



The effect of grain moisture content and temperature on the efficacy of diatomaceous earths from different geographical locations against stored-product beetles

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Abstract

Source of diatomaceous earth (DE), insect species, grain moisture content, temperature, method of application and duration of exposure were all factors that influenced the mortality of stored-product insects. In all tests, regardless of the insect species, or source of DE, the lower the moisture content of grain, the greater the mortality. DEs from different geographical locations had different efficacies. The ranking of the different DEs remained similar at different moisture–temperature combinations. However, the mortality response with respect to moisture content did change among DEs from different sources for *Sitophilus oryzae* (L.), but not for *Tribolium castaneum* (Herbst).

Of all the insects tested, *Cryptolestes ferrugineus* (Stephens) was the most sensitive to DE. *Oryzaephilus surinamensis* (L.) and *S. oryzae* were more tolerant than *C. ferrugineus*. *Rhyzopertha dominica* (F.) and *T. castaneum* were the most tolerant species tested. Applying DE as a dust was more effective than applying DE as an aqueous spray.

For *C. ferrugineus*, lower temperatures reduced DE efficacy. The opposite was true for *T. castaneum*, as lower temperatures increased efficacy for most DEs tested. For *S. oryzae* some DEs had increased efficacy with lower temperatures and others had decreased efficacy with lower temperatures. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Diatomaceous earth; Stored-product insects; Moisture content; Temperature; Efficacy

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1. Introduction

The choice of insecticides that may be used on and around stored food commodities is limited by strict requirements to ensure safety for consumers, grain-handlers and livestock (White and Leesch, 1995). The use of synthetic pesticides is under increasing scrutiny because of problems with environmental contamination, atmospheric ozone-depletion (i.e., methyl bromide), potential carcinogens, concern over residues in commodities, exposure to applicators, environmental and work space restriction, resistance in pests, and general consumer aversion to the use of chemicals. Therefore, there is a growing need for nonchemical pest control methods.

Diatomaceous earth (DE) is used as an alternative to synthetic insecticides because it has low mammalian toxicity, does not break down rapidly and does not affect end-use quality (Desmarchelier and Dines, 1987; Korunic et al., 1996). The rat oral lethal concentration (LC₅₀) of silicon dioxide, the major constituent of DE is 3160 mg/kg (NIOSH, 1977). DE consists of prehistoric skeletons of either freshwater or marine organisms, predominantly single-cell algae called diatoms. Most DEs are 70–90% amorphous silicon dioxide with the balance being made up of inorganic oxides and salts (Quarles, 1992; Quarles and Winn, 1996; Korunic, 1997). DE absorbs the cuticular lipids of insects, causing death by desiccation (Ebeling, 1971).

Temperature and moisture play an important role in the population dynamics of stored-product insect pests. An increase in the moisture content of grain results in a decrease in the efficacy of synthetic insecticides, as they degrade faster (Snelson, 1987). Higher grain moisture contents also reduce efficacy of DE, because the mode of action of DE is due to desiccation (Carlson and Ball, 1962; La Hue, 1965; Maceljski and Korunic, 1972; Desmarchelier and Dines, 1987; Aldryhim, 1990, 1993). However, these tests were conducted with only a single source of DE. Recent research has shown that DEs from different geographical locations can have different insecticidal activity, diatom species, pH, density, particle size distribution, internal surface area, lipid adsorption capability and effects on grain bulk density (Korunic, 1997).

The objective of this study was to determine if DEs from various geographical sources and formulations reacted differently to grain moisture content. As temperature plays an important role in the biology of stored-product insects and the effectiveness of synthetic insecticides, we also determined the effect of temperature on DE efficacy. For the control of *Cryptolestes ferrugineus* (Stephens) with certain DEs, it is recommended that 100 ppm be applied to wheat, 14% moisture content (m.c.) or lower, at harvest. Our final objective was to determine if *C. ferrugineus* could be controlled with higher concentrations of DE in wheat that is cooler than freshly harvested grain and moister than 14% m.c.

