Blanket application rates for synthetic grain protectants across agro-climatic zones: Do they work? Evidence from field efficacy trials using sorghum grain

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Abstract

Many smallholder farmers in sub-Saharan Africa rely on synthetic pesticides for protecting stored-grain. Recommendations on use of these grain protectants are typically based on "blanket" application rates which are fixed rates that are not varied according to grain type, pest range or agro-climatic regions. There are numerous anecdotal reports of storage pesticide failure or reduced efficacy from farmers. Might rising global temperatures be a contributory factor? Smallholder farmers are responding by over-applying pesticides, increasing the application frequency or switching to non-recommended pesticides; leading to a pesticide treadmill. Trials to determine the efficacy and persistence of five commercially-available synthetic pesticides applied at manufacturer's recommended rates on stored sorghum grain under contrasting climatic conditions were conducted in Mbire (mean temperatures of 32 – 42 ^{o}C and 30 – 50 % rh) and Harare (18 – 32 ^{o}C; 42 – 75 % rh) districts in Zimbabwe. Grain samples were collected at 8-

week intervals throughout a 10 month period in the 2014/15 and 2015/16 storage seasons. The samples were analyzed for insect grain damage, weight loss, total number of storage insects by species) and grain moisture content. Results showed significant differences in the performance of treatments ($p < 0.001$). Grain damage was consistently higher in Harare than in Mbire. *Tribolium castaneum* was the dominant pest in Mbire, while *Sitotroga cerealella* and *Sitophilus oryzae* were dominant in Harare. *Tribolium castaneum* populations were high in the Shumba Super dust® (fenitrothion 1% + deltamethrin 0.13%) treatment in Mbire, while *S. cerealella* was dominant in Super guard® (pirimiphos-methyl 1.6% + permethrin 0.4%) and Actellic Gold dust® (pirimiphos-methyl 1.6% + thiamethoxam 0.36%) treated grain in Harare. Grain moisture content varied with ambient conditions, and was high in treatments with high insect pest levels. The results show that differences in climatic conditions influence insect pest species dynamics and response to pesticide treatments. Storage pesticides are not equally effective across different climatic conditions; thus more context-specific application recommendations are required.

Key words: synthetic pesticides, pesticide degradation, pesticide tolerance, sorghum grain storage, climate change and variability, storage pest dynamics

1. Introduction

Improvements in the food and nutrition security status of many sub-Saharan African (SSA) countries through enhanced crop production are being hampered by a rapidly growing human population and the effects of climate change and variability (Kaminski and Christiaensen, 2014). Rising temperatures and less predictable rainfall patterns and amounts are already occurring in SSA (Niang et al., 2014). Temperatures are projected to increase by up to 4 ^{o}C by the end of the century, depending on the development pathway chosen (IPCC, 2014; Serdeczny et al., 2016). Due to this and inadequate and more intermittent rains during the growing season, the success of dryland crop production is getting more unpredictable. The importance of efficient postharvest grain management to protect whatever is harvested against loss due to storage insect pest damage is becoming ever more important (Stathers et al., 2013; Vassilakos et al., 2015). To guard against storage pest damage, many smallholder farmers in SSA rely on applying synthetic pesticides composed of organophosphates and synthetic pyrethroids (Arthur, 1996; Stathers et al., 2002, Vassilakos, 2015). However, rising temperatures may promote increased degradation of these synthetic pesticides (Ismail et al., 2012) and may also favour development of many grain storage insect pests (Gornall et al., 2010) and affect their distribution and biology (Palikhe, 2007) such as shortening of life cycles. Shortened life cycles can increase the chances of insects developing resistance to pesticides as the insects more quickly adapt to treatments (Musolin and Saulich, 2012, Velázquez-Fernández et al., 2012).

In many areas characterized by inadequate rainfall and high temperatures in SSA, small grains such as sorghum are staples and therefore widely grown as a coping and resilience strategy to these climatic conditions. However, the postharvest losses that occur reduce the amount of grain available for human consumption. Informed estimates suggest annual sorghum postharvest weight losses of 12.1 % for SSA (APHLIS, 2014). Most of these farm-level postharvest losses are due to poor postharvest handling and insect pest attack (World Bank, 2011) and the latter necessitates effective control strategies, such as synthetic pesticides.

However, over-reliance on a narrow range of synthetic pesticides makes the development of pest resistance inevitable (Hagstrum and Subramanyam, 2006). Although most of the evidence is anecdotal, farmers across SSA frequently report storage pesticide failure or reduced efficacy (De Groote et al., 2013; Mlambo et al., 2017), and tend to respond by increasing the pesticide application rates, using non-recommended pesticides and/or increasing application frequencies to effect kill, which increases safety risks for users, consumers and the environment, and can trigger a pesticide treadmill effect.

The application of synthetic pesticides on stored grain is based on “blanket” or generalised application rates (Pretty, 2012). There are fixed rates that are not varied according to grain type, pest range or agro-climatic regions (temperature, relative humidity), despite the often wide variability in these factors under field conditions. This is also irrespective of possible implications on pesticide stability and dominant insect pest species in the different physical environments. These synthetic grain protectants are supposed to be applied just once at the start of a 6 to 12-month storage period. The use of “blanket” application rates, make manufacturers’ recommendations easier for agricultural extension agents to extend, and are simpler to implement for farmers. However, this practice could eventually render the pesticides ineffective; a potential drawback not always understood by stakeholders. The objective of the current study was to determine the suitability of “blanket” application rates across different agro-climatic regions, a topic which has not previously been well-investigated under field conditions.

Much of the research undertaken to investigate insect response to synthetic pesticides has focussed on acute effects of adult mortality under rigidly controlled experimental conditions in the laboratory. There is, therefore, limited information on the effect on insect fecundity, pesticide persistence, or the effects on mixed populations of insects *in vivo*. The current studies were on sorghum, a small-grain grown in some of the more marginal agro-climatic zones; areas which are likely to get even warmer in the future. Therefore, information generated in this study is important in terms of deepening understanding of crop postharvest protection and food security in already highly vulnerable situations. The study, therefore, also sought to determine the diversity of storage insect species found on sorghum under the prevailing ambient conditions in two contrasting agro-climatic zones

2. Materials and methods

2.1 Description of trial sites

On-station researcher-managed trials to determine the persistence and effectiveness of synthetic grain protectants under contrasting agro-climatic conditions were set up at Mahuwe Rural Service Centre in Mbire district (20^{o} 43′ S; 30^{o} 34′ E), Zimbabwe, and at the Department of Crop Science, University of Zimbabwe in Harare (17^{o} 47’ S; 31^{o} 03’ E), Zimbabwe, during the 2014/15 and 2015/16 storage seasons. Mbire district is located in the Zambezi valley, in northern Zimbabwe, about 283 km from the capital city, Harare (Fig. 1). The district is characterized by high annual temperature ranges of 32 – 42 ^{o}C, low rainfall of less than 450 mm per annum, and low mean annual relative humidity of 30 – 50 %. Harare, is located in central Zimbabwe, and receives warm to high temperatures ranging between 18 – 30 ^{o}C, a high mean annual rainfall range of 900 – 1000 mm, and has a mean annual relative humidity of 42 – 75 %.

