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Degradation and residual efficacy of beta-cyfluthrin as a surface treatment for control of *Tribolium castaneum* Herbst: Effects of temperature and environment

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ABSTRACT

Concrete arenas were treated with the low and high label rates of beta-cyfluthrin Tempo SC Ultra® (10 and 20 mg Active Ingredient [AI]/m^2, respectively) and stored during the summer and autumn in two separate years inside an empty grain bin, inside a rice mill, and inside a laboratory at an approximate ambient temperature of 27 °C. Bioassays were conducted by removing the arenas at 0 (1 day) to 10 weeks post-treatment from the three locations where they were stored, and exposing adults of *Tribolium castaneum* (Herbst), the red flour beetle, for 0.5−3 h on the arenas. Rapidity of knockdown was used to assess residual efficacy. Application rate was significant ($P < 0.05$) for rapidity of knockdown for the summer storage period but not for autumn ($P \geq 0.05$). As the weeks progressed during summer, knockdown was progressively slower during the 0.5 to 3-h exposure period on arenas held inside the grain bin compared to the arenas inside the rice mill and the laboratory. During autumn the order was reversed for the grain bin and laboratory as the weeks progressed but at 10 weeks knockdown after 3 h was still much less on arenas held inside the bin and mill compared to the laboratory. Extreme high temperatures in the grain bin during the summer, and the fluctuating temperatures during autumn, may have promoted residual degradation on arenas held in the bin and mill compared to the constant temperatures in the laboratory. Results show that residual persistence of contact insecticides for control of stored product insects may be less on treated surfaces outside of a laboratory setting, and caution is warranted when predicting time periods for residual efficacy in sites that are outside of research laboratories with stable environmental conditions.

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1. Introduction

Recent studies have documented the prevalence of stored product insects in and around grain storage and processing facilities in the United States (US) (Campbell and Mullen, 2004; Semeao et al., 2013; Tilley et al., 2017). Insect infestations can be present in residual grain left in bins and elevator silos, while resident populations of various species, including pests associated with raw grains, such as *Rhizopertha dominica* (Fab.), the lesser grain borer, and *Sitophilus* species, along with secondary pest species, can be found as well (Reed et al., 2003; Arthur et al., 2006). Insect species associated with milling and processing facilities include *Plodia interpunctella* (Hübner), the Indianmeal moth, and flour beetles of the genus *Tribolium*, which can be found throughout the warmer months of the year (Campbell et al., 2010a,b; Buckman et al., 2013; McKay et al., 2017; McKay et al., 2019). Cleaning and sanitation are recommended to help eliminate food sources for resident populations, along with pre-binning contact insecticides applied to the concrete or metal flooring of storage bins and silos. Residual treatments inside mills and processing plants can also be part of integrated pest management (IPM) programs to control stored product insects.

The pyrethroid insecticide beta-cyfluthrin (Tempo SC Ultra®) is one such residual insecticide registered in the US as a general surface treatment to flooring surfaces, at two label rates, 10 and 20 mg active ingredient [AI]/m^2 (Arthur et al., 2015). Beta-cyfluthrin has excellent residual persistence on different flooring surfaces, though generally residual persistence is greater on non-

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porous surfaces compared to porous surfaces such as concrete (Arthur et al., 2018). In addition, studies with *Tribolium castaneum* (Herbst), the red flour beetle, and *Tribolium confusum* Jacqueline duVal, the confused flour beetle, show that survival increases when adults are given food material during or after exposure to beta-cyfluthrin and other contact insecticides applied to treated surfaces (Athannasiou et al., 2013; Arthur, 2013, 2015). The presence of extraneous material reduced residual efficacy of older trade formulations of cyfluthrin, as evidenced by results from studies with the cyfluthrin wettable powder (WP) and emulsifiable concentrate (EC) formulations (Arthur, 2000). These formulations were replaced by Tempo SC Ultra®, which has the beta isomer of cyfluthrin along with a lower percentage of active ingredient compared to the previous WP and EC formulations (Arthur et al., 2015).

In the previous Arthur et al. (2015) study that included an assessment of impact of accumulated rice milling residues on beta-cyfluthrin efficacy, time to knockdown of *T. castaneum* on the concrete surfaces, referred hereafter as rapidity of knockdown, was used as a criterion for efficacy evaluation along with measurements of insect recovery after knockdown or eventual mortality. This approach utilizing rapidity of knockdown could be useful to mimic applications in a natural situation where exposed adult insects may have an opportunity to escape a treated surface, therefore time to knockdown or incapacitation is a realistic measure of residual efficacy. Also, in this previous test, rapidity of knockdown at various post-treatment intervals on the concrete surfaces held inside two rice mills was greatest for one summer trial compared to two autumn trials.

As beta-cyfluthrin is also used as a residual treatment for grain bins, additional data are needed to determine how this insecticide will perform in different environments. Therefore, the purpose of this study was to determine: 1) The residual efficacy of beta-cyfluthrin applied at the low and high label rates on concrete treatment arenas held at different locations and environmental conditions, and 2) The impact of temperatures during summer versus autumn on residual efficacy. For both objectives, rapidity of knockdown was used as the assessment criterion.