2. Materials and methods

2.1. Diatomaceous earths

The diatomaceous earths are described in Table 1. Protect-It™ (Korunic and Fields, 1995) was obtained from Hedley Technologies Ltd, 5160 Explorer Drive, Unit 20, Mississauga, Ontario, L4W 4T7, Canada. Insecto® was obtained from Natural Insect Products Inc., North

Table 1
The description of the different DEs used in the tests¹

DE	Source	Diatom type	Additives	SiO ₂ (%)	Maximum crystalline SiO ₂ (%)	Median particle size (µm)	Respirable dust (% less than 10 µm)
Protect-It™	USA	Marine	10% silica aerogel	87	3	6.6	66.3
Diaherb	Macedonia	Marine	None	> 80	4	– ²	100
Dryacide®	Australia	Freshwater	0.1–0.2% silica aerogel	94	1	11.1	29.2
Insecto®	USA	Marine	10% bait	87	3	8.2	57.1
Japan 3	Japan	Marine	None	80	NA	22.1	28.1
Perma Guard®	USA	Freshwater	None	93	1	11.7	42.7
Celite 209	USA	Marine	None	87	3	8.2	57.1

¹ SiO₂ taken from insecticide label, crystalline SiO₂ taken from material data safety sheet and particle size was determined using the Cilas granulometre 715 F155 method, NA = not available.

² All particles less than 4 µm.

Eckhoff Street, Orange, CA 92668, USA. The marine DE Japan 3 was obtained from Ithochu Agri-System Co. Ltd, Japan. Diaherb was produced by aqueous sedimentation to select the finest particles from a DE from Macedonia (Korunic, 1997). Dryacide[®] (Hedges and Belford, 1985) was obtained from Dryacide Australia PTY Ltd, P.O. Box 38, Maddington, Western Australia, 6019, Australia. Perma-Guard[®] D-10 was obtained from Perma Guard Inc., PO Box 25282, Albuquerque, NM 87125, USA. Celite 209 was obtained from Celite Corp., P.O. Box 519, Lompoc, CA 93438, USA, and was used for the scanning electronic microscope work. Since the completion of these tests, Protect-It[™] and Dryacide[®] have changed their source of DE.

2.2. Test insects

The species tested were adults of: the rusty grain beetle, *C. ferrugineus*; the rice weevil, *Sitophilus oryzae* (L.); the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.); the lesser grain borer, *Rhyzopertha dominica* (F.) and the red flour beetle *Tribolium castaneum* (Herbst). Insects were reared at $30 \pm 1^\circ\text{C}$ and $65 \pm 5\%$ r.h. in the dark on whole wheat for *S. oryzae* and *R. dominica*, whole wheat and 5% (by weight) wheat germ for *C. ferrugineus*, wheat flour and 5% (by weight) brewer's yeast for *T. castaneum*, or rolled oats and 5% (by weight) brewer's yeast for *O. surinamensis*. Unsexed, adults of mixed ages were used in all experiments. Insects were obtained from cultures maintained in the laboratory for at least three years, with no history of exposure to insecticides.

2.3. Bioassay

Hard Red Spring wheat was used in all bioassays. Moisture content was measured using a dielectric moisture meter (model 919, Labtronics, Winnipeg) following AACC (1995) Method 44-11. To adjust moisture content, water was added to wheat, and the grain in each jar was mixed on a mechanical roller (Norton, Chemical Process Product Division, Akron, OH, USA) for 30 min. To maintain the moisture content, grain was held in hermetically closed jars at 25°C for seven days.

After adding different concentrations of DE (0, 100, 200, 300, 400 or 600 ppm) to preconditioned grain in each jar, lids were closed tightly and jars were rolled by hand for one minute. Grain was then divided into 20-g lots and placed in glass vials (35 ml). Test insects, 50 (*C. ferrugineus*) or 25 (other species) adults, were introduced into vials. Each species was tested separately. The vials were held at constant temperature (15, 20, or 30°C) and relative humidity (65–70% r.h.) for one or two durations before mortality was assessed. Durations were chosen as a function of the insect's tolerance to DE, determined in previous studies (Korunic 1997, 1998). There were five replicate vials for each assessment. Untreated grain (0 ppm) served as a control.

For the trial with *C. ferrugineus* at 15 and 20°C , relative humidity was maintained using saturated salt solutions: CaCl_2 , r.h. = 35–33%, grain m.c. = 12%; NaCl , r.h. = 76%, grain m.c. = 15% and KCl , r.h. = 86%, grain m.c. = 17%. There were three replicate vials with 25 insects/replicate. For the slurry application, grain was spread out to one kernel thickness, sprayed with a DE at 15% aqueous solution (by weight) using an aerosol applicator (Crown

Industrial Products, 1500 McConnell Rd, Woodstock, IL 60098, USA) placed in a jar and rolled by hand for 30 s.