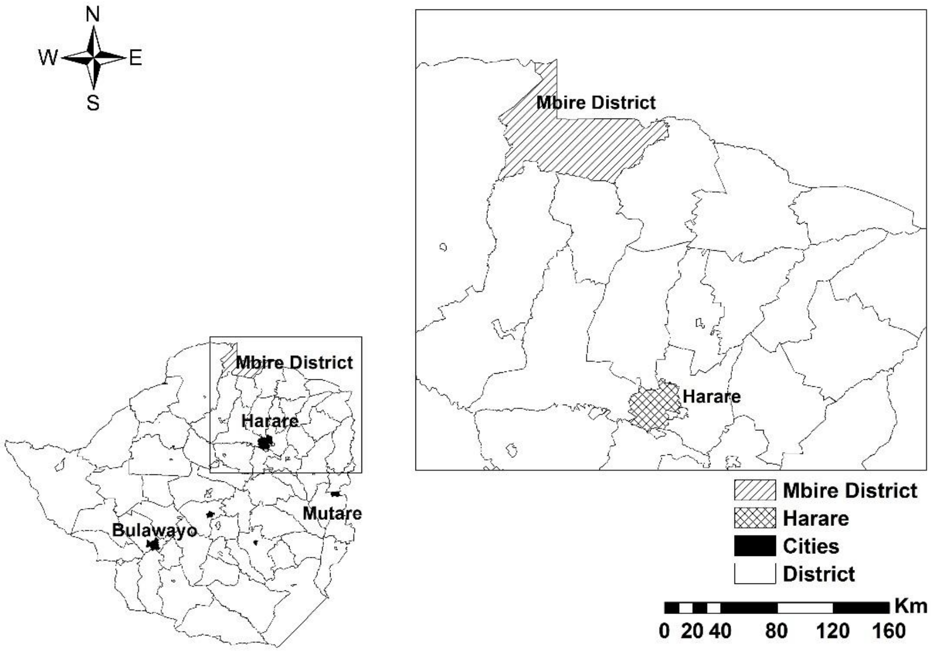

Figure 1: Map of Zimbabwe showing the trial sites: Harare and Mbire district

2.2 Experimental layout

Five commercially available synthetic grain protectant pesticides commonly used in Zimbabwe and an untreated control treatment were evaluated in this study (Table 1). In response to numerous anecdotal reports from farmers that locally-purchased grain protectants had lower efficacy than those bought at agro-dealers in urban centres, two Shumba Super dust® pesticide products were evaluated in the first season; one was purchased from a registered agro-dealer in Harare and the other bought from a local agro-dealer in Mbire. The Mbire local Shumba Super dust was not applied in Harare. However, as no significant differences between the locally-bought and Harare-bought pesticides were found in the first season trials, the Mbire locally purchased Shumba Super treatment was replaced by a newly introduced synthetic pesticide dust, Actellic Gold dust® during the second season.

Sorghum grain weighing 450 kg was thoroughly mixed to ensure it was as homogenous as possible before dividing it into lots of 75kgs of threshed grain per treatment. The 75 kgs of the threshed grain was sub-divided into three 25 kg lots before being separately admixed with pesticides at the application rates recommended on their labels (Table 1). During the 2014/15 season, SC Sila variety of sorghum was used, while in the 2015/16 storage season, a 1:1 mixture of SC Sila and Macia varieties of sorghum grain was used. These smallholder farmers commonly change and mix the crop varieties they store as grain for food. Therefore grain protectants need to be effective on a range of varieties and mixtures.

After admixing, each treatment replicate was loaded into new polypropylene bags, which were then labelled and placed on brick dunnage to avoid direct contact with the floor and therefore reduce the chances of moisture accumulation in the stored grain. The trials were conducted over a 40-week period (~10 months) during each storage season. The treatments were laid out in a completely randomized design with three replicates of each treatment per site. Temperature and relative humidity data were collected using Easylog data loggers (Model EL-USB-1, Whiteparish, Wiltshire, SP5 2SJ, United Kingdom) installed 1.5 m above the ground in the storage rooms. The trials were housed in brick-walled rooms, with ceilings, and iron sheet roofs at both sites.

2.3 Sampling, sample analysis and measurements

Composite samples of 500 g were collected from each treatment at each sampling timepoint using a Seedburo Bag Trier spear (No. 76 13”, Nickel Plated steel, 1½” outside diameter at the large end, 7 3/8” long with top slot of 1¼” tapering down to ¼”). The 500 g (approximately 18 000 grains) sample was used for analysis of grain moisture content, grain damage, storage insect numbers present by species, and grain weight loss. The grain samples were collected by probing from at least five equidistant points around the bag, ensuring that grain was collected from the top, middle and bottom sections of each bag. Sampling was done every eight weeks until trial termination at 40 weeks. Insect counts per species were expressed per kilogram of grain; % grain damage was calculated as a proportion of the total number of grains in the sub-sample; and grain weight loss was determined using the count-and-weigh method (Boxall, 1986). Grain moisture content was measured using a pre-calibrated Dickey-John digital moisture meter (M3G™ model; Dickey-John Corporation, Minneapolis, USA).

Table 1: Grain protectant treatments used in the trial, and their active ingredients

Trade name	Active ingredients	Application rate (g / 25kg grain)*	Pesticide groups combined in product			Harare district		Mbire district	
			Organophosphates	Pyrethroids	Neonicotinoids	2014/15 season	2015/16 season	2014/15 season	2015/16 season
1. Super guard dust®	pirimiphos-methyl 1.6% + permethrin 0.4%	13.9	●	●		✓	✓	✓	✓
2. Chikwapuro®	pirimiphos-methyl 2.5% + deltamethrin 0.1%	10.0	●	●		✓	✓	✓	✓
3. Harare Shumba super dust®	fenitrothion 1% + deltamethrin 0.13%	12.5	●	●		✓	✓	✓	✓
5. Mbire Shumba super dust®	fenitrothion 1% + deltamethrin 0.13%	12.5	●	●		x	x	✓	x
6. Actellic gold dust®	pirimiphos-methyl 1.6% + thiamethoxam 0.36%	12.5	●		●	x	✓	x	✓
7. Ngwena yedura®	pirimiphos-methyl 2.5% + deltamethrin 0.2%	10.0	●	●		✓	✓	✓	✓
8. Untreated control	N/A					✓	✓	✓	✓

** For pesticides, manufacturer's label application rates were used. Shumba super dust® obtained from Mbire agro-dealers for use in the 2014/15 storage season was replaced by Actellic gold dust® during the 2015/16 storage season;* x *– indicates absence of the treatment in that specific trial*

2.4 Data analysis and data presentation

The percentage number of damaged grains, and the percentage weight loss data were analysed in Genstat version 14, using a repeated measures analysis of variance (rANOVA) as the samples were collected from the same experimental unit throughout the trial. Initially all data were subjected to the Shapiro-Wilk test for normality. Data on percentage number of damaged grains and percentage weight loss which failed the normality test were transformed using the square root transformation (Bartlett et al., 1936). Where the ANOVA showed significant differences, means were further separated using Fisher's protected LSD at 5 % probability.

Data on total *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae) populations in Harare were presented separately in tables derived from ANOVA means because of their abundance which masked other insect species. Data on total counts of *S. cerealella* did not meet the assumptions of analysis of variance and were $\log_{10}(\mathbf{x} + 1)$ transformed, with $\mathbf{x}$ representing the recorded original mean (De Muth, 2014).

3. Results

3.1 Pest dynamics

The dominant insect pest species in the Harare trial during the 2014/15 storage season was *S. cerealella*, which developed extensively in grain treated with Super guard dust and in untreated grain (Table 2 compared to Fig. 2). The highest populations of the moth were recorded in July 2015 (at 32 weeks storage) and the total populations decreased thereafter. However, the protectants Chikwapuro and Ngwena yedura managed to suppress the development of the moth throughout the 40 week storage period. High numbers of *Sitophilus oryzae* L. (Coleoptera: Curculionidae) developed in the untreated control grain in the Harare trial during the 2014/15 storage season (Fig 2).