2. Materials and methods

2.1. General information

This study was conducted for two years, 2015 and 2016, with separate tests done during summer and autumn of each year, under the direction of personnel at Arkansas State University (A-State), Jonesboro, AR, USA. The individual exposure arena was the bottom portion of plastic Petri dish, which had an approximate total area of 62 cm^2. A driveway patching material, Rockite (Hartline Products, Cleveland OH, USA), was used to create a concrete surface inside each dish (hereby termed arenas). This process has been described in detail in a several previous publications (Arthur et al. 2015, 2018). Briefly, it involves mixing the dry concrete with water to create a liquid slurry, which is poured to an approximate depth of about 1.25 cm inside each arena. The test insects were unsexed one-two-week old *T. castaneum*, obtained from stock cultures reared at A-State, in a Percival Incu set at about 27 °C in total darkness except when lights were turned on, on a diet of 95% whole-wheat flour and 5% Brewer's yeast. The insects originated from a pesticide-susceptible laboratory strain at the USDA-ARS Center for Grain and Animal Health Research, where it had been in culture for more than thirty years.

2.2. Treatment procedures

The first set of experiments were conducted in summer of 2015, using three different locations where arenas were held: inside a lab at A-State, on the floor of an unused grain bin outside of a rice mill, and inside the rice mill. The insecticide used in the test was the pyrethroid beta-cyfluthrin (Tempo SC Ultra®, obtained from Bayer Corporation (Bayer, RTP, NC, USA). The insecticide has two rates specified on the product label, either 8 or 16 ml in 3.8 L of water to cover 94 m^2 (10 and 20 mg of Active Ingredient [AI]/m^2). The equivalent volumetric spray rate for the 62 cm^2 area of the concrete arena was 0.27 ml, which was rounded up to 0.3 ml for ease of application. These two rates (low and high rate, respectively), and controls treated with water only, comprised three treatments. Stock solutions of the two rates were created by formulating 0.1 ml of the low rate in 50 ml of water and 0.1 ml of the high rate in 25 ml of water and applying the 0.3 ml to an arena using a Badger 100 artist's air brush (Badger Corporation, Franklin Park, IL, US), as described for earlier studies with beta-cyfluthrin at A-State (Arthur et al., 2015). There were five replicates for each treatment, and for each of the beta-cyfluthrin rates, separate formulations were mixed for each replicate.

The arenas were treated on 18 June 2015. After the treatment process was completed, the arenas were placed in metal forms in which six holes had been cut to hold the arenas (described in Arthur, 2018). Placement of the arenas in the metal holders was done as follows. For the low rate, the five replicates, and an untreated control, were placed in each of a set of three holders, one for each of the locations, inside the mill, inside the grain bin, and inside the lab. The five replicates for the high rate were placed in a set of three holders in the same manner. For the untreated control replicate, six untreated controls were placed in a holder. Thus, for untreated controls, there were a total of 12 arenas. At each location, a HOBO temperature logger (Onset Computer, Bourne, MA, USA) was placed on the metal holder to record temperature each hour during the residual holding period. Arenas were stored in the respective locations until 24 August.

2.3. Bioassays

At 1 day after treatment the holders from the two field locations were brought back into the lab. Bioassays were conducted by exposing the ten adults from the stock cultures described above, on each arena. Knockdown of adults, as defined as individual insects on their backs and unable to right themselves, or upright but unable to sustain motor movement, was assessed every 30 min for 3 h. After the tests were completed, the arenas were returned to the field sites. The entire process was repeated every two weeks for ten weeks, on the same sets of arenas (repeated measure).

2.4. Subsequent tests

The treatment process was repeated on 10 October 2015 for the autumn tests, and arenas were stored until 6 January 2016. The following year, arenas were treated on 29 June and stored until 6 September for the summer test and treated on 26 October and stored until 11 January 2017 for the autumn test. New treatment arenas were constructed, insecticides were formulated, arenas were treated and placed in the metal holders, and transferred to the holding sites as described above. All bioassay procedures were the same as described above. Temperatures were also recorded during these subsequent storage periods.

2.5. Statistical analysis

Data for both trials during the summer, and both trials during autumn, were combined for analysis, which was done using Mixed Model Procedures in the Statistical Analysis System (SAS version

9.2, SAS Institute, Cary, NC, USA) with bioassay week as a repeated measure. Main effects were treatment, bioassay time, and knockdown at the different 30-min exposure intervals. Individual one-way ANOVA tests were done for the main effects, and means were separated using Tukey's Honestly Significant Difference test at $P < 0.05$, as an option under PROC Mixed in SAS. Graphs were constructed using Sigma-Plot software (Version 13, SPSS, San Jose, CA, USA). Temperature accumulations in the three storage locations were determined by eliminating the times when the arenas were brought into the lab for testing; and summing the temperatures only for the hours when the arenas were inside the grain bin, the mill, and the laboratory. The Means Procedure under SAS was used to determine hours of temperature accumulation above specified thresholds in the summer, and below specified thresholds in autumn in the three locations.

