Field efficacy and persistence of synthetic pesticidal dusts on stored maize grain under contrasting agro-climatic conditions

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Abstract

Grain storage trials were conducted in two districts of Zimbabwe with contrasting agro-climatic conditions (mean annual temperature of 18 - 30 °C and 28 – 42 °C; total rainfall of 750-1000 mm per annum and < 450 mm per annum; respectively) to determine the comparative efficacy of commercially-available grain storage synthetic pesticides under contrasting climatic conditions. The five grain protectants, namely Shumba super dust® (fenitrothion 1 % + deltamethrin 0.13 %), Actellic gold dust® (pirimiphos-methyl 1.6 % + thiamethoxam 0.36 %), Super guard® (pirimiphos-methyl 1.6 % + permethrin 0.4 %), Chikwapuro® (pirimiphos-methyl 2.5 % + deltamethrin 0.1 %) and Ngwena yedura® (pirimiphos-methyl 2.5 % + deltamethrin 0.2 %) were evaluated at label rates on stored shelled maize. The trials were conducted for a 40 week-long storage season in 2014/15 and again in 2015/16. Samples were analysed for insect grain damage, total insects per kilogram, grain weight loss, insect feeding chaff and grain moisture content. Temperature and relative humidity within stores were recorded using data loggers. The results highlighted the generally poor efficacy of the synthetic pesticides under both cooler and hotter climatic test conditions. The pesticides failed to prevent insect grain damage or suppress insect pest numbers. Only Actellic gold dust®, introduced in the 2015/16 storage season was effective under both the agro- climatic conditions. The current study suggests that only Actellic gold dust® can be recommended for smallholder farm grain protection under both cooler and hotter climatic conditions. The findings confirm the frequent claims of smallholder farmers in east and southern Africa regarding poor storage pesticide performance, and emphasize the need to develop alternative effective storage insect pest control options.

Key words: Grain storage, synthetic pesticide efficacy, insect feeding chaff, grain damage, *Prostephanus truncatus*

1. INTRODUCTION

The increased production and use of synthetic pesticides worldwide since the 1960s has helped reduce pest infestations, boost food production and extend food shelf-life (Ortiz-hernández et al., 2013). Most pesticides are targeted at reducing pest species which attack crops during the field growth stages, thus helping to increase agricultural production. Far fewer pesticides are available for protecting grain from insect infestation after harvest. Given the climatic projections of global increases in temperatures, the efficacy of pesticides may be reduced (Arthur et al., 1992; Stathers et al., 2013), while pest infestation may rise, affecting both the crop production and storage stages.

In the current study, the efficacy of the five commercially available grain storage pesticides in Zimbabwe was investigated on stored maize. These grain storage synthetic pesticides are widely used in Zimbabwe, with at least 75 % of farmers relying on them to protect their stored grain from insect pests (Mvumi and Stathers, 2003; Nyabako et al., in preparation). Grain protectants containing a wide variety of active ingredients, including carbamates, pyrethroids, organophosphates and neonicotinoids have been formulated, and most of them contain more than ingredient (Arthur, 1996). These binary formulations are employed to improve efficacy and reduce development of insect tolerance which can occur more easily to products with a single active ingredient (Daglish and Nayak, 2012; Rumbos et al., 2013). However, little information is available on the effect of temperature and relative humidity on the efficacy of binary pesticides in grain storage (Rumbos et al., 2013). Theses is particularly important under farm conditions where a combination of extreme temperatures and new pests such as the larger grain borer (LGB), *Prostephanus truncatus* Horn. (Coleoptera: Bostrichidae) are experienced.