2.4. Scanning electron micrographs

Adult insects were placed in wheat (14% m.c., 600 ppm Celite 209), and held at 30°C. After one to six days, dead insects were removed from the grain and glued to SEM stubs. Insects were dried in a desiccator at 0% r.h. for 48 h, and coated with gold using a sputter coater (Polaron) to reduce charging effects. Their ventral abdomens were photographed at 845 to 1690 power magnification using a scanning electron microscope (Philips 515).

3. Results

In all the tests run (Tables 2, 3 and 4, Figs. 1 and 2), regardless of the species, or source of DE, the lower the moisture content, the greater the mortality. For example, *T. castaneum* and

Table 2

The mortality of two insect species held at various temperature and moisture conditions on wheat treated with six different diatomaceous earths for five days at 400 ppm for *S. oryzae* and at 600 ppm for *T. castaneum*

Insect	DE Source	Mortality \pm SEM (%) ¹				ANOVA ²		
		20°C		30°C		m.c.	T	m.c. \times T
		12% m.c.	14% m.c.	12% m.c.	14% m.c.			
<i>Sitophilus oryzae</i>	Protect-It™	99 \pm 1 a	60 \pm 6 a	97 \pm 3 a	41 \pm 7 a	****	*	NS
	Diaherb	95 \pm 3 a	67 \pm 7 a	94 \pm 2 a	41 \pm 4 a	****	*	NS
	Dryacide®	78 \pm 10 b	15 \pm 4 bc	96 \pm 1 a	33 \pm 7 a	****	*	NS
	Insecto®	74 \pm 6 b	29 \pm 5 b	96 \pm 7 a	32 \pm 6 a	****	*	*
	Japan 3	44 \pm 8 c	19 \pm 6 bc	46 \pm 9 c	4 \pm 3 b	****	NS	NS
	Perma Guard®	29 \pm 3 c	7 \pm 1c	77 \pm 6 b	2 \pm 1 b	****	*	***
	Untreated	2 \pm 2 d	0 \pm 0 d	17 \pm 7 d	2 \pm 1 b	**	***	NS
<i>Tribolium castaneum</i>	Protect-It™	92 \pm 4 a	79 \pm 8 a	78 \pm 4 a	49 \pm 17 a	**	NS	NS
	Diaherb	93 \pm 3 a	72 \pm 5 a	75 \pm 7 a	42 \pm 9 a	***	**	NS
	Dryacide®	68 \pm 5 b	36 \pm 4 b	31 \pm 7 b	6 \pm 2 b	****	****	NS
	Insecto®	63 \pm 4 b	18 \pm 3 c	66 \pm 9 a	30 \pm 12 ab	***	NS	NS
	Japan 3	55 \pm 4 b	12 \pm 3 c	30 \pm 6 b	1 \pm 1 b	****	***	NS
	Perma Guard®	21 \pm 5 c	9 \pm 2 c	6 \pm 3 c	1 \pm 1 b	**	***	NS
	Untreated	0 \pm 0 d	1 \pm 1 d	0 \pm 0 d	0 \pm 0 b	NS	NS	NS

¹ For a given species, moisture and temperature combination, means followed by different letters are significantly different $p \leq 0.05$ Student–Newman–Keuls test.

² A 2-way ANOVA was run specifically for each DE; NS=not significant $p > 0.05$, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, ****= $p \leq 0.0001$, for analysis, control mortality was corrected using Abbot's formula, $n = 5$.

Table 3

The mortality of *C. ferrugineus* held at various temperature and moisture conditions on wheat treated with Protect-It™ diatomaceous earth