3. Results

3.1. General analysis

There was little or no knockdown of adult *T. castaneum* on untreated arenas at any time during the test, hence these data were eliminated from analysis. Because of the expected increase in knockdown as the exposure intervals progressed in order from 0.5 to 3 h, data for main seasons (summer versus autumn), storage location, knockdown at bioassay weeks, and application rate (low vs high) were analyzed for each of the exposure times. Generally, all main effects were significant at each of the exposure intervals (Table 1). However, when application rate was analyzed with respect to the different seasons, rate was not significant in summer for application rate at exposure times greater than 1.5 h, and there was a general pattern of decreasing significance as exposure time increased (Table 2). Thus, data for application rate was combined for further analysis. All knockdown times were significant for application rate in autumn except 2.5 h (Table 2), hence data for autumn were analyzed separately by application rate in the next series of analysis. Also, because of the extensive data that were collected during the test, the knockdown data at times 1.5 and 2.5 h were then eliminated in the next analysis for both the summer and autumn seasons to focus on differences between location with respect to knockdown.

Table 1
ANOVA statistics for percentage knockdown of adult *T. castaneum* with respect to main effects season (summer vs autumn), bioassay week (0–10), application rate (low vs high rate of beta-cyfluthrin SC Ultra), and location (inside the grain bin, inside the mill, and inside the laboratory). Analyses done for exposure times 0.5, 1, 2, and 3 h.

Time (h)	Effect	*F*	df	*P*
0.5	Season	42.2	1, 697	<0.001
	Week	50.1	5, 697	<0.001
	Rate	22.7	1, 697	<0.001
	Location	11.5	2, 697	<0.001
1.0	Season	14.8	1, 698	<0.001
	Week	122.8	5, 698	<0.001
	Rate	47.5	1, 698	<0.001
	Location	250.1	2, 698	<0.001
1.5	Season	30.7	1, 698	<0.001
	Week	118.8	5, 698	<0.001
	Rate	19.6	1, 698	<0.001
	Location	438.9	2, 698	<0.001
2.0	Season	13.2	1, 698	<0.001
	Week	96.2	5, 698	<0.001
	Rate	4.7	1, 698	= 0.030
	Location	296.7	2, 698	<0.001
2.5	Season	21.0	1, 698	<0.001
	Week	94.1	5, 698	<0.001
	Rate	2.8	1, 698	= 0.096
	Location	225.6	2, 698	<0.001
3.0	Season	10.5	1, 698	<0.001
	Week	87.9	5, 698	<0.001
	Rate	3.0	1, 698	= 0.085
	Location	172.9	2, 698	<0.001

Table 2
ANOVA statistics for percentage knockdown of adult *Tribolium castaneum* at each of the two seasons with respect to main effects bioassay week (0–10), application rate (low vs high rate of beta-cyfluthrin SC Ultra), and location (inside the grain bin, inside the mill, and inside the laboratory). Analyses done for exposure times 0.5, 1, 2, and 3 h.

Time (h)	Season	Effect	*F*	df	*P*
0.5	Summer	Week	65.5	5, 338	<0.001
		Rate	15.6	1, 338	<0.001
		Location	5.6	2, 338	<0.004
1	Summer	Week	74.8	5, 339	<0.001
		Rate	15.7	1, 339	<0.001
		Location	158.8	2, 339	<0.001
1.5	Summer	Week	69.2	5, 339	<0.001
		Rate	5.0	1, 339	= 0.025
		Location	202.8	2, 339	<0.001
2	Summer	Week	54.1	5, 339	<0.001
		Rate	0.7	1, 339	= 0.410
		Location	138.7	2, 339	<0.001
2.5	Summer	Week	51.4	5, 350	<0.001
		Rate	0.6	1, 350	= 0.422
		Location	101.9	2, 350	<0.001
3	Summer	Week	48.8	5, 339	<0.001
		Rate	0.1	1, 339	= 0.7557
		Location	95.5	2, 339	<0.001
0.5	Autumn	Week	4.5	5, 350	<0.001
		Rate	13.9	1, 350	<0.001
		Location	10.2	2, 350	<0.001
1	Autumn	Week	57.3	5, 350	<0.001
		Rate	36.7	1, 350	<0.001
		Location	111.6	2, 350	<0.001
1.5	Autumn	Week	64.3	5, 350	<0.001
		Rate	20.2	1, 350	<0.001
		Location	320.4	2, 350	<0.001
2	Autumn	Week	57.9	5, 350	<0.001
		Rate	5.8	1, 350	= 0.016
		Location	172.1	2, 350	<0.001
2.5	Autumn	Week	66.5	5, 350	<0.001
		Rate	3.8	1, 350	= 0.053
		Location	247.3	2, 350	<0.001
3	Autumn	Week	57.9	5, 350	0.001
		Rate	5.8	1, 350	= 0.016
		Location	172.1	2, 350	<0.001

3.2. Summer analyses

In the first analysis, percentage knockdown of *T. castaneum* is analyzed at each bioassay week by location for exposure intervals of 0.5, 1, 2, and 3 h. Knockdown after 0.5 h of exposure was greater on arenas held inside the laboratory versus the arenas held inside the mill or inside the grain bin at several of the bioassay weeks (Fig. 1A), but knockdown did not exceed 30% except at week 0, 1 day after treatment. When exposure time increased to 1 h (Fig. 1B), knockdown on arenas in the lab was at least 60% at all bioassay weeks, and except for week 0 was at least 2x greater than knockdown on arenas held in the two field sites. After 2 h of exposure knockdown was at least 95% on all arenas at bioassay times of 0 and 2 weeks,