The documented effects of temperature on pesticide activity differ by pesticide class. The efficacy of organophosphate and neonicotinoid-based insecticides increases with increasing temperature from 20 to 30 ^{o}C (Arthur et al., 2004; Vassilakos and Athanassiou, 2013) while that of pyrethroid pesticides decrease as temperatures increase (Subramanyam and Cutkomp, 1987; Arthur, 1999). Some studies suggest that although high temperatures generally decrease the efficacy of pesticides; organophosphates are more effective at temperatures above 20 ^{o}C, than $\leq$ 20 ^{o}C (Arthur et al., 2004). This is understood to be due to increased pest movement, breathing and uptake rate of the pesticide at higher temperatures (Arthur et al., 2004). Other researchers noted that whilst mortality increased at high temperatures in the first few days of pesticide (organophosphates) application, general efficacy and pesticide persistence decreased over a long storage period (Hamacher et al., 2002). Similarly, studies by Afridi et al. (2000) concluded that degradation of organophosphate (chlorpyriphos-methyl and pirimiphos-methyl) and pyrethroid (permethrin) admixed pesticides is faster at temperatures of 35 ºC to 40 ºC than at 25 to 30 ºC, and faster still on grain with a higher moisture content.

Furthermore, higher insect mortality was recorded at 75 % r.h. than at 55 % r.h., not as a result of "insecticide activity *per se* but due to the increased metabolic stress of the target insect species" (Vassilakos and Athanassiou, 2013). However, in most studies, temperature is considered more important than relative humidity in influencing pest activity resulting in increased pesticide contact or uptake at elevated temperatures (Rumbos et al., 2013). In terms of degradation, the residues of organophosphate pesticides degrade more rapidly than those of pyrethroids. For example, organophosphate residues on stored grain were below detection point after 52 weeks of grain storage, while the pyrethroid permethrin was more stable (Afridi et al., 2000). In terms of insect survival, Arthur et al. (2004) reported that the rusty red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera; Tenebrionidae), a secondary pest of stored cereals, has a better chance of survival after pesticide application since it attacks stored maize at a later stage when the pesticide has likely degraded, compared to primary pests such as the maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera; Curculionidae) which infests grain as it matures and persists throughout the postharvest stages.

Three classes of insecticides namely; organophosphates, pyrethroids and neonicotinoids; are commonly used in Zimbabwe and other countries in sub-Saharan Africa in grain protection as dust formulations. The insecticidal dusts are admixed with dried grain to protect it against storage insect pest damage. The organophosphates include pirimiphos-methyl and fenitrothion (Hazard class II). This class of pesticides has a quick knock-down effect and a fast degradation pathway and hence do not leave long-term residues after application (Tadeo, 2008). The pyrethroids include deltamethrin and permethrin. They are contact poisons which affect the nervous system and present low mammalian toxicity risks (Hazard class II); hence they are often viewed as the safest of all pesticides in terms of use (Kamrin, 2000). The neonicotinoids group of insecticides include thiamethoxam which interferes with the nicotinic acetylcholine receptors

(Arthur et al., 2004), thus affecting the insect nervous system (Maienfisch et al., 2001). This unique mode of action makes them desirable for controlling insect pests which have developed some resistance to organophosphate, pyrethroid and carbamate insecticides (Maienfisch et al., 1999). The insecticide thiamethoxam, is widely used for seed treatment of most field crops but its documented use as a stored grain protectant is very low (Arthur et al., 2004).

An efficacy and persistence study of five synthetic insecticidal dusts admixed with maize grain was conducted in two agro-climatic regions of Zimbabwe with contrasting environmental conditions; one cool and sub-humid and the other hot and dry. The objective of the study was to determine the comparative efficacy and persistence of the grain protectants in contrasting climatic conditions, to deepen understanding of how the protectants perform as temperature and r.h. alter due to changing climatic conditions and provide guidance on validity of current recommendations.

2. MATERIALS AND METHODS

2.1. *Site description*

Field trials were conducted in Hwedza (18^{o} 37′ S; 31^{o} 34′ E) and Mbire (20^{o} 43′ S; 30^{o} 34′ E) districts in Zimbabwe. Hwedza district, located in agro-ecological region II b receives an annual rainfall of 750 - 1000 mm and mean annual temperatures of 18 – 30 ^{o}C (FAO, 2006). Mbire district, is located in agro-ecological region V characterised by low rainfall below 450 mm per annum and extreme temperatures ranging from 28 - 42 ^{o}C (FAO, 2006). A rise of about 2.6 ^{o}C and 2 ^{o}C in minimum and maximum daily temperatures respectively, has been recorded in the last 30 years in Zimbabwe (Brown, 2012). This warming has resulted in increasing aridity as well as marked shifts in the onset of rains, increased proportions of low rainfall years and increased frequency of mid-season dry spells (Nyabako and Manzungu, 2012; Rurinda et al., 2013). The changes have resulted in a proposed shifting of Zimbabwe's agro-ecological zoning (Nyabako and Manzungu, 2012; Brown, 2012; Mugandani et al., 2012).