Duration of exposure (days)	Dose (ppm)	Mortality \pm SEM (%) ¹						ANOVA ²		
		15°C			20°C			m.c.	T	m.c. \times T
		12% m.c.	15% m.c.	17% m.c.	12% m.c.	15% m.c.	17% m.c.			
3	0	0 \pm 0 a	0 \pm 0 a	3 \pm 3 a	0 \pm 0 a	0 \pm 0 a	0 \pm 0 a	NS	NS	NS
	100	15 \pm 3 b	5 \pm 1 b	1 \pm 1 a	41 \pm 4 b	29 \pm 3 b	3 \pm 3 a	***	**	*
	200	89 \pm 1 c	43 \pm 1 c	47 \pm 3 b	95 \pm 1 c	80 \pm 5 c	89 \pm 1 b	****	****	****
	300	99 \pm 1 d	87 \pm 1 d	57 \pm 1 c	100 \pm 0 c	95 \pm 1 d	100 \pm 0 c	****	****	****
7	0	11 \pm 1 a	9 \pm 1 a	8 \pm 2 a	0 \pm 0 a	5 \pm 3 a	7 \pm 1 a	NS	NS	NS
	100	77 \pm 1 b	28 \pm 2 b	28 \pm 2 b	76 \pm 5 b	61 \pm 7 b	21 \pm 4 b	****	*	***
	200	100 \pm 0 c	100 \pm 0 c	99 \pm 1 c	100 \pm 0 c	100 \pm 0 c	96 \pm 2 c	*	NS	NS
	300	100 \pm 0 c	100 \pm 0 c	100 \pm 0 c	100 \pm 0 c	100 \pm 0 c	100 \pm 0 c	NS	NS	NS

¹ For a given duration, moisture and temperature combination, means followed by different letters are significantly different $p \leq 0.05$ Student–Newman–Keuls test.

² A 2-way ANOVA was run for each DE source; NS=not significant $p > 0.05$, *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, ****= $p \leq 0.0001$, for the analysis control mortality was corrected using Abbot's formula, $n = 3$.

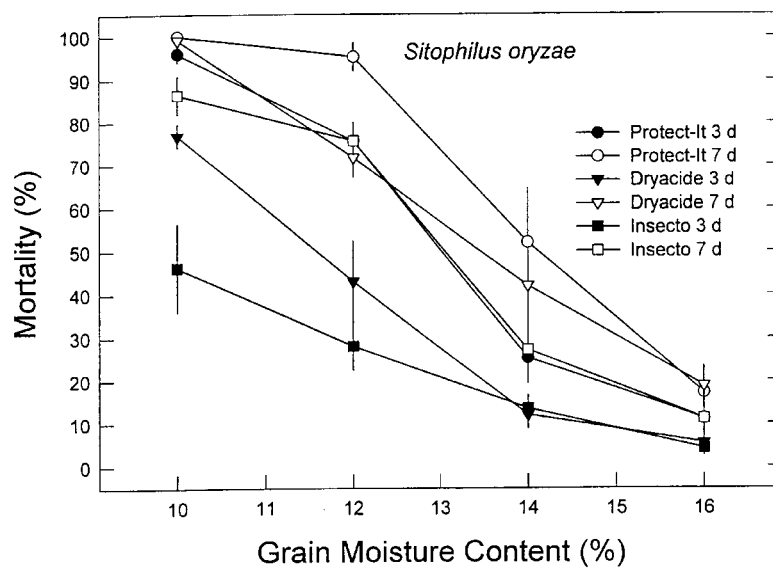


Fig. 1. The mortality of *S. oryzae* held at 30°C on wheat treated with three diatomaceous earths at 300 ppm. Mortality of insects on untreated wheat was less than 4%, $n = 5$.

Table 4

The mortality of four insect species held at 25°C at various moisture contents on wheat treated with Protect-It™ diatomaceous earth at 300 ppm. Insects held on untreated wheat had less than 2% mortality

Insect	Duration of exposure (days)	Mortality ± SEM (%) ¹						ANOVA ²		
		11.8% m.c.		13.9% m.c.		15.0% m.c.		m.c.	Dust vs Spray	m.c. × app.
		Dust	Spray	Dust	Spray	Dust	Spray			
<i>Cryptolestes ferrugineus</i>	1	92 ± 3 b	57 ± 15	100 ± 0 a	47 ± 4	75 ± 5 a	55 ± 6	NS	****	NS
	2	100 ± 0 a	–	100 ± 0 a	–	100 ± 0 b	–	NS	–	–
<i>Oryzaephilus surinamensis</i>	5	100 ± 0 a	88 ± 3 a	92 ± 2 a	79 ± 2 a	71 ± 3 a	45 ± 4 a	****	****	NS
	9	98 ± 2 a	98 ± 1 b	99 ± 1 b	94 ± 1 b	95 ± 3 b	83 ± 1 b	****	***	NS
<i>Sitophilus oryzae</i>	5	95 ± 3 a	56 ± 6	74 ± 3 b	89 ± 3	53 ± 2 a	33 ± 4 a	***	****	**
	9	97 ± 2 a	97 ± 2	99 ± 1 a	80 ± 4	99 ± 2 b	95 ± 1 b	*	****	**
<i>Rhyzopertha dominica</i>	5	72 ± 3 a	–	39 ± 7 a	–	17 ± 2 a	–	***	–	–
	14	90 ± 3 b	–	68 ± 5 b	–	58 ± 5 b	–	***	–	–

¹ For a given species, moisture and application combination, means followed by different letters are significantly different $p \leq 0.05$ Student–Newman–Keuls test.