Table 2: Mean total *Sitotroga cerealella* counts (± SEM) per kilogram of sorghum grain in the different storage protectant treatments during the 2014/15 storage season in Harare (n = 3)

	Storage duration (weeks)					
Treatment	**0**	**8**	**16**	**24**	**32**	**40**
Untreated control	7.24 ± 2.07	9.11 ± 2.55a	556.08 ± 148.39c	1382.84 ± 68.62c	6163.77 ± 2831.63b	1395.86 ± 119.03b
Super guard dust	10.35 ± 1.94	207.5 ± 17.04b	251.35 ± 19.26c	1289.02 ± 90.4c	9818.79 ± 1126.41b	1627.91 ± 201.77b
Ngwena yedura	5.07 ± 4.28	6.75 ± 1.76a	7.17 ± 0.07b	4.06 ± 1.45a	8.14 ± 2.31a	3.41 ± 1.01a
Chikwapuro	6.97 ± 5.12	3.68 ± 1.01a	0.0 ± 0.00a	8.01 ± 2.05ab	12.24 ± 6.42a	1.83 ± 0.99a
Shumba Super dust (Harare)	6.85 ± 2.68	24.76 ± 22.36a	24.67 ± 21.54b	61.07 ± 53.48b	93.28 ± 81.35a	246.14 ± 240.95a
p-value	**0.79**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
$F_{4,10}$	**0.42**	**48.59**	**12.7**	**164.37**	**11.11**	**27.82**

**Means in the same column followed by different alphabetical letters are significantly different using Fisher's protected 5 % LSD test*

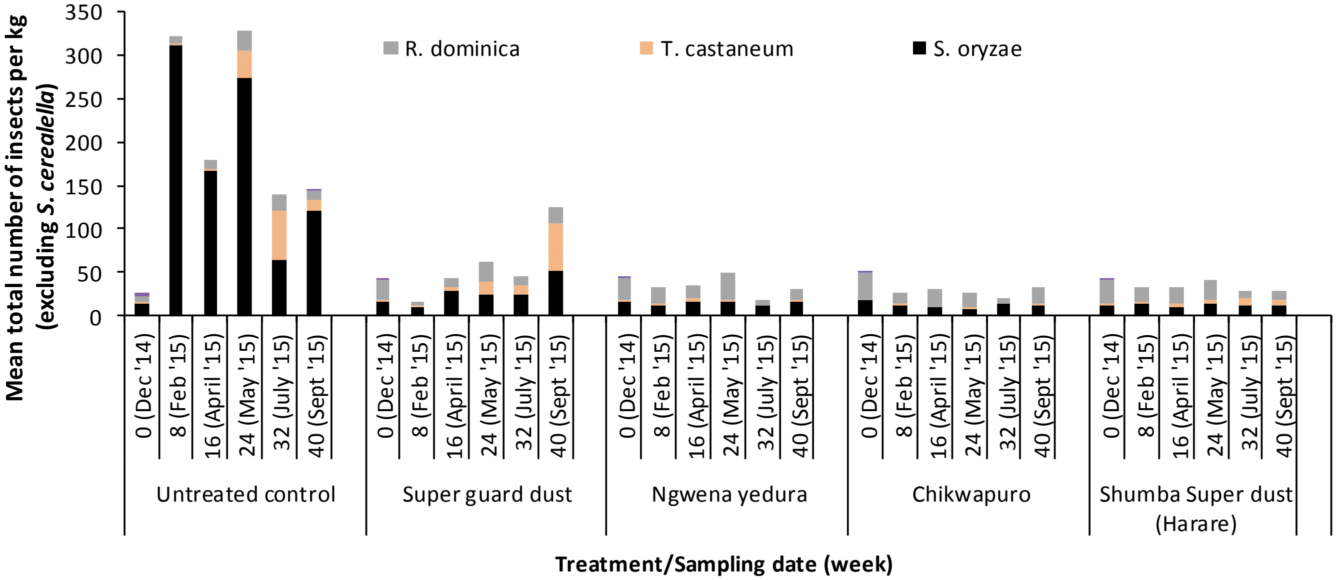

Figure 2: Comparison of mean total number of adult insects by species (excluding *Sitotroga cerealella*) per kilogram of sorghum grain in different grain protectant treatments in Harare during the 2014/15 storage season (n = 3)

Although *S. cerealella* and *S. oryzae* were dominant in Harare, they failed to establish in the Mbire trial during the two seasons, except during the relatively warmer months, between April and June where temperatures of 28 – 30 ^{o}C were experienced. *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) and *Rhyzopertha dominica* (Fabricius) (Coleoptera: Bostrichidae) were the dominant storage pests in Mbire during the 2014/15 storage season (Fig. 3). *Sitotroga cerealella* populations were recorded between January and May 2015 (week 8 to 24) (end of summer season to the onset winter).

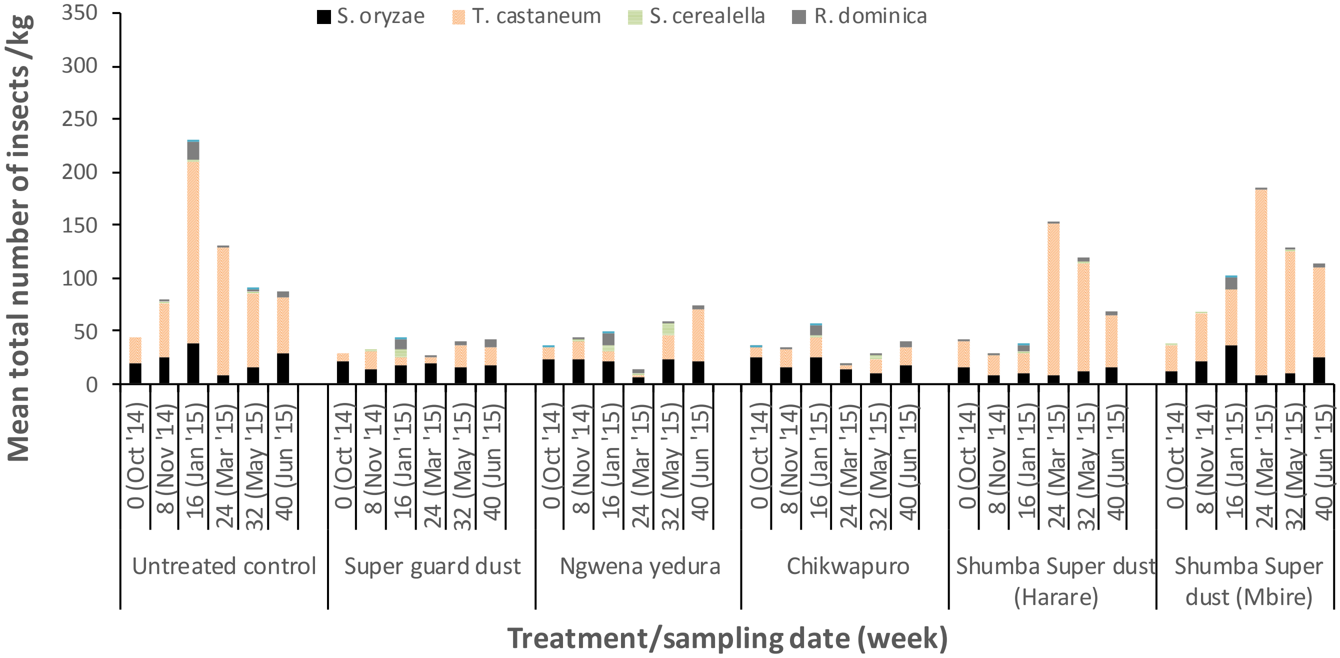

Figure 3: Comparison of the mean total number of adult insects by species per kilogram of sorghum grain in Mbire during the 2014/15 storage season (n = 3)

Higher initial pest populations were recorded in the Harare trial during the 2015/16 than the 2014/15 storage season. In the Harare 2015/16 trial, there was a decline in the number of insect pests recorded in all the pesticide-treatments after the baseline samples were collected. *Sitotroga cerealella* and *S. oryzae* were the dominant pest species in Harare during the 2015/16 season, with *S. cerealella* managing to develop in Super guard treated grain while the other pesticide treatments suppressed it (Table 3). Numbers of *S. oryzae* increased in the untreated control (Fig. 4), but failed to increase in the synthetic pesticide treatments. Low populations of *T. castaneum* were recorded in the untreated grain and in Shumba Super dust.