2.2. *Treatments*

Most of the grain protectant pesticides used in Zimbabwe are organophosphate- and pyrethroid-based including Shumba super dust®, Chikwapuro®, Ngwena yedura® and Super guard®; even though they differ in terms of their specific active ingredients and respective percentages (Table 1). Only Actellic gold® dust contains a neonicotinoid active ingredient in combination with an organophosphate. The pesticides were purchased from Farm & City, a registered agro-dealer in Harare, Zimbabwe. Untreated grain in polypropylene bags was used as a control for the experiment.

Insert Table 1 about here

2.3. *Trial setting and management*

In Hwedza district, a 1:2 mixture of two hybrid maize varieties; Sirda 113 (Seed Company of Zimbabwe- Seed-co) and PHB 30G19 (Pioneer Seed Company) were used in the trials during the 2014/15 season whilst in the 2015/16 season a 1:3 mixture of PHG 30G19 and Pioneer 2859 (Pioneer Seed Company) was used. Mixtures were used due to a local shortage of sufficient bulk grain of a single variety as a result of poor growing seasons. In Mbire district, a single variety of PHB 30G19 was used in both the grain storage seasons. In both districts, grain was purchased in the same locality where the trials were conducted.

The same grain treatment process was used in both districts. The trial grain was thoroughly mixed at one place. Each treatment was allocated 75 kg of grain and treated with a respective pesticide. Manufacturer's recommended application rates were used for all pesticides (Table 1). After pesticide treatment, the 75 kg lot of each treatment was sub-divided to make three 25 kg replicates contained in polypropylene bags.

Brick wall structures with cement floors, ceiling boards and asbestos roofs housed the treatments in both districts. Data loggers (EL-USB-2, USA) were used to record temperature and rh in the trial rooms. In the 2014/15 season, the loggers were installed eight weeks after trial setting due to their late delivery. Polypropylene bags of 50 kg capacity were used to contain the treated grain and these were placed on a raised platform (about 10 cm above the floor) of mud bricks in a completely randomised design (CRD). Immediately after trial setting, baseline samples were collected. Thereafter, sampling was conducted at eight-week intervals over a period of forty weeks. Sampling was done using 40 cm bag probes (Hodges, 2013) inserted horizontally at multiple points across the circumference and different levels of the bag. Grain samples were analysed to determine grain moisture content, presence of live and dead insects, grain damage, chaff weight and grain weight loss. The trials relied on natural insect infestation; no insects were artificially introduced into the treatments.

2.4. *Sample analysis and calculations*

For each sample, the weight was recorded before sieving off the insects. Two and five millimetre aperture standard test sieves were nested to separate the chaff and insects respectively from the grain. Live and dead insect counts were converted to the number of live or dead insects per kilogram of sample. The live and dead insects per kilogram were summed up to give total insects per kilogram of sample weight. Grain moisture content was measured using a pre-calibrated GrainPro moisture meter (model GMK- 303CF, GrainPro Inc, Philippines). Thereafter, samples were kept in a freezer at ≤ -18 ^{o}C to stop further insect damage whilst grain damage assessment was underway. For damage assessment, each maize sample was sub-divided into eight sub-samples using a grain sample divider. Three sub-samples, equivalent to three-eighths of the total sample were analysed for grain damage. Damaged and undamaged grain was separated manually and each category counted using a seed counter (Numigral seed counter, CHOPIN, Villeneuve LA Garenne, France). Damage was then converted to percentage as [*Nd*/ (*Nd*+ *Und*)] ×100 % where *Nd* represents the number of damaged grains and *Und* represents the number of undamaged grains (Boxall, 1986). Grain weight loss was calculated using the count and weigh assessment method (Equation 1):

$$\text{Weight loss \%} = \frac{NdWu - WdNu}{(Nd+Nu)\times Wu} \times 100 \text{ (Boxall, 1986) } \textit{Equation 1}$$

where *Nd* = number of damaged grains in a sample, *Nu* = number of undamaged grains in a sample, *Wu* = weight of undamaged grains in a sample and *Wd* = weight of damaged grains in a sample.

