery, with few exceptions. Although not a new technique in insect control, incorporated packaging

346 materials are likely to play an increasingly important role in the near future for protection of
347 raw and processed durable products.

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Table 1

Repeated measures MANOVA parameters for immediate knockdown of *T. variabile*, *P. truncatus*, *R. dominica*, *T. castaneum*, *S. oryzae*, *S. zeamais* and *D. maculatus* adults (error df = 16 for all species).

	All between variables					
	Intercept			Surface of the bags		
Insect species	df	F	P	df	F	P
<i>T. variabile</i>	1	1183.0	<0.01	1	4.9	0.04
<i>P. truncatus</i>	1	5496.2	<0.01	1	27.6	<0.01
<i>R. dominica</i>	1	3464.1	<0.01	1	12.5	<0.01
<i>T. castaneum</i>	1	20277.8	<0.01	1	0.6	0.44
<i>S. oryzae</i>	1	3618.0	<0.01	1	141.1	<0.01
<i>S. zeamais</i>	1	1605.4	<0.01	1	997.8	<0.01
<i>D. maculatus</i>	1	20.3	<0.01	1	20.3	<0.01
	All within variables					
	Exposure			Exposure x surface of the bags		
	df	F	P	df	F	P
<i>T. variabile</i>	5	142.7	<0.01	5	1.1	0.42
<i>P. truncatus</i>	5	139.2	<0.01	5	6.2	<0.01
<i>R. dominica</i>	5	25.1	<0.01	5	2.1	0.14
<i>T. castaneum</i>	5	0.8	0.60	5	0.8	0.60
<i>S. oryzae</i>	5	124.2	<0.01	5	45.6	<0.01
<i>S. zeamais</i>	5	11.4	<0.01	5	4.3	0.02
<i>D. maculatus</i>	5	0.5	0.74	5	0.5	0.74

Table 2

Repeated measures MANOVA parameters for immediate mortality of *T. variabile*, *P. truncatus*, *R. dominica*, *T. castaneum*, *S. oryzae*, *S. zeamais* and *D. maculatus* adults (error df = 16 for all species).

	All between variables					
	Intercept			Surface of the bags		
Insect species	df	F	P	df	F	P
<i>T. variabile</i>	1	892.0	<0.01	1	2.8	0.11
<i>P. truncatus</i>	1	458.7	<0.01	1	26.2	<0.01
<i>R. dominica</i>	1	87.4	<0.01	1	12.5	<0.01
<i>T. castaneum</i>	1	2.3	0.15	1	2.3	0.15
<i>S. oryzae</i>	1	819.0	<0.01	1	2.0	0.18
<i>S. zeamais</i>	1	5.7	0.03	1	5.7	0.03
<i>D. maculatus</i>	1	5.5	0.03	1	5.5	0.03
	All within variables					
	Exposure			Exposure x surface of the bags		
	df	F	P	df	F	P
<i>T. variabile</i>	5	114.0	<0.01	5	1.2	0.35
<i>P. truncatus</i>	5	138.4	<0.01	5	6.1	<0.01
<i>R. dominica</i>	5	25.1	<0.01	5	2.1	0.14
<i>T. castaneum</i>	5	0.6	0.70	5	0.6	0.70
<i>S. oryzae</i>	5	12.6	<0.01	5	0.3	0.91
<i>S. zeamais</i>	5	0.9	0.53	5	0.9	0.53
<i>D. maculatus</i>	5	0.8	0.56	5	0.8	0.56

Figure Captions

Fig. 1. Percentage mortality (means $\pm$ SE) of *T. variabile*, *P. truncatus*, *R. dominica*, and *T. castaneum* on the outside (solid inverted triangle) and inside (clear inverted triangle) surface of deltamethrin-impregnated storage bags. Asterisks above the mean for the outside surface denote a significant difference ($P < 0.05$) in mortality compared to the inside surface at the 3 or 5-hour post-exposure interval. Curve-fit lines for mortality data for outside and inside surface denoted with dashed and dotted lines, respectively.

Fig. 2. Percentage knockdown (mean $\pm$ SE) of *S. oryzae* exposed on the outside (solid bar) and inside (light bar) surface of deltamethrin-impregnated storage bags, at the 1-3 hour exposure intervals (A) and the 1-5 day exposure intervals (B), and the same for *S. zeamais* (C and D, respectively). The inverse of knockdown at the 1-3 hour intervals is percentage active, the inverse of knockdown at the 1-5-day intervals is mortality. Asterisks above the means for the outside surface denote a significant difference ($P < 0.05$) in knockdown compared to the inside surface at both sets of exposure intervals.

Fig. 3. Percentage of *D. maculatus* active and running (black bar) and knocked down (grey bar) (means $\pm$ SE) after 1-3 hours of exposure on the outside surface of deltamethrin-impregnated storage bags (A), and percentage active and running (black bar), knocked down (light grey bar), and dead (solid grey bar) (means $\pm$ SEs) after 1-5 days of exposure on the outside surface of deltamethrin-impregnated storage bags (B). None knocked down or dead when exposed on the inside surface of the bag.

Fig. 4. Percentage of knockdown (A) *T. variabile* (T.v.), *P. truncatus* (P.t.), *T. castaneum* (T.c.), *S. zeamais* (S.z.), and *D. maculatus* (D.m.) (means $\pm$ SEs) 5 days after removal from the treated arenas with the deltamethrin-impregnated bags to the untreated arenas, and percentage mortality (B). Mortality of *S. oryzae* was 100% after the 5-day exposures. The

519 dark and light bars are means for insects exposed on the outside and inside surfaces,
520 respectively.

Figure

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