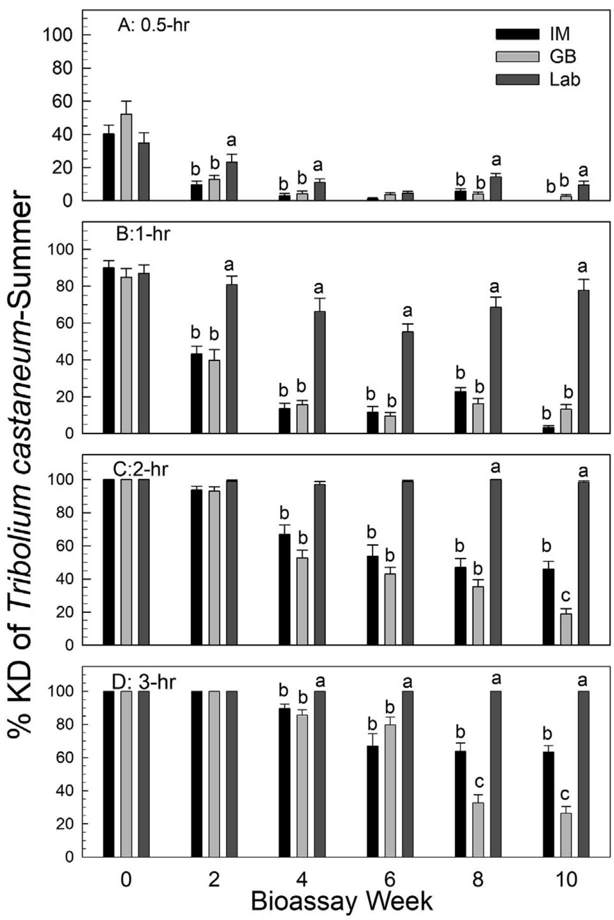

Fig. 1. Percentage knockdown (means ± SE) of adult *T. castaneum* exposed for 0.5, 1, 2, and 3 h (A–D) on concrete arenas treated with the low and high rate of beta-cyfluthrin SC Ultra (10 and 20 mg of Active Ingredient [AI]/m^2), and held inside the rice mill (IM), inside the grain bin (GB), or inside the laboratory (Lab) at Arkansas State University. Bioassays conducted on the arenas at 1 day after treatment (week 0) and 2–10 weeks post-treatment. Separate tests done for two summer testing periods in 2016 and 2017 (see Table 3), data combined for years. Initial analysis showed no significant difference between rates ($P \geq 0.05$, data combined for analysis). Means for location followed by different letters at each time are significantly different ($P < 0.05$).

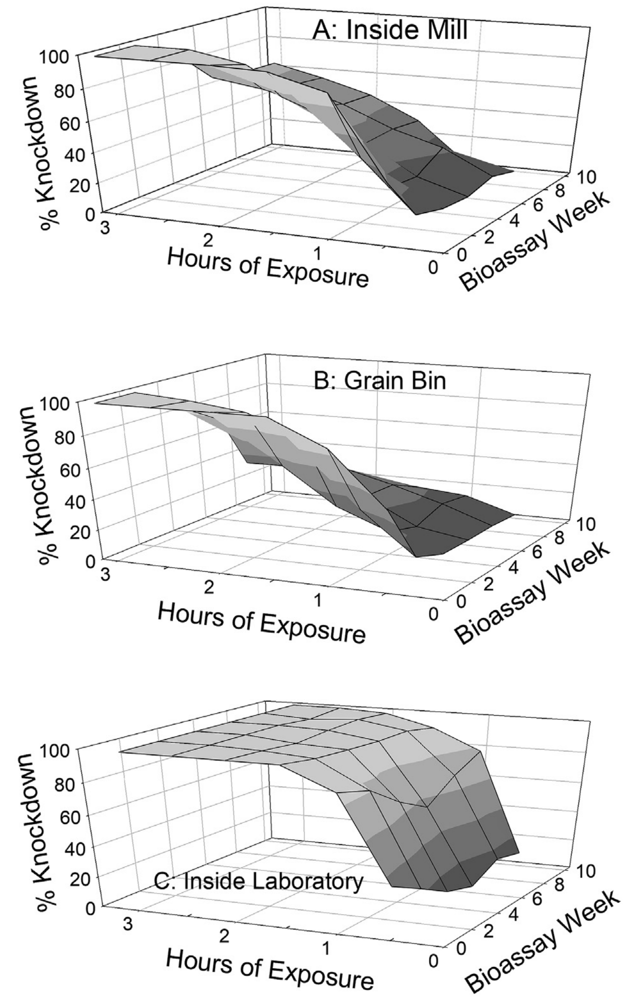

Fig. 2. 3D-response surfaces for knockdown of *T. castaneum* at all exposure intervals (0.5–3 h in 0.5 h increments) (z axis), for treated arenas held inside the mill (A), inside the grain bin (B), or inside the laboratory (C) during summer. Response surfaces generated using mean values for knockdown at each exposure interval (x-axis) and bioassay time (y-axis).

but after this time knockdown percentage began declining on arenas held in the two field sites (Fig. 1C). At week 8 knockdown on arenas held inside the field sites declined and was 2x less than knockdown percentage, and by week 10 knockdown percentage was lower on arenas held inside the bin versus the mill. Knockdown after 3 h was virtually 100% on arenas held inside the lab versus the two field sites, with lower knockdown on arenas held inside the bin versus the mill at the bioassay times of 8 and 10 weeks (Fig. 1D).