2.5. *Data analysis*

Square root transformations were done on the data including insect grain damage, weight loss and insect feeding chaff to stabilise data variance and conform to normality (Kirchner, 2001). Thereafter, the data were subjected to a two-way analysis of variance in Genstat 14 (VSN

International, 2011) to test for significant differences between treatments, sites and treatment-site interactions. In case of significant differences, Fisher's protected LSD at 5 % probability was used to separate means. Temperature data, recorded using data loggers for the two sites, were analysed using a paired sample t-test.

3. RESULTS

3.1 Grain damage

3.1.1 Season 1 (2014/15)

In Hwedza, grain insect damage increased swiftly in the untreated control from slightly above 10 % at 16 weeks to above 40 % of grains at week 24. However, in the pesticide treatments, grain damage remained much lower throughout the trial (Fig. 1). It was only after 32 and 40 weeks storage, respectively, that grain damage in two of the pesticide treatments, Ngwena yedura® and Super guard®, rose above 10 % during the 2014/15 storage season. In Mbire district, grain damage levels were generally higher in the respective treatments, than those recorded in Hwedza except for the untreated control where damage levels began to rise at week 16 whereas in the pesticide treatments, this occurred as from week 32 (Fig. 1). Differences in grain damage among treatments were significant ($F_{4, 20}$ = 5.60; P = 0.003) within sites at week 40. However, there were no significant differences ($F_{1, 20}$ = 2.35; P = 0.141) for inter-site comparison. Treatment-site interactions were significant ($F_{4, 20}$ = 4.62; P = 0.008) showing that treatments performed differently across the two sites. For combined data across sites, Shumba super dust® had the least damage followed by Super guard®, Chikwapuro®, Ngwena yedura® and untreated control.

Insert Figure 1 about here

3.1.2 Season 2 (2015/16)

In the 2015/16 storage season in Hwedza, grain damage remained below 10 % in all treatments only up to week 16. In contrast to the previous season, grain damage remained below 10 % throughout the 40 weeks of storage only in the Actellic gold dust® treatment. While over 75 % of grains were damaged in the untreated control, Shumba super dust®, Chikwapuro®, Ngwena yedura® and Super guard® by week 40 (Fig. 2). It is striking that all the organophosphate- and pyrethroid-based pesticide treatments (Shumba super dust®, Ngwena yedura®, Super guard® and Chikwapuro®) experienced very high grain damage similar to levels found in the untreated control grain. However, the Actellic gold dust® treatment, which contains a neonicotinoid in combination with an organophosphate active ingredient was effective throughout the storage period.

In Mbire district, grain damage levels were much lower than in Hwedza. In the Actellic gold dust®, Chikwapuro® and Shumba super dust® treatments mean percentage insect damaged grain remained below 10 % throughout the 40 weeks of storage (Fig. 2). Statistically, treatments were significantly different ($F_{5, 24} = 33.20$; $P < 0.001$) when data was combined across the sites at 40 weeks. Site comparisons were also significant ($F_{1, 24} = 311.67$; $P < 0.001$); together with treatment-site interactions ($F_{5, 24} = 16.56$; $P < 0.001$). Actellic gold dust® produced a stand-alone performance followed by Shumba super dust®, Chikwapuro® and Ngwena yedura® whilst Super guard® and the untreated control had the highest damage for combined sites data.