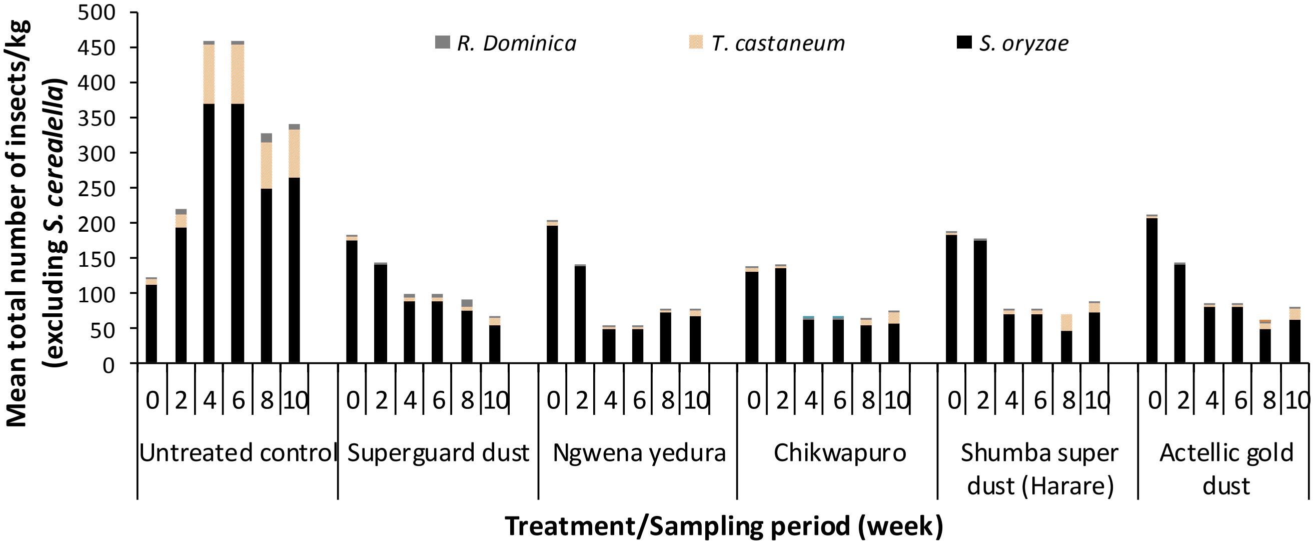

Figure 4: Comparison of the mean total number of adult insects by species in different grain protectant treatments in Harare during the 2015/16 storage season (n = 3)

Table 3: Comparison of the mean total adult *Sitotroga cerealella* counts (± SEM) in different grain protectant treatment in Harare during the 2015/16 storage period (n = 3)

Treatment	**0 weeks**	**8 weeks**	**16 weeks**	**24 weeks**	**32 weeks**	**40 weeks**
Untreated control	5.82± 1.32	5.46 ±1.67	34.04 ± 15.12ab	34.04 ± 15.12ab	41.38 ± 9.62bc	135.84 ± 61.22abc
Super guard dust	3.47 ± 1.35	17.46 ± 8.23	119.05 ± 41.24c	119.05 ± 41.24c	199.09 ± 163.87c	1060.51 ± 633.64c
Ngwena yedura	5.86 ± 1.41	17.67 ± 10.16	6.86 ± 4.84a	6.86 ± 4.84a	30.14 ± 11.86abc	34.00 ± 14.26a
Chikwapuro	3.50 ± 1.84	3.86 ± 2.57	40.54 ± 10.38b	40.54 ± 10.38b	8.70 ± 2.84a	40.77 ± 21.48a
Shumba Super dust (Harare)	9.45 ± 0.76	21.23 ± 1.54	30.26 ± 4.92ab	30.26 ± 4.92ab	19.03 ± 6.84ab	22.97 ± 6.14a
Actellic Gold dust	7.88 ± 1.49	26.37 ± 18.49	52.58 ± 16.49bc	61.83 ± 7.47bc	105.47 ± 29.17c	174.19 ± 20.68bc
p-value	**0.07**	**0.28**	**0.01**	**0.01**	**0.02**	**<0.01**
$F_{5,12}$	**2.27**	**0.85**	**3.72**	**4.19**	**1.14**	**2.41**

**Means in the same column followed by different alphabetical letters are significantly different using Fisher's protected 5 % LSD test*

In the 2015/16 Mbire trial, the dominant insect pest species were *S. oryzae* and *T. castaneum* (Fig. 5). *Tribolium castaneum* build-up was high in the untreated and the Shumba Super dust treated grain. The pest also developed in lower numbers in all the other pesticide treatments from week 24 onwards (Fig. 5).

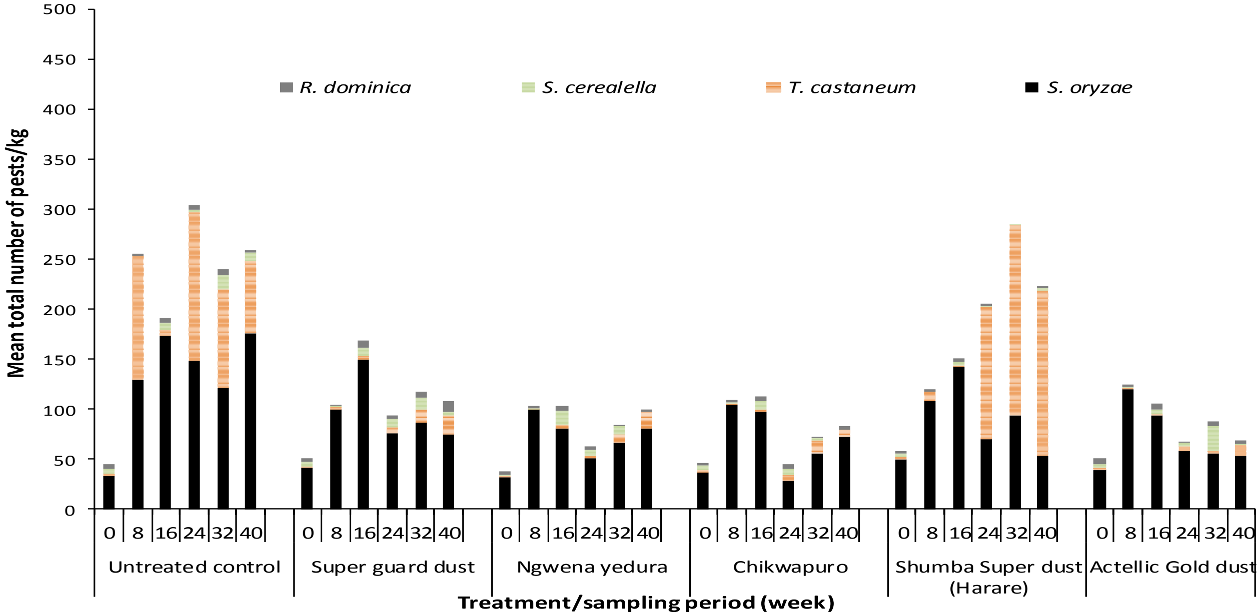

Figure 5: Comparison of the mean total adult insect counts per kilogram of stored sorghum grain in different grain protectant treatments in Mbire district during the 2015/16 storage season (n =3)

3.2 Grain damage

Grain damage was high in the untreated and the Super guard dust treated grain in Harare in 2014/15 (Table 4). While damage was suppressed in the Chikwapuro, Ngwena yedura and Shumba Super dust treatments throughout the storage season. From 8 weeks storage onwards, significant differences in the percentage number of damaged grains were noted between treatments ($F_{4, 10} = 46.06$; $p < 0.01$), and the differences became wide at the 40 weeks ($F_{4, 10} = 32.34$; $p < 0.01$). In Mbire, significant differences ($F_{5, 12} = 6.47$; $p < 0.004$) in grain damage between grain protectant treatments were recorded from 16 weeks of storage (Table 4), with an increase in grain damage in the two Shumba Super dust treatments, Super guard dust and untreated control. However, the overall changes in grain damage were low in Mbire district as compared to Harare during the 2014/15 storage season.