It was expected that knockdown on arenas would increase with exposure interval and decrease with bioassay week. This relationship was explained by using 3D response surface analysis rather than by doing statistical tests on ordered sequences. In addition, all data were used for the bioassay times from 0.5 to 3 h in the 0.5 h increments. Response surfaces were constructed using the mean knockdown values at each exposure time-bioassay time combination for the three locations. The response surface for the arenas held inside the mill (Fig. 2A) shows the progressive decline in knockdown with bioassay week even with an increasing exposure interval. The flatter response surface for the arenas held inside the grain bin shows an even worse decline in efficacy, as by week 10 knockdown was only about 20% after the 3-h exposures (Fig. 2B). In contrast to the arenas held inside the two field sites, there is almost no loss in efficacy during the residual testing period for the arenas held inside the laboratory (Fig. 2C), as shown by an almost uniform plane in the response surface with increasing bioassay week. Knockdown was consistently > about 90% after the 2-h exposures for all bioassay weeks.

3.3. Autumn analyses

Knockdown after 0.5 h of exposure on the arenas treated with the low rate of beta-cyfluthrin SC Ultra did not exceed 10% at any time (Fig. 3A), but was increased on all arenas after the 1-h exposures (Fig. 3B). However, there was a different pattern compared to results for the Summer studies, as knockdown on two instances was greater on arenas held inside the mill versus inside the grain bin. On all occasions except week 0 knockdown was greatest at each exposure interval on arenas held inside the laboratory versus the field sites. This pattern continued at the 2-h exposures, as knockdown was 100% on all arenas but from weeks 2–10 the knockdown percentage order was inside mill < bin < laboratory, with knockdown on arenas inside the lab at 95–100% at all exposure times (Fig. 3C). At the 3-h exposures knockdown on arenas was 95–100% at all exposure times and was always greater than knockdown on

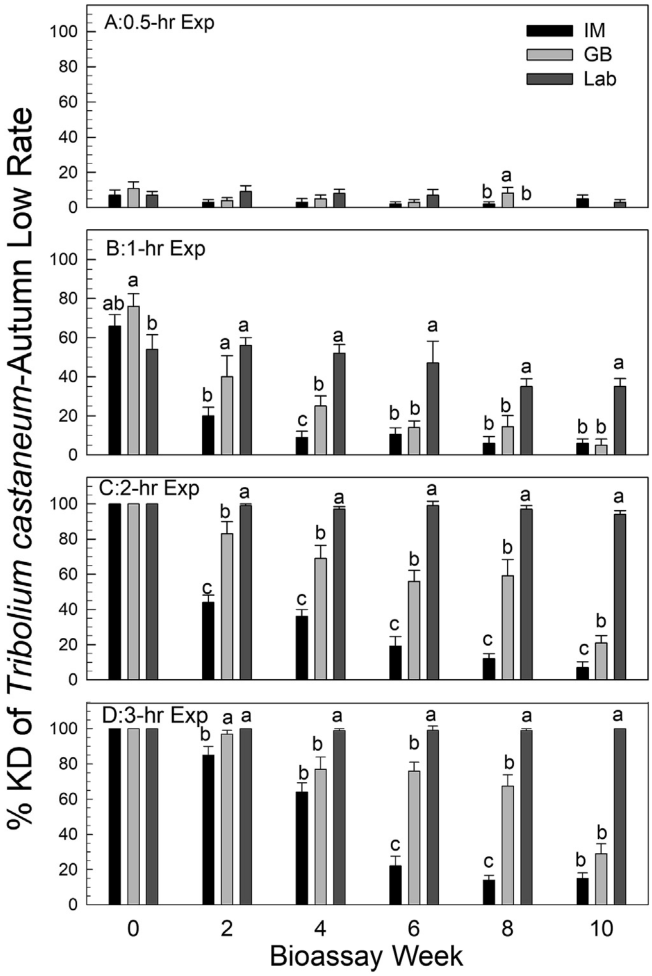

Fig. 3. Percentage knockdown (means ± SE) of adult *T. castaneum* exposed for 0.5, 1, 2, and 3 h (A–D) on concrete arenas treated with the low rate of beta-cyfluthrin SC Ultra (10 mg of Active Ingredient [AI]/m^2),and held inside the rice mill (IM), inside the grain bin (GB), or inside the laboratory (Lab) at Arkansas State University. Bioassays conducted on the arenas at 1 day after treatment (week 0) and 2–10 weeks post-treatment. Separate tests done for two autumn testing periods in 2016 and 2017 (see Table 4), data combined for years. Means for location followed by different letters at each time are significantly different ($P < 0.05$).

