Immediate and Delayed Mortality of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) and *Sitophilus oryzae* (Coleoptera: Curculionidae) Adults Exposed to Spinosad-Treated Commodities

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ABSTRACT A series of tests was conducted to characterize differences in the mortality of the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), and rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), exposed to three commodities treated with a liquid and dry spinosad formulation. In laboratory bioassays, adults of the two insect species were exposed to untreated wheat, *Triticum aestivum* L., corn, *Zea mays* L., and sorghum, *Sorghum bicolor* (L.) Moench., and to commodities treated with 1 mg (AI)/kg of liquid and dry spinosad formulations. Mortality was assessed from independent samples examined at specific time intervals to determine immediate mortality and after 24 h of recovery on untreated grain at 28°C and 65% RH to determine delayed mortality. Comparison of the time required for 50% (LT_{50}) and 95% (LT_{95}) mortality indicated that *R. dominica* adults were consistently and significantly more susceptible (died quickly) than *S. oryzae* adults when exposed to spinosad-treated commodities. In general, the toxicity of liquid and dry spinosad formulations was similar against *R. dominica* or *S. oryzae*. The toxicity of spinosad to each species varied slightly among the three commodities, and there were no consistent trends to suggest that spinosad was more effective on one commodity versus another. LT_{50} values based on immediate mortality for *R. dominica* on all commodities ranged from 0.45 to 0.74 d; corresponding values based on delayed mortality ranged from 0.04 to 0.23 d, suggesting delayed toxic action of spinosad in *R. dominica*. LT_{50} values based on immediate and delayed mortality for *S. oryzae* on all three commodities treated with the two spinosad formulations were essentially similar and ranged from 2.75 to 4.56 d. LT_{95} values for *R. dominica* based on immediate mortality on spinosad-treated commodities ranged from 1.75 to 3.36 d, and those based on delayed mortality ranged from 0.49 to 1.88 d. There were no significant differences in LT_{95} values based on immediate and delayed mortality for *S. oryzae* on spinosad-treated commodities, and the LT_{95} values ranged from 7.62 to 18.87 d. The toxicity of spinosad was enhanced during a 24-h holding period after removal from spinosad-treated commodities only against *R. dominica* adults, and possible reasons for increased postexposure mortality of *R. dominica* adults after brief exposures to spinosad warrant further study.

KEY WORDS spinosad, stored-grain insects, susceptibility differences

Spinosad, a bacterium-derived non-antibiotic insecticide, is registered for use on >100 crops in >24 countries, including the United States (Thompson et al. 2000). In January 2005, spinosad was approved by the United States Environmental Protection Agency for use on stored wheat, corn, sorghum, oats, rice, barley, millet, and birdseed at 1 mg (AI)/kg grain, and the tolerance level was established at 1.5 mg (AI)/kg (Anonymous 2005). Both laboratory and field trials with spinosad on stored grains at 1 mg (AI)/kg (Fang et al. 2002a,b; Flinn et al. 2004; Huang et al. 2004; Nayak et al. 2005; Getchell 2006) and on various surfaces at 0.001–0.79 mg (AI)/cm^2 (Toews and Subramanyam 2003a,b) have shown considerable variation in susceptibility of adults of several stored-product insect species. These trials have shown that adults of the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), are highly susceptible to spinosad, both on grains and surfaces, and the adults of rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), and the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), are moderately and least susceptible to spinosad, respectively. Fang et al. (2002a) reported that all adult *R.*

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dominica were killed within 7 d at 0.1 and 1 mg (AI)/kg spinosad on four classes of wheat (*Triticum aestivum* L.) (hard red winter, hard red spring, soft red winter, and durum wheat), whereas the mortality of *S. oryzae* and *T. castaneum* increased with an increase in exposure time and spinosad rate. Except at 1 mg (AI)/kg on durum wheat where the mortality of *S. oryzae* adults was 100%, the mortality on all other wheat classes at 0.1 and 1 mg (AI)/kg ranged from 33 to 93%. The mortality of *T. castaneum* adults at the two spinosad rates on all wheat classes ranged from 0 to 55%. It is unclear whether exposures shorter than 7 d are sufficient for complete control of adult *R. dominica*. In contact toxicity tests on glass surfaces, Toews and Subramanyam (2003a) reported a similar trend in susceptibility of these three species by using dose–response and time–response tests.