The level of grain damage was significantly higher ($p < 0.001$) in the untreated (36.5 %), Actellic Gold dust (19.0 %) and Super guard dust (11.9%) treated grain than in the other treatments in Harare by the end of the 2015/16 storage season (Table 5). Significant differences between treatments were recorded from 8 weeks storage onwards in Harare, whereas in Mbire they only occurred at 24 and 32 weeks storage. Grain damage levels were higher in Harare than Mbire district during the 2015/16 storage season (Table 5). In Harare, the pesticides Ngwena yedura, Chikwapuro and Shumba Super dust suppressed insect grain damage throughout the 2015/16 storage season, whilst Chikwapuro, Actellic Gold dust and Super guard dust were effective in Mbire although grain damage levels were low in all treatments (< 10 %) for up to 32 weeks (Table 5).

3.3 Grain weight loss

Grain weight loss was lower in Harare (0.42 %) than in Mbire (1.28 %) at trial set-up in 2014/15. From 16 weeks of storage onwards, significant differences in grain weight loss were recorded between the different protectant treatments ($F_{5, 10} = 5.31$; $p = 0.015$). In the Harare trial, grain weight loss was significantly higher in the untreated and Super guard dust treated grain while in

Mbire district, higher grain weight loss was recorded in the untreated control and the two Shumba Super dust pesticide treatments (Table 6). Overall, grain weight loss was higher in Harare than in Mbire district during the 2014/15 storage season.

During the 2015/16 storage season, significant differences ($F_{5, 17} = 17.13$; $p < .001$) in grain weight loss were recorded from week 24 weeks until trial termination in Harare, but only at 40 week's storage in Mbire district ($F_{5, 17} = 6.35$; $p = 0.004$) (Table 7). Weight loss was significantly higher in the untreated grain than in the treated grain from 24 weeks' storage in Harare although by 32 weeks' storage weight loss in the Super guard dust and Actellic Gold dust was also significantly higher than in the grain treated with the other protectants in Harare. In Mbire, significantly higher grain weight loss was only recorded in the untreated control and Shumba Super dust treatments after 40 weeks' storage (Table 7).

3.4 Grain moisture content and storage room temperatures

Mean temperatures in storage rooms in Harare were lower (22 – 24 ^{o}C) than those in Mbire district (29 – 34 ^{o}C) (Figs. 6**a** and **b**) during the 2014/15 storage season. In Harare, grain moisture content fluctuated in all treatments, with highest peaks occurring in the untreated and Super guard dust treated grain. However, in Mbire district, grain moisture content increased from week 8 (November) and reached a peak in week 16 (13.5 ± 0.08). An increase in temperatures within the storage rooms was linked to an increase in grain moisture content at both sites (Figs 6**a** and **b**).

The room temperatures within the storage rooms in Harare were lower than those of Mbire district during the 2015/16 storage season. The mean temperature ranges within the storage rooms in Harare were between 20 and 26 °C, and dropped slightly from week 24 until the end of the season. Grain moisture content in the Harare trial increased from 9 to 12 % between week 8 and 16 of storage (Fig. 7**a**). However, untreated control and Super guard treated grain had higher moisture contents at week 40. In the Mbire trial, high mean temperatures (27 – 33 °C) were recorded in the storage room (Fig. 7**b**) and low grain moisture content of (9 – 10 %) ranges were recorded. A drop in grain moisture content at week 8 in Mbire district coincided with an increase in mean temperatures during the same period (Fig. 7**b**).

Table 4: Comparison of mean percentage number of damaged grains in different grain protectant treatments in Harare and Mbire district during the 2014/15 storage season (n = 3)

Treat-ment	**Harare**						**Mbire**					
	0 weeks	8 weeks	16 weeks	24 weeks	32 weeks	40 weeks	0 weeks	8 weeks	16 weeks	24 weeks	32 weeks	40 weeks
1	1.92±0.15	7.36±0.30c	10.33±2.09c	24.95±0.03b	19.97±2.75b	35.59±6.27b	7.22±0.88	6.67±0.92	12.18±0.83cd	12.31±0.43	16.75±0.83c	17.83±1.50c
2	2.54±0.15	4.99±0.50b	6.20±0.30b	23.23±1.10b	30.33±2.41c	41.46±4.00b	6.63±0.41	6.07±0.75	9.49±1.01ab	10.70±0.46	10.70±0.78a	12.78±0.54ab
3	2.16±0.26	2.43±0.15a	2.53±0.23a	2.54±0.07a	2.69±0.23a	2.75±0.47a	7.06±0.89	4.88±0.49	10.13±0.73abc	10.45±0.49	10.93±1.73a	11.65±0.45a
4	2.10±0.24	2.92±0.22a	2.74±0.23a	3.18±0.41a	3.05±0.36a	2.30±0.36a	6.99±0.10	6.33±0.40	8.88±0.29a	9.56±0.21	11.12±0.14a	11.01±0.11a
5	2.21±0.14	3.25±0.15a	4.70±1.34ab	4.57±1.50a	8.96±5.53a	5.13±0.37a	7.37±0.73	7.44±0.63	13.30±0.39d	12.05±1.49	11.51±0.57a	15.88±0.81bc
6	*	*	*	*	*	*	8.21±0.79	6.94±0.78	11.43±0.44bcd	10.79±0.08	14.15±0.62b	14.04±0.70ab
P-value	**0.31**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0 .01**	**0.71**	**0.22**	**<0.01**	**0.12**	**<0 .01**	**<0.01**
$F_{5,12}$	**1.38**	**46.06**	**10.17**	**177.18**	**16.21**	**32.34**	**0.59**	**1.65**	**6.47**	**2.19**	**15.38**	**5.51**

1 = Untreated control ; 2 = Super guard dust;3 = Ngwena yedura ;4 = Chikwapuro; 5 = Shumba Super dust (Harare); 6 = Shumba Super dust (Mbire)

All means in the same column followed by a different letter are significantly different from one another at 5% LSD

Table 5: Comparison of mean percentage number of damaged grains (±SEM) in different grain protectant treatments in Harare and Mbire district during the 2015/16 storage season (n=3).

Treat-ment	**Harare**						**Mbire**					
	0 weeks	8 weeks	16 weeks	24 weeks	32 weeks	40 weeks	0 weeks	8 weeks	16 weeks	24 weeks	32 weeks	40 weeks
1	4.10±0.01	6.97±0.41b	18.41±1.11c	25.13±2.29c	31.28±1.49c	36.49±1.15c	4.60±0.60	4.98±0.93	4.40±0.58	6.62±0.74b	8.71±1.19c	10.25±2.10
2	4.81±0.31	5.29±0.51a	5.03±0.60a	6.50±0.43ab	10.70±0.77b	11.92±0.97ab	4.20±0.23	4.25±0.23	4.85±0.57	4.27±0.28a	4.80±0.47ab	5.8±0.52
3	4.58±0.07	5.90±0.30ab	4.72±0.32a	4.85±0.37a	4.50±0.31a	4.99±0.30a	4.11±0.45	4.26±0.41	4.21±0.24	3.9±0.14a	6.80±1.21bc	9.29±1.93
4	4.27±0.06	4.76±0.62a	5.30±0.26a	5.88±0.08ab	5.07±0.32a	5.44±0.38a	3.48±0.49	3.62±0.51	3.44±0.11	3.72±1.00a	5.04±0.64ab	7.65±1.58
5	4.37±0.21	6.63±0.10b	5.61±0.66ab	5.99±0.57ab	5.42±0.14a	6.38±0.41a	5.02±1.10	4.93±1.05	4.37±0.08	6.69±0.50b	8.16±0.30c	8.65±0.11
6	4.34±0.20	5.04±0.32a	8.19±1.53b	9.67±2.64b	11.19±2.6b	18.96±6.31b	3.94±0.79	3.93±0.79	3.24±0.30	3.51±0.12a	4.31±0.13a	4.62±0.15
P-value	**0.17**	**0.02**	**<0 .01**	**<0 .01**	**<0 .01**	**<0 .01**	**0.69**	**0.73**	**0.69**	**<0.01**	**0.01**	**0.12**
$F_{5,12}$	**1.89**	**4.56**	**37.03**	**27.86**	**53.46**	**21.06**	**0.62**	**0.56**	**2.76**	**6.73**	**5.22**	**2.23**