² A 2-way ANOVA was run for each row; NS = not significant $p > 0.05$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, **** = $p \leq 0.0001$, $n = 5$.

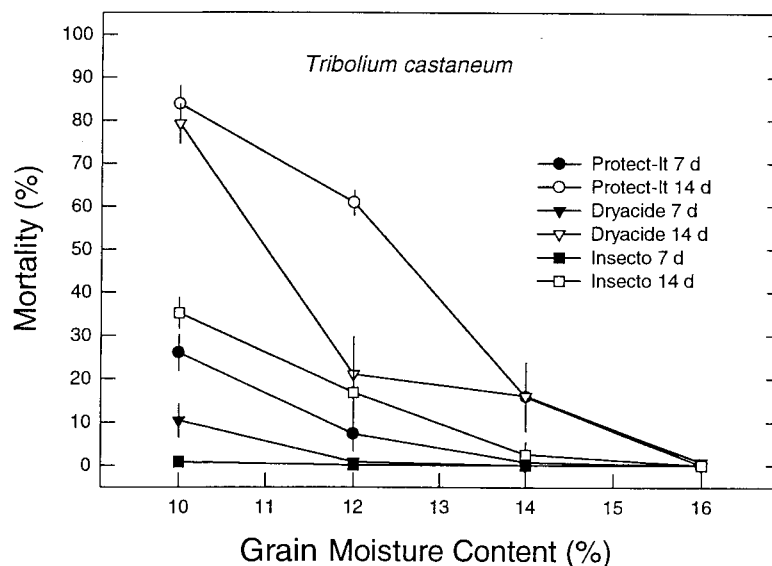


Fig. 2. The mortality of *T. castaneum* held at 30°C on wheat treated with three diatomaceous earths at 300 ppm. Mortality of insects on untreated wheat was less than 4%, $n = 5$.

S. oryzae were essentially unaffected by DE in wheat with 16% m.c., but 40–100% of adults died in wheat with 10% m.c., at the longest duration of exposure (Figs. 1 and 2). For *S. oryzae*, different DEs reacted differently to moisture, as the slopes of the mortality vs. m.c. curves are different and there is a significant interaction between m.c. and DE source (Fig. 1, 2-way ANOVA, duration=3 d, for DE source $p < 0.0001$, for m.c. $p < 0.0001$, for interaction DE source and m.c. $p = 0.0007$). In the test with *S. oryzae* with six different DE sources, there was also a significant interaction between m.c. and DE (Table 2, 2-way ANOVA, temperature=20°C, for DE source $p < 0.0001$, for m.c. $p < 0.0001$, for interaction DE source and m.c. $p = 0.011$; temperature=30°C, for DE source $p < 0.0001$, for m.c. $p < 0.0001$, for interaction DE source and m.c. $p = 0.0001$). For *T. castaneum*, there were no significant interactions between DE source and m.c. (Table 2, 2-way ANOVA, temperature=20°C, for DE source $p < 0.0001$, for m.c. $p < 0.0001$, for interaction DE source and m.c. $p = 0.062$; temperature=30°C, for DE source $p < 0.0001$, for m.c. $p < 0.0001$, for interaction DE source and m.c. $p = 0.71$). For the experiments that ranged from 10 to 16% m.c. (Figs. 1 and 2), we did not test *S. oryzae* at 7 d or *T. castaneum* at either duration, because there were treatments that caused either 0 or 100% mortality, which would constrain the slopes and make it impossible to determine if there was an interaction between DE source and m.c.

Different DEs had different efficacies. Depending upon the conditions, there was up to a 70% difference in mortality between DE sources (Table 2). However, the ranking between the DEs remained similar at different moisture–temperature combinations (Table 2, Figs. 1 and 2).

For *C. ferrugineus*, lower temperatures caused significant reductions in efficacy (Table 3). The opposite was true for *T. castaneum*, as lower temperatures caused increased efficacy for most DEs tested (Table 2). For *S. oryzae* some DE sources showed increased efficacy with lower temperatures, and others showed decreased efficacy with lower temperatures (Table 2).