Plausible reasons for differences in susceptibility of adults of stored-product insects exposed to spinosad-treated commodities could be due to differences in consumption, uptake, and penetration through the cuticle, effects at the GABA and nicotinic acetylcholine receptor sites (Salgado 1998), detoxification, and excretion. In many laboratory and field bioassays, adults of *R. dominica*, *S. oryzae*, and *T. castaneum* are exposed to insecticide-treated commodities for 7 or 14 d. It is difficult to gauge differences between immediate and delayed mortality effects with stored-product insects exposed for 7 and 14 d to insecticide-treated commodities, because of continuous exposure on the treated substrate. Differences between immediate and delayed mortality effects of an insecticide can be best gauged if insects are exposed to treated surfaces (Barson 1991, Arthur 1998) or commodity (Arthur 1999) for short durations and then allowed to recover on untreated commodity.

The immediate and delayed mortality effects of stored-product insects exposed for short time periods to spinosad-treated commodities are unknown. Therefore, laboratory experiments were designed to compare these effects against *R. dominica* and *S. oryzae* exposed to three commodities treated with commercial dry and liquid spinosad formulations.

Materials and Methods

Uninfested organic hard red winter wheat, yellow organic dent corn (*Zea mays* L.), and sorghum [*Sorghum bicolor* (L.) Moench.] were cleaned using a 1.63-mm-wide by 3.1-mm-long slotted-hole sieve, and 100 g of each commodity was placed in separate 0.47-liter glass jars. The moisture content of commodities used in various tests was 13% for wheat, 14–16% for sorghum, and 11–13% for corn as determined using an air-oven method (Christensen 1982). The grain in each jar was treated with either a dust (0.5% [AI]; L1247 [AI]) or a liquid (SpinTor 2 SC containing 240 mg [AI]/ml spinosad formulation, Dow AgroSciences, LLC, Indianapolis, IN) to obtain a rate of 1 mg ([AI])/kg. Exactly 0.02 g of dry spinosad or 100 μl of an aqueous suspension of spinosad from a solution containing 1 mg/ml was applied to 100 g of each commodity in jars, and shaken manually for 1 min. Untreated commodities in the case of dry spinosad, and commodities treated with 100 μl of distilled water in the case of liquid spinosad, served as the corresponding control treatments. Unsexed adults (25) of mixed ages of *R. dominica* or 25–50 adults of *S. oryzae*, separated from culture jars maintained in the Department of Grain Science and Industry, Kansas State University, were added into each jar. Infested jars were closed with lids and placed in growth chambers at 28°C and 65% RH.

Both the untreated and spinosad-treated commodities infested with *R. dominica* were removed from the growth chamber at 0.02, 0.04, 0.08, 0.25, 0.33, 0.42, 0.5, 1, 2, 3, and 5 d. For *S. oryzae*, the exposure intervals were 1, 2, 3, 4, 5, 7, 9, 11, 13, and 19 d. A separate set of jars was removed at each time interval. There were three jars (replicates) for each species, formulation, commodity, time, and treatment (0 and 1 mg [AI]/kg) combination. At each time interval, adults in each jar were separated from the commodity to assess mortal-

Table 1. Mortality (mean ± SE) of *R. dominica* adults on untreated commodities at exposure times (0.02–5 d) corresponding to spinosad formulation treatments

Commodity	No. insects	Formulation	Effect[a]	Mortality (%), range	
				Min.	Max.
Wheat	825	Dry	Immediate	0	9.3 ± 2.7
			Delayed	1.3 ± 1.3	10.7 ± 3.5
	825	Liquid	Immediate	0.0 ± 0.0	6.7 ± 1.3
			Delayed	1.3 ± 1.3	18.7 ± 5.3
Corn	750	Dry	Immediate	0	13.3 ± 2.7
			Delayed	1.3 ± 1.3	12.0 ± 2.3
	750	Liquid	Immediate	0	18.7 ± 4.8
			Delayed	0	17.3 ± 11.4
Sorghum	750	Dry	Immediate	0	20.0 ± 8.3
			Delayed	0	24.0 ± 9.2
	750	Liquid	Immediate	0	36.0 ± 28.0
			Delayed	0	58.0 ± 10.0

Each mean is based on $n = 3$ replications.