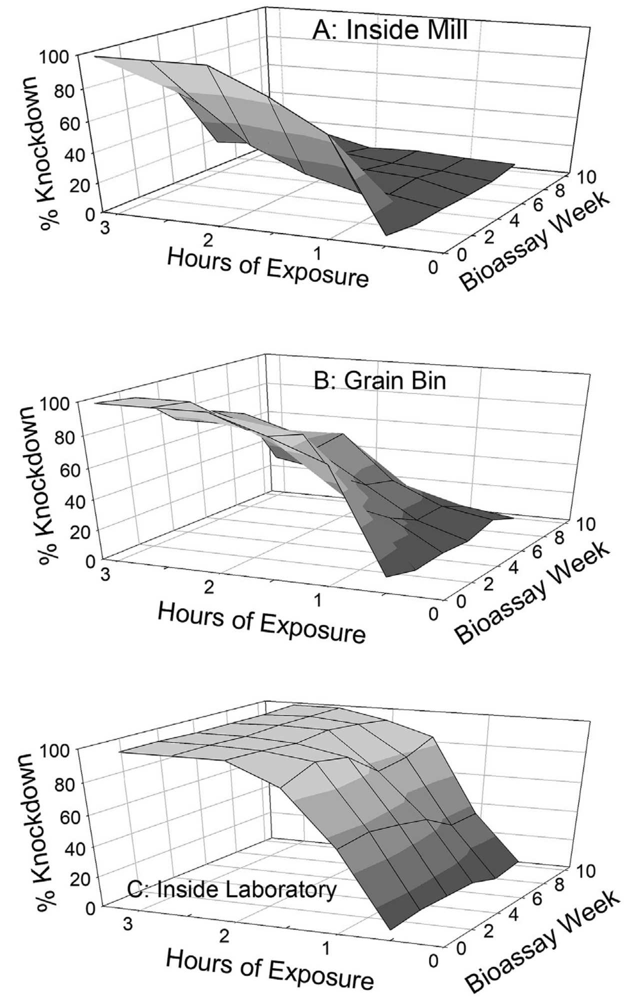

Fig. 4. 3D-response surfaces for knockdown of *T. castaneum* at all exposure intervals (0.5–3 h in 0.5 h increments) (z axis), for arenas treated with 10 mg [AI]/m^2 beta-cyfluthrin SC Ultra and held inside the mill (A), inside the grain bin (B), or inside the laboratory (C) during summer. Response surfaces generated using mean values for knockdown at each exposure interval (x-axis) and bioassay time (y-axis).

arenas held at the two field sites (Fig. 3D).

The flattened response surface as bioassay weeks progressed for the arenas treated with the low rate of beta-cyfluthrin and held inside the mill during autumn (Fig. 4A) indicates a rapid loss in residual persistence, much more than what occurred on the treated arenas held inside the mill during the summer trials. The response surface was not as flat for the arenas held inside the grain bin, which again contrasted with results of the summer trial (Fig. 4B). There is almost no loss in efficacy during the residual testing period for the arenas held inside the laboratory for the autumn trials (Fig. 4C), again indicated by an almost uniform plane in the response surface with increasing bioassay week.

Knockdown after 0.5 h of exposure on the arenas treated with the high rate of beta-cyfluthrin varied during the bioassay weeks but was occasionally >20%, (Fig. 5A). After 1 h the patterns observed for the low rate were evident here as well, with much greater knockdown on the arenas held inside the laboratory versus the two field sites (Fig. 5B). After 2 h knockdown percentage was increased for all three sets of arenas, and the order of knockdown percentage at weeks 4–10 was inside mill < grain bin < laboratory, which was similar to the results for the low rate (Fig. 5C). After 3 h of exposure knockdown percentage was usually 100% on arenas held inside the laboratory regardless of bioassay week, with the same order in percentage knockdown as observed for 2 h (Fig. 5D).

The response surfaces for the high rate of beta-cyfluthrin followed the same general patterns as observed for the low rate, but degradation of residues and decline in efficacy was much more apparent for the arenas held inside the mill (Fig. 6A) versus inside the grain bin (Fig. 6B). Percentage knockdown after 3 h of exposure at week 10 was about 3x less on the arenas held inside the mill versus the grain bin. The response plane for the arenas held inside the laboratory again indicated high persistence of residues and rapid knockdown of exposed *T. castaneum* throughout the 10-week residual testing period (Fig. 6C).