Of all the insects tested, *C. ferrugineus* was the most sensitive to DE. There was 100% mortality after two days even in the moistest grain at 300 ppm (Table 4). *Oryzaephilus surinamensis* and *S. oryzae* were more tolerant than *C. ferrugineus*, with the same or less mortality after five days. *Rhyzopertha dominica* was even more tolerant with only 17% mortality after five days at 15% m.c., whereas *O. surinamensis* had 71% and *S. oryzae* had 53% mortality. *Tribolium castaneum* had greater survival than *S. oryzae* in tests with three different DEs (Figs. 1 and 2). The method of application also affected mortality. Dusting was more effective than spraying (Table 4). *Tribolium castaneum* had noticeably less DE attached to its cuticle than *C. ferrugineus*, *S. oryzae* and *R. dominica* (Fig. 3).

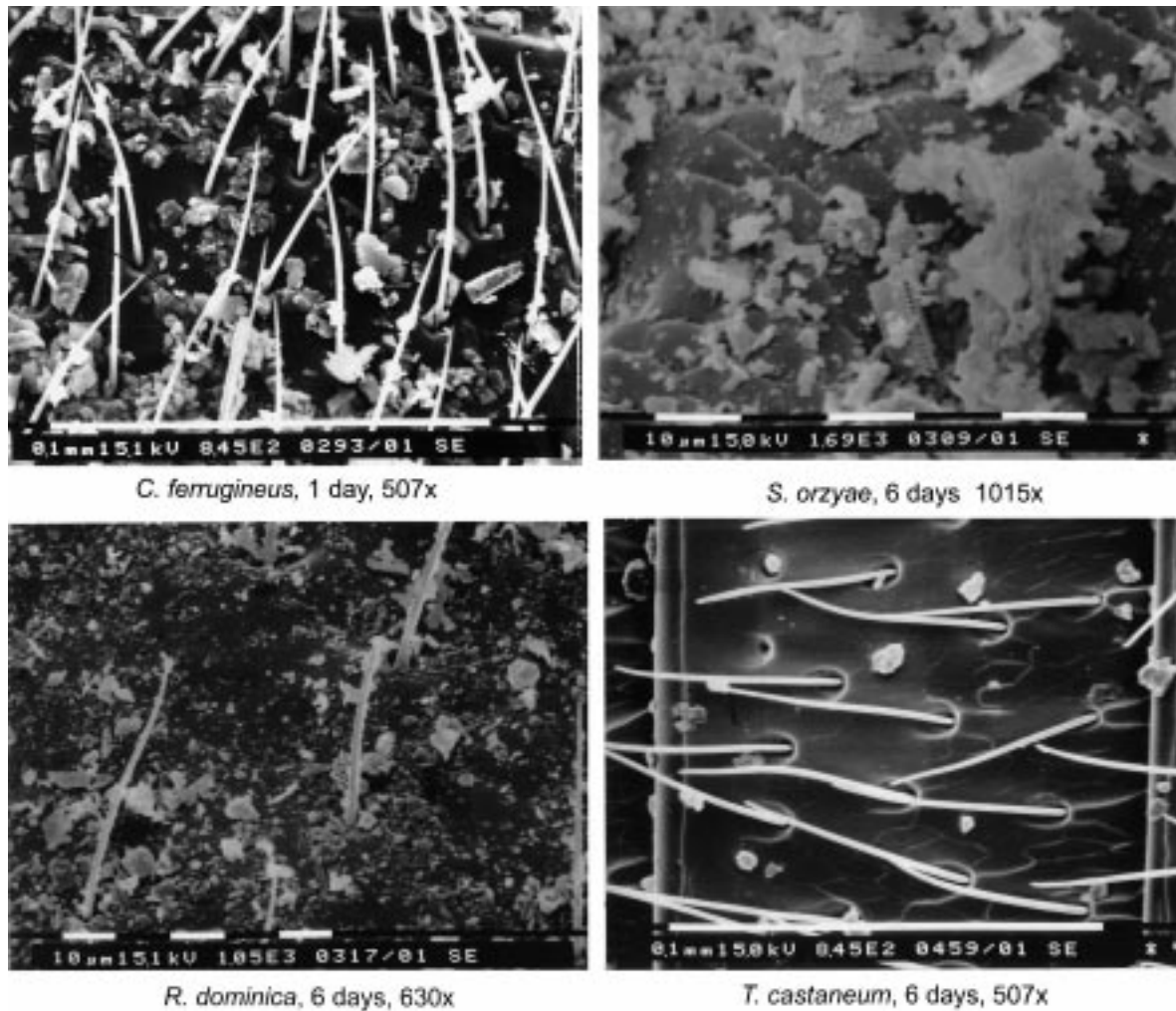


Fig. 3. Scanning electron micrographs of the ventral surface of abdomens of insects held in wheat with 600 ppm diatomaceous earth (Celite 209) for various durations.