1 = Untreated control ; 2 = Super guard dust;3 = Ngwena yedura ;4 = Chikwapuro; 5 = Shumba Super dust (Harare); 6 = Actellic Gold dust

Means in the same column followed by different alphabetical letters are significantly different using Fisher's protected 5 % LSD test

Table 6: Comparison of mean % grain weight loss (±SEM) in different grain protectant treatments in Harare and Mbire during the 2014/15 storage season (n = 3)

Treatment	**Harare**				**Mbire**			
	16 weeks	**24 weeks**	**32 weeks**	**40 weeks**	**16 weeks**	**24 weeks**	**32 weeks**	**40 weeks**
Untreated control	2.34 ± 0.46b	6.1 ± 0.26b	4.4 ± 0.46bc	8.39 ± 0.49b	3.1 ± 0.45b	3.18 ± 0.09d	4.19 ± 0.21c	3.81 ± 0.2c
Super guard dust	1.44 ± 0.12ab	4.98 ± 1.22b	6.74 ± 0.41c	9.79 ± 0.41b	1.63±0.4a	2.13 ± 0.06ab	1.98 ± 0.11a	2.16 ± 0.15a
Ngwena yedura	0.61 ± 0.05a	0.59 ± 0.06a	0.46 ± 0.05a	0.5 ± 0.05a	2.01 ± 0.16a	2.08 ± 0.14ab	2.16 ± 0.22a	2.03 ± 0.17a
Chikwapuro	0.62 ± 0.04a	0.34 ± 1.22a	0.52 ± 0.41a	0.57 ± 0.1a	1.79 ± 0.46a	1.69 ± 0.27a	2.23 ± 0.09a	1.95 ± 0.05a
Shumba Super dust (Harare)	1.2 ± 0.5a	1.27 ± 0.46a	2.79 ± 1.97ab	2.14 ± 1.97a	3.58 ± 0.28b	2.58 ± 0.24bc	2.86 ± 0.12b	3.31 ± 0.36bc
Shumba Super dust (Mbire)	*	*	*	*	3.15 ± 0.14b	2.77 ± 0.19cd	3.81 ± 0.08c	3.2 ± 0.1b
p-value	**0.02**	**<0 .01**	**<0.01**	**<0 .01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
$F_{5,12}$	**5.31**	**20.16**	**8.27**	**19.85**	**8.28**	**8.75**	**38.11**	**15.99**

Figures presented in the table are original mean losses per treatment, and were compared per column. Figures within a column followed by a different letter are significantly different from one another. (*) indicates treatment excluded

Table 7: Mean % grain weight loss (±SEM) in Mbire and Harare during the 2015/16 storage season (n = 3)

Treatment	**Harare**				**Mbire**			
	16 weeks	**24 weeks**	**32 weeks**	**40 weeks**	**16 weeks**	**24 weeks**	**32 weeks**	**40 weeks**
Untreated control	1.58 ± 0.58	5.97 ± 0.14b	6.58 ± 1.61b	8.14 ± 1.94c	0.4 ± 0.13	1.79 ± 0.32	1.72 ± 0.32	2.43 ± 0.41c
Super guard dust	1.01 ± 0.1	1.69 ± 0.33a	4.49 ± 0.76b	5.8 ± 0.48bc	1.17 ± 0.52	1.64 ±0.35	0.34 ±0.11	1.25 ± 0.08ab
Ngwena yedura	0.51 ± 0.1	0.5 ± 0.1a	0.58 ± 0.12a	0.85 ± 0.08a	0.95 ± 0.32	0.74 ± 0.11	1.11 ± 0.55	0.96 ± 0.32a
Chikwapuro	1.13 ± 0.57	1.35 ± 0.74a	0.59 ± 0.2a	0.97 ± 0.13a	0.71± 0.23	1.36 ± 0.68	0.67 ± 0.29	0.62 ± 0.11a
Shumba Super dust (Harare)	0.68 ± 0.11	0.62 ± 0.19a	1.36 ± 0.52a	1.17 ± 0.11a	0.97 ± 0.01	1.87 ± 0.28	1.17 ± 0.16	1.78 ± 0.14bc
Actellic Gold dust	0.57 ± 0.18	1.6 ± 0.84a	5.51 ± 1.29b	3.35 ± 1.06ab	0.62 ± 0.11	0.88 ± 0.02	0.64 ± 0.03	0.97 ± 0.27a
p-value	**0.3**	**<0 .01**	**<0.01**	**<0.01**	**0.47**	**0.20**	**0.11**	**<0.01**
$F_{5,12}$	**1.38**	**17.13**	**14.92**	**10.56**	**0.97**	**1.75**	**2.29**	**6.35**

Figures presented in the table are original mean losses per treatment, and were compared per column. Figures within a column followed by a different letter are significantly different from one another

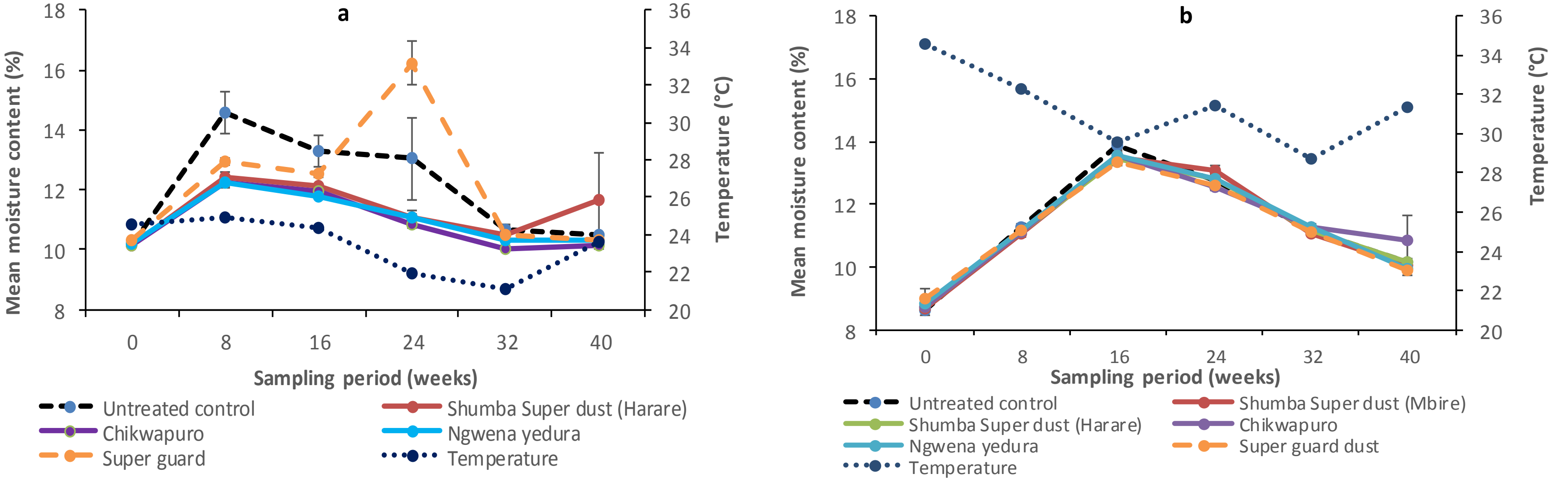

Figure 6: Comparison of the mean % grain moisture content (±SEM) in different grain protectant treatments and mean store room temperature in Harare (**a**) and Mbire (**b**) during the 2014/15 storage season (n = 3*). In some cases, error bars are not visible due to little variation between the treatment replications.*