4. Discussion

Pyrethroids are generally considered to be more stable at higher temperatures compared to organophosphates (Noble et al., 1982), but there is also evidence of increased degradation of cyfluthrin at elevated temperatures. Noble and Hamilton (1985) examined breakdown of four isomers of cypermethrin and four isomers of cyfluthrin applied to wheat held at either 25 or 35 °C. They reported

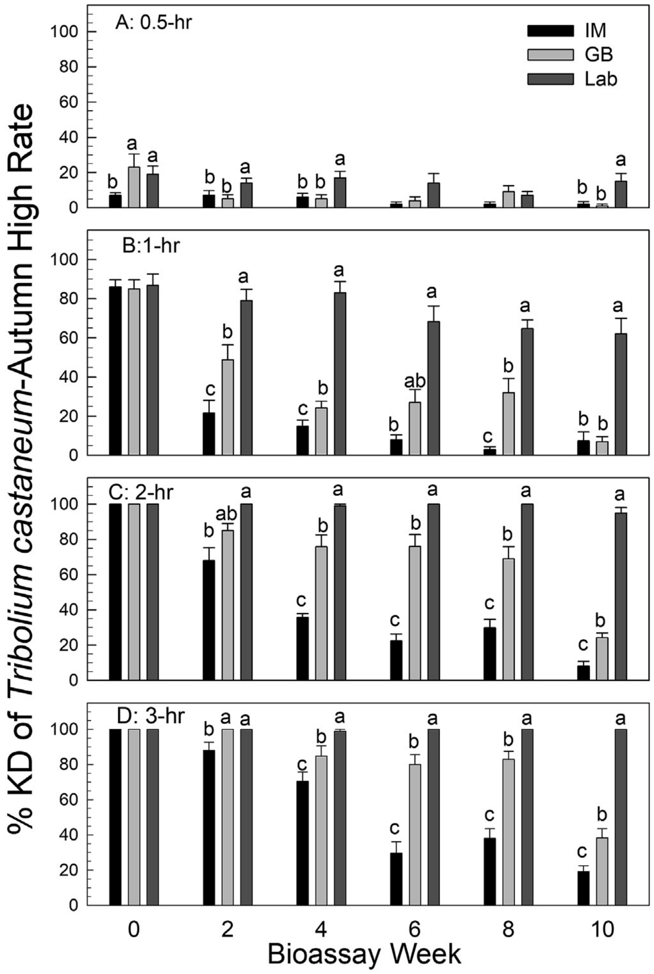

Fig. 5. Percentage knockdown (means ± SE) of adult *T. castaneum* exposed for 0.5, 1, 2, and 3 h (A–D) on concrete arenas treated with the high rate of beta-cyfluthrin SC Ultra (20 mg of Active Ingredient [AI]/m^2), and held inside the rice mill (IM), inside the grain bin (GB), or inside the laboratory (Lab) at Arkansas State University. Bioassays conducted on the arenas at 1 day after treatment (week 0) and 2–10 weeks post-treatment. Separate tests done for two autumn testing periods in 2016 and 2017 (see Table 4), data combined for years. Means for location followed by different letters at each time are significantly different ($P < 0.05$).

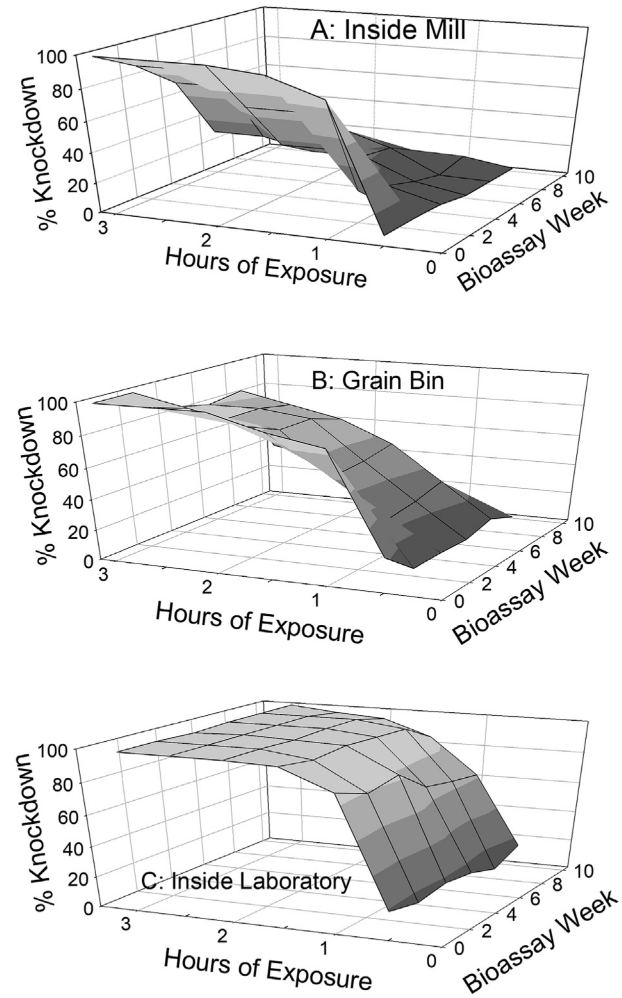

Fig. 6. 3D-response surfaces for knockdown of *T. castaneum* at all exposure intervals (0.5–3 h in 0.5 h increments) (z axis), for arenas treated with 10 mg [AI]/m^2 beta-cyfluthrin SC Ultra and held inside the mill (A), inside the grain bin (B), or inside the laboratory (C) during summer. Response surfaces generated using mean values for knockdown at each exposure interval (x-axis) and bioassay time (y-axis).

Table 3
Average temperature (mean ± SE), temperature range, total temperature accumulation units, and number of hours below specified temperatures inside the mill (IM), inside the grain bin (GB), and inside the laboratory (L), no temperatures below specified ranges), where the treated arenas were stored from 10 October 2015 to 6 January 2016 and from 26 October 2016 to 11 January 2017 (Data combined for both years).