4. Discussion

There are many examples of increased moisture content or relative humidity reducing the effectiveness of diatomaceous earth and other inert dusts (Nair, 1957; Carlson and Ball, 1962; La Hue, 1965; Ebeling 1971; Maceljski and Korunic, 1972; Desmarchelier and Dines, 1987; Aldryhim, 1990, 1993). For example, an increase in relative humidity from 40 to 60%, which corresponds to 9 and 12% m.c. in wheat (Pixton and Warburton, 1971), causes a three-fold increase in LD₅₀ for Dryacide[®] against *Tribolium confusum* Jacquelin du Val (confused flour beetle) and *S. oryzae* (Aldryhim 1990). We also saw decreases in effectiveness with higher grain moisture contents with all DEs tested. Some of these results were similar to those seen in other studies. In our tests with Dryacide[®] at 300 ppm, *S. oryzae* had 75% mortality at 12% m.c. after seven days and 30°C, and Aldryhim (1990) estimated a LD₅₀ of 369 (307–421) ppm under similar temperature and humidity levels after seven days. The increased efficacy under dryer conditions is due to increased dessication, which is the mode of action of DE (Ebeling, 1971).

DE from different geological sources, or even from the same location have different physical properties (SiO₂ content, tapped density, oil absorbency, particle size and pH) that are correlated to their insecticidal efficacy against stored-product insects (Korunic, 1997, 1998). Comparison among DEs are difficult because there is significant variation in insecticidal activity from the same geographical source, and only small quantities of DE are used for laboratory testing. For example, unlike our results, Dryacide[®] was shown to have greater efficacy than Insecto[®] and similar efficacy as Protect-It[™] in another study (Bhadriraju Subramanyam, 1999, personal communication). Also, the rank, among species did not change with the different DEs. Thus, blending DEs would not produce a DE that was effective against a broad range of stored-product insects.

If there was no interaction between DE source and moisture content, then it would be sufficient to determine the moisture response for a single DE source to determine how all DEs would respond to changes in grain moisture content. Granted, different DEs would require different concentrations, but the rate of change in mortality with respect to moisture content would be the same and independent of the DE source. One problem with a study of this nature is that mortality is constrained between 0 and 100%. There are two solutions to this problem; choose conditions which produce mortalities between these values, or test a range of concentrations and estimate the LD₅₀ or the LD₉₅, variables that are not constrained. We had some data sets that had all mortalities between 0 and 100%, and we concluded that for *S. oryzae* DE source and moisture interacted, whereas there was no interaction for *T. castaneum*. More detailed work with estimates of LD₅₀ should be done to confirm this work, and to determine what is the response of other insect species on different commodities.

The effect of temperature on DE is less well studied than the effect of moisture content. *Rhyzopertha dominica* and *S. granarius* are approximately twice as sensitive to Dryacide[®] at 30°C than at 20°C, but *T. confusum* is slightly less sensitive to Dryacide[®] at the higher temperatures (Aldryhim, 1990, 1993). Our studies showed that increased temperatures caused *C. ferrugineus* to be more susceptible and *T. castaneum* to be slightly less susceptible to DE. *Sitophilus oryzae* needs further study at various temperatures, as temperature effects were not consistent among DEs.

Other insecticides, such as the organophosphates, have positive temperature coefficients

(Snelson, 1987), becoming more toxic at higher temperatures. This is understandable, as most chemical and biochemical reactions are faster at higher temperatures; usually the reaction increases two to three times for every 10°C (Mordue et al., 1980). A few insecticides such as DDT (Osborne, 1985), pyrethrum and the many of the pyrethroids (Snelson, 1987) usually have negative temperature coefficients, becoming more toxic at lower temperatures.