[a] Immediate mortality was assessed soon after the intended exposure period to spinosad, whereas delayed mortality was assessed 24 h after insects were transferred from treated grain to clean grain.

Table 2. Mortality (mean ± SE) of *S. oryzae* adults on untreated commodities at exposure times (1–19 d) corresponding to spinosad formulation treatments

Commodity	No. insects	Formulation	Effect[a]	Mortality (%), range	
				Min.	Max.
Wheat	1125	Dry	Immediate	2.7 ± 1.3	12.0 ± 6.1
			Delayed	6.7 ± 1.3	13.3 ± 7.4
	1125	Liquid	Immediate	4.0 ± 1.2	17.3 ± 7.0
			Delayed	4.0 ± 1.2	22.0 ± 2.0
Corn	750	Dry	Immediate	0.0 ± 0.0	8.0 ± 6.1
			Delayed	1.3 ± 1.3	13.3 ± 9.3
	750	Liquid	Immediate	0.0 ± 0.0	14.0 ± 2.0
			Delayed	2.7 ± 1.3	18.0 ± 2.0
Sorghum	1350	Dry	Immediate	1.3 ± 0.7	32.7 ± 4.7
			Delayed	1.3 ± 0.7	23.2 ± 3.7
	1350	Liquid	Immediate	2.0 ± 0.0	23.3 ± 5.7
			Delayed	1.3 ± 0.7	34.0 ± 5.0

Each mean is based on $n = 3$ replications.

[a] Immediate mortality was assessed soon after the intended exposure period to spinosad, whereas delayed mortality was assessed 24 h after insects were transferred from treated grain to clean grain.

Table 3. Time–mortality regression estimates (mean ± SE) for *R. dominica* (Rd) and *S. oryzae* (So) adults exposed to commodities treated with 1 mg (AI)/kg of dry and liquid spinosad formulations

Species	Commodity	Formulation	Effect	No. insects	Intercept ± SE	Slope ± SE	LT_{50} (95% CL), d	χ^2 (df)[a]	*P* value
Rd	Wheat	Dry	Immediate	825	0.15 ± 0.20	1.85 ± 0.39	0.53 (0.25–0.92)	32.47 (9)	<0.001*
			Delayed	825	1.45 ± 0.40	1.42 ± 0.46	0.05 (0.001–0.15)	66.64 (9)	<0.001*
		Liquid	Immediate	825	0.30 ± 0.11	2.08 ± 0.23	0.48 (0.37–0.60)	10.37 (9)	0.32
			Delayed	825	1.60 ± 0.34	1.60 ± 0.39	0.06 (0.009–0.12)	33.76 (9)	<0.001*
	Corn	Dry	Immediate	750	0.40 ± 0.14	2.72 ± 0.33	0.52 (0.41–0.64)	12.85 (8)	0.12
			Delayed	750	0.85 ± 0.16	0.90 ± 0.21	0.04 (0.003–0.12)	16.91 (8)	0.03*
		Liquid	Immediate	750	−0.08 ± 0.18	2.23 ± 0.30	0.74 (0.43–1.14)	19.90 (8)	0.01*
			Delayed	750	0.76 ± 0.11	1.28 ± 0.17	0.13 (0.08–0.20)	10.25 (8)	0.25
	Sorghum	Dry	Immediate	750	0.39 ± 0.22	2.16 ± 0.44	0.45 (0.21–0.74)	26.82 (8)	<0.001*
			Delayed	750	0.98 ± 0.16	2.09 ± 0.28	0.23 (0.16–0.29)	7.89 (8)	0.44
		Liquid	Immediate	750	0.50 ± 0.18	2.49 ± 0.41	0.45 (0.29–0.63)	14.37 (8)	0.07
			Delayed	750	0.98 ± 0.16	2.07 ± 0.27	0.22 (0.16–0.29)	9.85 (8)	0.28
So	Wheat	Dry	Immediate	1125	−1.68 ± 0.19	2.55 ± 0.25	3.27 (2.73–3.85)	7.52 (8)	0.48
			Delayed	1125	−1.32 ± 0.23	2.16 ± 0.30	2.75 (1.85–3.57)	14.12 (8)	0.08
		Liquid	Immediate	1125	−2.04 ± 0.51	3.77 ± 0.80	2.78 (1.68–3.65)	31.93 (7)	<0.001*
			Delayed	1125	−1.14 ± 0.57	2.46 ± 0.84	2.06 (0.13–3.67)	93.04 (8)	<0.001*
	Corn	Dry	Immediate	750	−0.99 ± 0.47	1.20 ± 0.52	3.30[b]	37.51 (8)	<0.001*
			Delayed	750	−1.03 ± 0.53	1.25 ± 0.59	3.41[b]	47.47 (8)	<0.001*
		Liquid	Immediate	750	−1.37 ± 0.23	1.93 ± 0.27	3.30 (2.34–4.19)	11.76 (8)	0.16
			Delayed	750	−1.31 ± 0.23	1.84 ± 0.27	3.24 (2.24–4.16)	9.10 (8)	0.33
	Sorghum	Dry	Immediate	1350	−3.81 ± 0.92	5.22 ± 1.18	4.56 (2.97–5.94)	55.63 (9)	<0.001*
			Delayed	1350	−3.63 ± 0.85	4.98 ± 1.07	4.52 (2.94–5.89)	53.55 (9)	<0.001*
		Liquid	Immediate	1350	−2.67 ± 0.27	4.27 ± 0.39	3.46 (3.09–3.81)	10.84 (9)	0.15
			Delayed	1350	−2.82 ± 0.29	4.58 ± 0.43	3.43 (3.08–3.76)	11.69 (9)	0.11