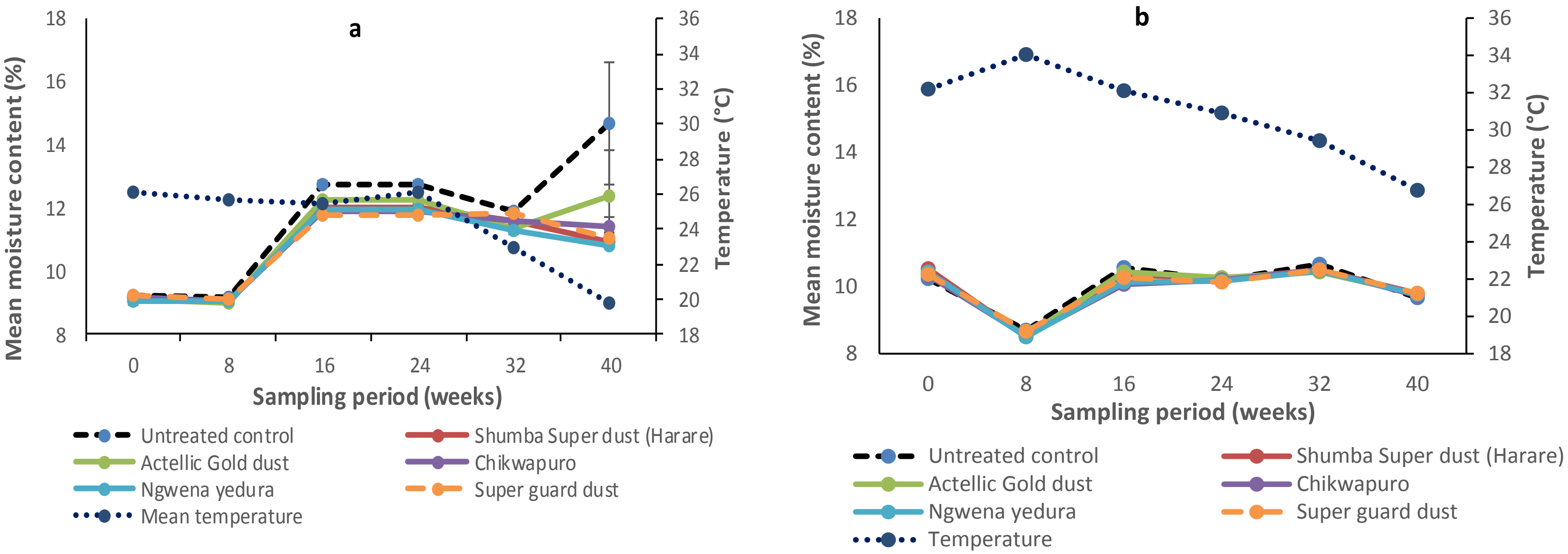

Figure 7: Comparison of the mean percentage grain moisture content (± SEM) in different grain protectant treatments and mean storage room temperatures in Harare **(a)** and Mbire **(b)** during the 2015/16 storage season (n = 3). *In some cases, error bars are not visible due to little variation between the treatment replications.*

Discussion

The climatic conditions at the two trial sites influenced which insect pest species became dominant. The warm mean temperatures (23.6 ± 0.8 ^{o}C) in Harare during the 2014/15 storage season, with mean temperature range of 22 – 24 ^{o}C, favoured the development of *S. oryzae* and *S. cerealella* which develop well between temperatures of 18 – 30 ^{o}C (Mason and McDonough, 2012; Akter et al., 2013). The high mean seasonal ambient store temperatures (31.8 ± 1.4 ^{o}C) in Mbire in the 2014/15 storage season, with a mean temperature range of 27 – 34 ^{o}C, favoured the development of pests such as *T. castaneum* and *R. dominica* which are tolerant to higher temperatures (Baldassari et al., 2004). Mean diurnal temperatures at the Mbire site ranged between 26.3 – 36.1 ^{o}C, during the 2014/15 storage season. High temperatures above 35 ^{o}C cause high mortality of many insect species due to disruption of their nervous and endocrine systems (Subramanyam and Hagstrum, 1991; Neven, 2000; Fields et al., 2015), and will have suppressed *S. cerealella* and *S. oryzae* population development in the Mbire trial. When temperatures rise beyond an individual storage insect's optimum conditions, they will enter into diapause (Bell, 2014), which stops their development and some of their metabolic processes, but leads to death if the conditions persist (Fleurat-Lessard and Dupuis, 2010).

Higher populations of *S. cerealella* in Super guard treated grain than in untreated control grain suggest the possibility of high tolerance levels to this pesticide by the pest. The pest, if tolerant, may manage to develop particularly well where there is a lack of interspecific competition with other species (Makundi et al., 2010). Such increased fecundity of one pesticide-tolerant species was also observed in trials involving the larger grain borer, *Prostephanus truncatus* on maize grain (Chigoverah and Mvumi, 2016). Differential responses to pesticide treatments by different species of storage insect pests has been reported by various researchers. Selected examples include: spinosad-treated wheat grain where *S. oryzae* was less susceptible than *R. dominica* (Athanassiou et al., 2009); diatomaceous earths (DEs) treatment where differentstrains of *T. castaneum* responded differently(Rigaux et al., 2001) and malathion treatement where major storage insect pests showed differences(Arthur, 1996). In field stored sorghum trials Stathers et al. (2002) observed that *R. dominica* was less susceptible than *S. oryzae* toDEs.

The occurrence of high *S. cerealella* numbers in Actellic Gold dust treated grain in Harare is also attributed to high levels of tolerance to the pesticide by this pest, which managed to develop in treated grain as from 8 weeks of storage. Both Actellic Gold dust and Super guard dust have low levels of pirimiphos-methyl (1.6 %) compared to other pesticides which share the same active ingredient. Ngwena yedura and Chikwapuro have higher levels of pirimiphos-methyl (2.6 %) in addition to deltamethrin, and these pesticides displayed better levels of control of *S. cerealella*. Elimination of natural enemies could also be the result of increased build-up of *S. cerealella* and *T. castaneum* in Super guard dust in Harare and Shumba Super dust in Mbire, respectively. This was demonstrated in earlier research on *S. oryzae* and *A. calandrae* where the latter was more susceptible than the former to a range of active ingredients (Baker and Weaver, 1993). Similarly, Stathers et al. (2002) attributed the dominance of *R. dominica* in DE-treated sorghum grain to elimination of its natural enemies compared to untreated grain, coupled with the lower efficacy of DEs against bostrichid beetles.

Sitotroga cerealella is known to use behavioral avoidance mechanisms to escape treatments, avoiding unfavorable patches within the grain, then re-infesting the grain when pesticide levels become sub-lethal (Oppert et al., 2010; Trematerra, 2015). Storage insects which are able to detect chemical treatments and avoid them have better chances of survival (Bell, 2014). The high mobility of this *S. cerealella* increases its ability to escape soon after treatment (Trematerra, 2015), reducing its exposure to pesticides and providing it with a chance to recover (Rumbos et al., 2016). High susceptibility to pirimiphos-methyl has been reported previously for *S. oryzae*, *T. confusum* and *T. castaneum* (Rumbos et al., 2016) and was also found in the current experiment where all the pesticides containing this active ingredient suppressed these pest species.

Massive build-up of *T. castaneum* in Shumba Super dust treated sorghum grain in Mbire from two months of storage onwards indicates the possibility that the pest has developed resistance to the grain protectant which has been in use for a long period of time (at least 15 years) in Zimbabwe. The initial grain damage level of around 7 % in Mbire district during the 2014/15 season, and approximately 4 % during the 2015/16 storage season would have been sufficient to support the development of *T. castaneum* which is a secondary pest. The point at which *T. castaneum* development commenced in treated grain can also mark a point whereby the pesticide's active compounds are degraded below potent levels (Afridi et al., 2001) due to predominantly high temperatures in the area. The quick and high rate of infestation by *T. castaneum* in Shumba Super dust treated grain is problematic, as in SSA smallholder farmers usually only treat the grain they intend to store for periods of more than 4 months (Stathers et al., 2013). Hence, this pesticide would fail to give the desirable protection. *Tribolium castaneum* build-up was low under the relatively low temperatures in Harare in all treatments. This could suggest that the pesticides were persistent for longer periods under cooler environments as compared to higher temperature environments, or that the temperatures were below the optimum development temperatures for this pest, or that the *T. castaneum* strain in Harare is not resistant to Shumba Super dust. Pesticide active ingredients have variable persistence periods in different grain ecosystems (Afridi et al., 2001).