	IM	GB	L			
Mean (°C)	13.3 ± 0.09	12.8 ± 0.09	21.1 ± 0.01		Hours	Hours
Range	−3.2 to 25.8	−0.2 to 26.4	19.0 to 23.5	<15.6	2137	2344
Total Units	42388	40801	67121	<10.0	768	921

slightly increased breakdown of both pyrethroids after 13 weeks at 35 °C compared to 25 °C, with breakdown most prevalent in the Trans IV isomer. All isomers had shorter half-lives at 35 °C compared to 25 °C. In studies in which various insecticides including cyfluthrin were applied to field crops on a 7-day schedule for insect control, there was evidence of a decline in efficacy with cypermethrin, esfenvalerate, and cyhalothrin during hot dry conditions at ca. 37 °C, but cyfluthrin maintained a higher efficacy level (Guillebeau et al., 1989). However, there was still some indication of decline in efficacy with temperature.

Under indoor or static conditions, pyrethroid residues are apparently much more persistent compared to outdoor sites. In a study where beta-cyfluthrin was applied to aluminum foil and held inside a test house protected from sunlight and rainfall, initial residue concentration was 17.3 mg/m^2 and had declined to only 16.8% after 56 days (Nakagawa et al., 2017). Arthur (1999) stored concrete arenas treated with cyfluthrin Wettable Powder at 20, 25, 30, and 35 °C, and conducted bioassays every two weeks for 8 weeks by exposing adult *T. castaneum* for 0.5, 1, or 2 h. There was no significant difference in knockdown of those adults until the final week of the test. In a recent test in which the pyrethroid deltamethrin was applied on a concrete surface and the arenas were subsequently held inside a laboratory and compared with concrete arenas held outside or in a shed, there was little loss in efficacy during 8-10-week residual testing periods for the arenas held inside the laboratory compared to the other sites (Arthur et al., 2019).

The current test was conducted with the commercial beta-cyfluthrin formulation, which is newer formulation with a low and high rate of application of 10 and 20 mg/m^2, respectively,

Table 4
Average temperature (mean ± SE), temperature range, total temperature accumulation units, and number of hours above and below specified temperatures inside the rice mill (IM), inside the grain bin (GB), and inside the laboratory (L), no temperatures above specified ranges), where the treated arenas were stored from 18 June to 24 August 2015 and from 29 June to 6 September 2016 (data combined for both years).

	IM	GB	L			
Mean (°C)	28.6 ± 0.05	29.7 ± 0.04	23.1 ± 0.03		Hours	Hours
Range	21.8 to 38.5	21.3 to 36.0	18.0 to 27.0	>29.4	1279	1707
Total Units	79085	82064	63745	>32.2	184	363
				>35.0	1	7

which is half the label rate specified by the older cyfluthrin WP and Emulsifiable Concentrate (EC) formulations (Ghimire et al., 2016; Arthur et al., 2018). This makes comparisons between older tests with cyfluthrin difficult, but results from this study with beta-cyfluthrin are also similar to results obtained from a recent study where concrete arenas were treated with three different rates of deltamethrin that were within the range specified on the product label, and stored inside an empty grain bin, inside a building, or inside an environmental laboratory set at 27 °C (Arthur, 2018). During the summer the accumulation of hours of temperature above levels of about 43–49 °C, and not the average temperature between locations, or the number of hours of accumulated temperatures above specified thresholds, was the most important factor affecting residual efficacy. In the current test with beta-cyfluthrin, the extreme summer temperatures inside the grain bin apparently led to faster degradation, as evidenced by slower knockdown of adult *T. castaneum* during the residual testing period. However, the trend in tests cited above is that efficacy as determined by rapidity of knockdown was usually greatest in arenas held inside the static conditions of a laboratory compared to alternate holding sites. In the current test the average temperatures and the accumulation of temperature units was determined for the three holding locations, as was done for the test with deltamethrin (Arthur, 2018), and like the results from the deltamethrin test, it appeared that the number of hours above the high-temperature thresholds could have led to increased degradation of the beta-cyfluthrin residues.

These recent tests (Arthur, 2018, 2019) also show that laboratory tests assessing residual efficacy of pyrethroids on a treated surface at constant or near-constant temperatures may produce discrepant results when compared to environments outside of a laboratory setting. The laboratory tests may overestimate residual efficacy, as the tests cited above show that residual efficacy was reduced on arenas held inside a shed or an enclosed building compared to arenas held inside a laboratory or laboratory. Since both beta-cyfluthrin and deltamethrin can be used as a pre-binning treatment for stored grains, depending on the specific crop, the timing of spray treatments could be important. If treatments are made too far in advance of grains being loaded into bins, efficacy could be compromised. Insects that persist in untreated areas within a bin, such as underneath the flooring, in elevator boots, and in other areas where a residual insecticide may be used (Tilley et al., 2007, 2014, 2017) could survive exposure should they encounter the treated surface. Future studies could explore this concept of residual efficacy in laboratory environments versus other indoor sites and also in outdoor areas as well.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jspr.2019.101514.

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