[a] Chi-square values for goodness-of-fit of the predicted mortality values to the observed mortality data, based on the complimentary log-log regression model.
[b] The 95% CL could not be estimated.
* Significant ($P < 0.05$).

ity. Immediate mortality was determined based on the number of adults that seemed dead (knocked-down and moribund adults) out of the total exposed. Insects that failed to respond when stimulated with a fine camel's-hair brush were assumed dead. All adults were then transferred to 150-ml plastic containers holding 25 g of clean wheat, sorghum, or corn. These containers were placed in the growth chamber at 28°C and 65% RH for an additional 24 h to assess delayed mortality effects after procedures described above for assessing immediate mortality. Immediate and delayed mortality for each insect species was expressed as a percentage, based on number of adults that died out of the total exposed. We recognize that the distinction between immediate and delayed mortality as described above is arbitrary. However, the focus of our work was to determine whether the toxicity of spinosad formulations against adults of the two species increased, decreased, or remained the same after brief exposures to spinosad-treated commodities.

The immediate or delayed mortality of each insect species at each time interval on a given commodity was corrected with corresponding mortality on the untreated commodity (Abbott 1925). Corrected mortality data over time were subjected to probit analysis using the complementary log-log (CLL) regression model (Robertson and Preisler 1992) for estimating the time required to kill 50% (LT_{50}) and 95% (LT_{95}) of the exposed insects using the PROBIT procedure (SAS Institute 1999). The chi-square (χ^2) statistic was

Table 4. Time required to kill 95% (LT_{95}) of *R. dominica* and *S. oryzae* adults on three commodities treated with two spinosad formulations

Species	Commodity	Formulation	LT_{95} (95% CL), d	
			Immediate mortality	Delayed mortality
R. dominica	Wheat	Dry	3.27 (1.66–15.74)	0.57 (0.21–11.68)
		Liquid	2.40 (1.77–3.69)	0.49 (0.25–2.05)
	Corn	Dry	1.80 (1.38–2.67)	1.88 (0.79–18.30)
		Liquid	3.36 (2.03–8.70)	1.84 (1.21–3.37)
	Sorghum	Dry	2.13 (1.21–7.08)	1.14 (0.83–1.84)
		Liquid	1.75 (1.15–3.80)	1.14 (0.83–1.81)
S. oryzae	Wheat	Dry	12.22 (10.07–15.91)	13.04 (9.43–22.73)
		Liquid	8.97[a]	8.12 (4.55–139.61)
	Corn	Dry	54.26[a]	50.47[a]
		Liquid	18.87 (14.10–29.76)	20.20 (14.74–33.70)
	Sorghum	Dry	8.69 (6.58–16.32)	8.89 (6.74–15.82)
		Liquid	7.62 (6.80–8.85)	7.17 (6.42–8.26)

[a] The 95% CL could not be estimated.