An increase in resistance to pesticides, particularly to organophosphates, has previously been reported for *R. dominica*, *T. castaneum* and *Sitophilus* spp. in Brazil (Lorini and Galley, 1999) and some parts of Australia (Collins et al., 2017). Some *R. dominica* strains resistant to deltamethrin were found in Taiwan and the resistance was attributed to selection pressure (Chen and Chen, 2013). Pesticide resistance in insect pests is achieved through the death of homozygous susceptible individuals within the treated grain, leaving homozygous resistant and heterozygous susceptible individuals (Hagstrum and Subramanyam, 2006) which may require increased dosages or different control treatments to effect kill. As a result of ineffective control, farmers often resort to increased application rates and/or frequencies with some resorting to using non-recommended pesticides e.g. the use of carbaryl on stored grain, which is normally used for controlling cotton pests in Mbire district.

The results of this experiment challenge the rationale behind blanket pesticide application recommendations across different climatic regions. Pesticides generally degrade faster under high temperatures (Katagi, 2004) due to increased photodegradation, and given the same application rates greater efficacy is expected in small grains than in large grains due to the smaller intergranular spaces which do not allow insects to so easily escape from areas in the grain bulk where pesticide dust concentrations are high (Athanassiou et al., 2003, Rumbos et al., 2016). However, other factors such as the texture of the grain surface also play a critical role in pesticide adherence and retention (Kabir et al., 2013; Kavallieratos et al., 2005) as the pesticides adhere more on rough grains.

The significant increase in grain damage levels at four months’ storage in Mbire, largely during the 2014/15 storage season, could reflect a decrease in pesticide efficacy to below potent levels, enabling pest re-infestation (Sallam, 2008). Chikwapuro, Ngwena yedura and Shumba Super dust suppressed grain damage and subsequent weight loss throughout the entire storage season in Harare. This could be due to high persistence of these pesticides under the relatively low temperature environments which prevailed in Harare. The superior performance of Shumba Super dust against sorghum pests in Harare as opposed to in Mbire shows the possible effects of differences in climatic conditions and dominant storage insect pest species on pesticide effectiveness. The failure of Shumba Super dust pesticides in suppressing grain damage in Mbire was also recorded against maize pests in the same district. An increase in percentage grain damage in Actellic Gold dust and Super guard dust and the development of *S. cerealella* in these treatments during the 2015/16 storage season in both Mbire and Harare indicates a high level of insecticide tolerance by this insect pest.

Low levels of grain damage in Mbire can be attributed to the high temperatures which suppressed many insect pests, with the exception of *T. castaneum* (Fleurat-Lessard and Dupuis, 2010; Wilches et al., 2016). When temperatures go beyond the optimum range of most of the pest species capable of damaging whole grains, lower grain damage is likely to occur (Fleurat-Lessard and Dupuis, 2010). High temperature-related insect mortality and suppression in Mbire district can explain why grain damage was low for a longer period of time in all treatments in Mbire (16 weeks), as compared to Harare (8 weeks). However, beyond 32 weeks storage in Mbire all the pesticides tested failed to prevent grain damage increases, indicating a loss of potency due to the high temperatures (Palikhe, 2007, Ismail, 2012).

Temperatures were much higher (up to 39 ^{o}C) and grain moisture content was lower (9 - 10 % mc) in the store room in Mbire district than in Harare during the 2014/15 and 2015/16 storage seasons. The rise in grain moisture content in Super guard dust and untreated control in Harare may have been linked to high infestations of storage insects. Temperature and relative humidity (local environmental conditions) play a critical role in influencing grain moisture content, pest development (Musolin and Saulich, 2012; Bendito and Twomlow, 2015), and influencing pesticide persistence and success (Katagi, 2004; Ismail et al., 2012; Bell, 2014). If the pesticides degrade beyond potent levels, re-infestation will occur (Afridi et al., 2001). The high temperatures (> 30 ^{o}C) experienced in Mbire and low grain moisture content of ~ 9 % can be catastrophic for most storage insects, with the exception of species such as *T. castaneum* and the bostrichids which can tolerate high temperatures (Fields et al., 2015). Most storage insects favour minimum relative humidity of 50 % for optimum survival (Bell, 2014), and their optimum temperatures for survival and development are narrow, and vary from species to species. For every 2 ^{o}C increase in temperature from the minimum developmental temperature of any pest, the rate of development doubles until optimum temperatures are reached (Subramanyam *et al*., 1991; Sharma and Prabhakar, 2014). The low grain moisture content in samples collected from Mbire district is likely to have led to suppressed insect development and grain damage levels in that location, particularly during the second season. Most storage insects favour high moisture content when temperatures are above their optimum, as was found by Bell (2014) in *S. granarius*. Increasing grain moisture in non-effective pesticide treatments can be attributed to insect respiration and presence of immature stages of insects within the grains.

The high temperatures, as experienced in Mbire district and the general rising regional temperatures in SSA, may cause the emergence of new pest species in new sites and/ or extinction of some storage insect species (Karuppaiah and Sujayanad, 2012) shorter pest lifecycles, more rapid build-up of pests in stored commodities and in the rate of field to store contamination, in addition to causing accelerated pesticide breakdown (Stathers et al., 2013). Warming temperatures expand insect overwintering areas and volatinism (Karuppaiah and

Sujayanad, 2012; Sharma and Prabhakar, 2014) and may modify insect behaviour and dispersal (Bell, 2014). This may require more frequent pesticide treatment (Sharma and Prabhakar, 2014) Under accelerated pest development, and increased pesticide degradation due to higher temperatures resulting from global warming, farmers may resort to increased pesticide applications to effect control (Gatto et al., 2014; Delcour et al., 2015). It is therefore, imperative that climate-smart agricultural investments across SSA build the understanding of smallholder farmers and their service providers, about these likely impacts and the many postharvest adaptation strategies which can be adopted (Stathers et al., 2013; Mvumi and Stathers, 2014), to help avoid situations of increased losses of stored grains and/or increased pesticide use and the associated food safety risks.

The findings of this study show that climatic conditions may influence the success or failure of grain protectant dusts. The recommended application rate of Super guard dust failed to suppress a build-up of *S. cerealella* in Harare, while Shumba Super dust was ineffective against *T. castaneum* at both sites. The dominant pest species plays a major role in determining pesticide efficacy. Further investigations are required to examine the exact nature of the pesticide failure to control *S. cerealella* and *T. castaneum* and how this is mediated by temperature and how natural enemies such as predators and parasitoids come into play.

The development and levels of damage caused by these insect pests, alongside the potency of the pesticide, are also influenced by the prevailing climatic conditions. *Tribolium castaneum* dominated the pest complex in the hotter climate (Mbire), while *S. cerealella* and *S. oryzae* dominated in the cooler environment (Harare). Chikwapuro and Ngwena yedura were effective at both sites, while Shumba Super dust and Actellic Gold dust were only effective in Harare and Mbire, respectively. This study suggests the current blanket application rate recommendations for grain protectants are insufficient, and there is a need to generate more context-specific pesticide recommendations based on both the expected dominant pest species, and the expected climatic conditions.

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Highlights

- The efficacy of the synthetic pesticides varied across the different agro-climatic sites
- *Sitotroga cerealella* and *Sitophilus oryzae* were dominant in the cooler climatic area
- *Tribolium castaneum* was the dominant pest in the hotter climatic area
- *Tribolium castaneum* displayed tolerance to fenitrothion 1% + deltamethrin 0.13% combination