There are several possible reasons why temperature would affect the efficacy of DE and why some insects have a positive temperature coefficient while others have a negative coefficient. Increased temperature would increase insect movement, causing increased contact with the DE and greater cuticular damage. Higher temperatures and increased movement would also increase water loss via the spiracles due to increased respiration. Losses via the spiracles are estimated to be three times greater than losses of water through the cuticle for a desert tenebrionid (Zachariassen, 1991). Also rate of cuticular transpiration rises only slightly with temperature until the transition temperature which for most insects is above 30°C (Wigglesworth, 1972). However, increased temperature would also increase feeding and therefore moisture replacement through the food and production of metabolic water. The synthesis of cuticular waxes may be faster at higher temperatures because of temperature effects on the biochemical pathways. However, there may be other overriding factors. In the cockroach, the synthesis of cuticular waxes is under hormonal control (Treherne and Willmer, 1975), and it is possible that damaging the cuticle or low water levels in the insect could trigger the production of cuticular waxes, causing changes in the cuticular waxes independent of the temperature. Unlike the synthetic insecticides, DE is inert and does not degrade in a temperature-dependent fashion. Within a grain bulk, the relative humidity will change slightly with temperature. For stored wheat there is about a 3% reduction in relative humidity for each 10°C increase in temperature (Pixton and Warburton, 1971). However, these changes would be too small to be responsible for the effects we observed.

Stored-product insects show a wide range of susceptibility to DE (Carlson and Ball, 1962; Desmarchelier and Dines, 1987; White and Loschiavo, 1989; Aldryhim, 1990, 1993). Though there are different rankings among these studies, overall the rankings are with the most to the least susceptible: *Cryptolestes* spp, *Oryzaephilus* spp, *Sitophilus* spp, *R. dominica* and *Tribolium* spp. In our tests *C. ferrugineus* > *O. surinamensis* = *S. oryzae* > *R. dominica*/*T. castaneum* in order of tolerance. A few studies have addressed why there are different susceptibilities among species. Nair (1957) working with magnesite dust and White and Loschiavo (1989) working with silica aerogel found that susceptible insects had more dust adhering to the cuticle. We observed that *C. ferrugineus*, the most susceptible insect, had more DE attached to its cuticle than *T. castaneum*, the least susceptible. General resistance to desiccation, either through better water retention, better water acquisition, or greater tolerance of desiccation could also be responsible for these differences in susceptibility. However, Nair (1957) and le Patourel (1986) stated that desiccation tolerance did not strictly follow resistance to DE, whereas Carlson and Ball (1962) found a good correlation. Other factors that may account for differences between the species are; size (volume to surface area ratio), quantitative or qualitative differences in cuticular lipids, differences in rate of movement through grain, behavioral reaction to DE, or desiccation.

Spraying has several advantages over dusting; workers are exposed to less dust, it does not affect grain bulk density as much (Korunic et al., 1998) and it is easier to apply. Sedimentation

of the dust can be overcome by using agitators in the spray tanks, though in some facilities access to water is limited. As seen in other studies (Maceljski and Korunic, 1972; McLaughlin 1994), slurry or spray application reduced efficacy. The suggested reason for this drop in activity is that when DE is applied as a slurry and dries, there is less contact between it and the insect than when it is applied dry (Maceljski and Korunic, 1972). Another possibility is that the particles in solution aggregate, reducing activity.

Current recommendations for *C. ferrugineus* are to apply 100 ppm of Protect-It™ at harvest only for wheat that is 14% m.c. or lower. Wheat immediately after harvest in Canada is usually between 25 and 35°C. However, in certain years, during cool wet harvests, wheat enters into storage at lower temperatures and with higher moisture content. Our results suggest that higher concentrations of Protect-It™ could control *C. ferrugineus* in these situations. These data would have to be confirmed in field trials. Also, higher concentrations of DE would cause greater reduction in bulk density, but this may not be a concern for the lower grades of wheat.

Our ultimate goal is to determine under what conditions DE can be used to control stored-product insect pests in farm and elevator storage facilities. This study has shown that there are many factors that determine if control will be obtained; concentration, duration, source of DE, insect species, grain moisture content, temperature and method of application. Not all these factors are under the control of the applicator. Often he or she must choose between a few local DE sources, and apply the DE to protect a given set of common insect pests. Moisture content and temperature can be measured, and they might be adjustable depending upon the equipment available. The application method and application rate are determined by the applicator, but may be constrained by costs or adverse effects on the grain's physical properties when using DE at higher concentrations. Laboratory studies such as this and the others cited here are useful in determining the parameters needed to control stored-product insects, but these must be verified in experiments carried out in commercial storage facilities.

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