Table 5. Pairwise comparisons testing differences in *R. dominica* and *S. oryzae* susceptibility to spinosad formulations on three commodities

Commodity	Formulation	Effect	Species[a]	LT_{50} ratio (95% CL)[b]
Wheat	Dry	Immediate	*R. dominica* vs. ***S. oryzae***	6.19 (3.65–10.5)
		Delayed	*R. dominica* vs. ***S. oryzae***	51.39 (13.66–193.28)
	Liquid	Immediate	*R. dominica* vs. ***S. oryzae***	5.83 (4.05–8.41)
		Delayed	*R. dominica* vs. ***S. oryzae***	34.78 (11.80–102.52)
Corn	Dry	Immediate	*R. dominica* vs. ***S. oryzae***	10.20 (6.00–17.34)
		Delayed	*R. dominica* vs. ***S. oryzae***	19.86 (13.61–28.98)
	Liquid	Immediate	*R. dominica* vs. ***S. oryzae***	7.69 (5.53–10.68)
		Delayed	*R. dominica* vs. ***S. oryzae***	15.39 (11.31–20.92)
Sorghum	Dry	Immediate	*R. dominica* vs. ***S. oryzae***	6.31 (2.42–16.47)
		Delayed	*R. dominica* vs. ***S. oryzae***	76.80 (16.06–387.15)
	Liquid	Immediate	*R. dominica* vs. ***S. oryzae***	4.45 (2.76–7.16)
		Delayed	*R. dominica* vs. ***S. oryzae***	24.36 (14.06–42.20)

[a] The species in bold letters has the larger LT_{50} value in the pair being compared.
[b] For each commodity, formulation, and effect, the LT_{50} values within a pair being compared are significantly different ($P < 0.05$) from one another because the ratio does not include 1 (Robertson and Preisler 1992).

used to determine the goodness-of-fit of the CLL model to data (SAS Institute 1999). The immediate and delayed mortality effects among species, commodities, and spinosad formulations were compared using LT_{50} ratios (Robertson and Preisler 1992), because lethal times are more precise at this level. The LT_{50} values of any two pairs being compared were significantly different ($P < 0.05$) from one another if the 95% confidence limit (CL) for the ratio did not include 1.

Results

The immediate and delayed mortality of *R. dominica* adults on untreated commodities over the time intervals examined ranged from 0 to 58% (Table 1), and control mortality was generally higher on sorghum than on corn or wheat and at longer exposure times. In contrast, *S. oryzae* control mortality ranged from 0 to 34% (Table 2), with higher mortalities associated with longer exposure times. Probit regression estimates for *R. dominica* and *S. oryzae* on the three commodities treated with the two spinosad formulations are shown in Table 3, and the LT_{95} estimates are shown in Table 4. The χ^2 statistic for goodness-of-fit of the probit model to the data were significant ($P < 0.05$) for 12 of the 24 regressions, indicating inadequate fit of the data to the CLL model. The LT_{50} for *R. dominica*, based on delayed mortality, was approximately four-fold lower than for *S. oryzae*, indicating that *R. dominica* adults are more susceptible to spinosad than *S. oryzae* adults. The LT_{95} (immediate and delayed) for *R. dominica* on the three commodities treated with spinosad formulations ranged from 0.5 to 3 d and that for *S. oryzae* ranged from 7 to 55 d (Table 4). In general, with *R. dominica*, the LT_{50} and LT_{95} values for delayed mortality were lower than similar values based on immediate mortality, but this trend was not seen with *S. oryzae*.

Pairwise comparisons of LT_{50} values based on immediate or delayed mortality showed significant differences ($P < 0.05$) between *R. dominica* and *S. oryzae* on each of the three commodities treated with the two spinosad formulations (Table 5). The LT_{50} values based on delayed mortality were significantly lower ($P < 0.05$) than those based on immediate mortality on all three commodities treated with the two formulations only in the case of *R. dominica* (Table 6). The

Table 6. Pairwise comparisons testing the influence of time of mortality assessment on toxicity of spinosad formulations to *R. dominica* and *S. oryzae* on three commodities

Species	Commodity	Formulation	Effect[a]	LT_{50} ratio (95% CL)[b]
R. dominica	Wheat	Dry	**Immediate** vs. Delayed	9.88 (2.45–39.75)*
		Liquid	**Immediate** vs. Delayed	8.03 (3.33–19.37)*
	Corn	Dry	**Immediate** vs. Delayed	11.77 (3.47–39.94)*
		Liquid	**Immediate** vs. Delayed	5.58 (3.06–10.18)*
	Sorghum	Dry	**Immediate** vs. Delayed	1.96 (1.13–3.41)*
		Liquid	**Immediate** vs. Delayed	2.02 (1.32–3.09)*
S. oryzae	Wheat	Dry	Immediate vs. **Delayed**	1.19 (0.87–1.62)
		Liquid	Immediate vs. **Delayed**	1.35 (0.65–2.78)
	Corn	Dry	Immediate vs. **Delayed**	1.03 (0.26–4.07)
		Liquid	**Immediate** vs. Delayed	1.02 (0.68–1.53)
	Sorghum	Dry	**Immediate** vs. Delayed	1.01 (0.71–1.42)
		Liquid	**Immediate** vs. Delayed	1.01 (0.87–1.17)

[a] The effect in bold has the larger LT_{50} value in the pair being compared.
[b] The LT_{50} values within a pair being compared are significantly different (*, $P < 0.05$) from one another because the ratio does not include 1.

Table 7. Pairwise comparisons testing the influence of formulation on toxicity of spinosad to *R. dominica* and *S. oryzae* on three commodities

Species	Commodity	Effect	Formulation[a]	LT_{50} ratio (95% CL)[b]
R. Dominica	Wheat	Immediate	**Dry** vs. Liquid	1.11 (0.63–1.94)
		Delayed	Dry vs. **Liquid**	1.11 (0.24–5.22)
	Corn	Immediate	Dry vs. **Liquid**	1.42 (0.91–2.21)
		Delayed	Dry vs. **Liquid**	3.00 (0.83–10.87)
	Sorghum	Immediate	Dry vs. **Liquid**	1.01 (0.57–1.77)
		Delayed	**Dry** vs. Liquid	1.02 (0.68–1.53)
S. oryzae	Wheat	Immediate	**Dry** vs. Liquid	1.18 (0.86–1.61)
		Delayed	**Dry** vs. Liquid	1.33 (0.65–2.75)
	Corn	Immediate	Dry vs. **Liquid**	1.00 (0.38–2.66)
		Delayed	**Dry** vs. Liquid	1.05 (0.37–2.99)
	Sorghum	Immediate	**Dry** vs. Liquid	1.32 (1.01–1.71)*
		Delayed	**Dry** vs. Liquid	1.32 (1.01–1.72)*

[a] The formulation in bold letters has the larger LT_{50} value in the pair being compared.
[b] The LT_{50} values within a pair being compared are significantly different (*, $P < 0.05$) from one another because the ratio does not include 1.

immediate or delayed LT_{50} values between dry and liquid spinosad formulations were similar ($P > 0.05$) for *R. dominica* on all three commodities and for *S. oryzae* on only wheat and corn (Table 7). Significant differences in *S. oryzae* LT_{50} values between formulations ($P < 0.05$) were detected on sorghum, but this difference was too small (1.3-fold) to be of any practical value. Comparison of LT_{50} values for *R. dominica* and *S. oryzae* showed no significant differences ($P > 0.05$) between wheat and corn for both immediate and delayed mortality effects (Table 8). Only six pairwise commodity comparisons were significant ($P < 0.05$), and in all cases, sorghum was involved, and there were no consistent trends that were apparent in these significant effects.

Discussion

This is the first report that characterizes time-mortality responses of *R. dominica* and *S. oryzae* on stored commodities at the labeled rate of 1 mg (AI)/kg. Both LT_{50} and LT_{95} values showed *R. dominica* to be more susceptible to spinosad than *S. oryzae*, and this finding is consistent with previous results observed after 7- or 14-d exposure on stored commodities treated with spinosad at 0.1 and 1 mg (AI)/kg (Fang et al. 2002a). Generally, LT_{50} values for *R. dominica* were four-fold lower compared with that for *S. oryzae*. However, these differences at the LT_{95} level ranged from 2- to 110-fold, because of reduced susceptibility of *S. oryzae* to spinosad, especially at longer exposure durations. Toews

Table 8. Pairwise comparisons testing the influence of commodity on toxicity of spinosad formulations to *R. dominica* and *S. oryzae*

Species	Formulation	Effect	Commodity[a]	LT_{50} ratio (95% CL)[b]
R. dominica	Dry	Immediate	**Wheat** vs. corn	1.01 (0.58–1.75)
			Wheat vs. sorghum	1.18 (0.59–2.36)
			Corn vs. sorghum	1.17 (0.70–1.97)
		Delayed	**Wheat** vs. corn	1.20 (0.21–7.07)
			Wheat vs. **sorghum**	4.26 (1.13–16.08)*
			Corn vs. **sorghum**	5.13 (1.49–17.65)*
	Liquid	Immediate	Wheat vs. **corn**	1.56 (0.99–2.46)
			Wheat vs. sorghum	1.06 (0.71–1.57)
			Corn vs. sorghum	1.65 (1.01–2.70)*
		Delayed	Wheat vs. **corn**	2.24 (0.86–5.88)
			Wheat vs. **sorghum**	3.76 (1.54–9.20)*
			Corn vs. **sorghum**	1.68 (0.97–2.90)
S. oryzae	Dry	Immediate	Wheat vs. **corn**	1.01 (0.39–2.60)
			Wheat vs. **sorghum**	1.39 (1.04–1.87)*
			Corn vs. **sorghum**	1.38 (0.53–3.63)
		Delayed	Wheat vs. **corn**	1.24 (0.44–3.49)
			Wheat vs. **sorghum**	1.64 (1.15–2.36)*
			Corn vs. **sorghum**	1.33 (0.47–3.72)
	Liquid	Immediate	Wheat vs. **corn**	1.19 (0.80–1.76)
			Wheat vs. **sorghum**	1.25 (0.93–1.66)
			Corn vs. **sorghum**	1.07 (0.79–1.44)
		Delayed	Wheat vs **corn**	1.57 (0.75–3.28)
			Wheat vs. **sorghum**	1.66 (0.84–3.29)
			Corn vs. **sorghum**	1.06 (0.77–1.45)

[a] The commodity in bold has the larger LT_{50} value in the pair being compared.
[b] The LT_{50} values within a pair being compared are significantly different (*, $P < 0.05$) from one another because the ratio does not include 1.

and Subramanyam (2003a) reported 100% mortality of *R. dominica* adults exposed for 48 h to glass surfaces treated with a liquid spinosad formulation at 0.0016 and 0.016 mg/cm^2; corresponding mortality of *S. oryzae* adults at these deposit levels was 11 and 85%, respectively.

The decrease in LT_{50} values in the case of *R. dominica* 24 h after exposure to spinosad suggested that brief exposures were sufficient to kill adults that did not die when examined at specific time intervals on the various commodities. The increase in susceptibility of *R. dominica* 24 h after exposure to spinosad was about two-fold on sorghum, but it ranged from 6- to 13-fold on wheat and corn. The LT_{50} values based on immediate and delayed mortality were similar for *S. oryzae*, suggesting that spinosad did not exhibit delayed poisoning effects. Additional studies using radiolabeled spinosad may help in understanding if the susceptibility differences observed between *R. dominica* and *S. orzae* adults are related to the insecticide uptake, penetration, metabolism, and excretion.

A majority of comparisons between commodities (18/24) showed that spinosad LT_{50s} for *R. dominica* or *S. oryzae* was essentially similar. Very little information is available on the adhesion, retention, and distribution of spinosad on stored commodities to explain reasons for the significant differences observed in six of the 24 comparisons. Both the liquid and dry spinosad formulations performed equally well on corn, wheat, and sorghum, regardless of the species. However, the time–mortality relationships on spinosad-treated commodities varied significantly between the species, with *R. dominica* adults being significantly more susceptible than *S. oryzae.* Additionally with *R. dominica*, delayed time–mortality effects seem to be more pronounced than immediate time-mortality effects and may indicate why adults of this particular species are more susceptible to spinosad than *S. oryzae* adults.

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