Insert Figure 2 about here

3.2 Grain weight loss

3.2.1 Season 1 (2014/15)

Weight losses remained below 4 % in all the pesticide treatments in Hwedza during the 2014/15 season. Only 11 % weight loss occurred in the untreated control by 40 weeks storage. In Mbire district, grain weight losses were generally low, remaining below 8 % throughout the trial, with the highest figures of 7.8 % and 6.8 % occurring in the Chikwapuro® and Ngwena yedura® treatments respectively (Fig. 3). Differences in grain weight losses for combined treatments were significant ($F_{4, 20} = 3.13$; $P = 0.037$) at 40 weeks of storage. The site differences were not significant but treatment-site interactions had significant differences ($F_{4, 20} = 3.82$; $P = 0.018$). Across sites, Shumba super dust® had the least weight losses, followed categorically by Super guard®, Chikwapuro®, Ngwena yedura®, with the untreated grain experiencing the highest weight losses.

Insert Figure 3 about here

3.2.2 Season 2 (2015/16)

In Hwedza district, weight loss started to increase from week 16 onwards in the untreated control, Shumba super dust®, Chikwapuro®, Ngwena yedura® and Super guard®, all these treatments suffered very high weight losses of 20 % and above by 32 and 40 weeks storage. It was only in the Actellic gold dust® treatment that weight loss remained below 1 % throughout the 40 weeks of storage (Fig. 4). In Mbire, weight losses were much lower (≤ 10 %) compared to those in Hwedza. Significant differences at 40 weeks were recorded between treatments ($F_{5, 24}$ = 10.57; P < 0.001), sites ($F_{1, 24}$ = 144.56; P < 0.001) and treatment-site interactions ($F_{5, 24}$ = 9.98; F < .001). The lowest weight losses were incurred in Actellic gold dust® followed surprisingly by the untreated control. Shumba super dust®, Chikwapuro® and Ngwena yedura® recorded similarly high losses and Super guard® had the highest across site weight losses.

Insert Figure 4 about here

3.3 Adult insect species diversity

3.3.1 Season 1 (2014/15)

In Hwedza, the maize weevil *S. zeamais* was the dominant insect species recorded during the 2014/15 storage season. The beetle *P. truncatus* was recorded at week 32 and 40 in most treatments. The highest number of insects was recorded in the untreated controls, with over 300 adult insects per kilogram at week 24. The insect population remained below 50 insects per kg in the Shumba super dust® (in both Mbire and Hwedza) as well as Chikwapuro® and Ngwena yedura® treatments during the entire 40 weeks of storage, and Super guard® only exceeded 50 insects per kilogram at 32 and 40 weeks (Fig. 5).

In the same season lower populations of insects were recorded in Mbire than in Hwedza, but the spectrum of insect species was wider. *Prostephanus truncatus* was more prevalent in the pesticide-treated grain especially Chikwapuro®, Ngwena yedura® and Super guard®, whereas *S. zeamais* was more pronounced in untreated and Shumba super dust treatments. *Tribolium castaneum*, being a secondary pest of maize, was more prevalent towards the end of the storage season although in the untreated control it was recorded earlier at 16 weeks. The grain moth

Sitotroga cerealella (Olivier) (Lepidoptera; Gelechiidae) and wasps of the hymenoptera order were also recorded in most treatments (Fig. 5).

Treatments had significant differences ($F_{4, 20} = 7.26$; $P < 0.001$) for across site comparisons at 40 weeks. Treatment-site interactions were also significant ($F_{4, 20} = 7.59$; $P < 0.001$). However, site differences were not significant in influencing insect populations. The insects were highest in untreated control, followed by Super guard® and Ngwena yedura®, Chikwapuro® and Shumba super dust® in that order.

Insert Figure 5 about here

3.3.2 Season 2 (2015/16)

In Hwedza, *P. truncatus* was the main insect pest recorded in treated grain whilst high populations of *S. cerealella* were also present in the untreated grain. High insect populations (600 - 800 insects per kg) were recorded in the Ngwena yedura®, untreated control, Shumba super dust®, Chikwapuro® and Super guard® (Fig. 6). Actellic gold dust® out-performed the other treatments, with less than 50 adult insects per kg by 40 weeks storage. In contrast to the 2014/15 season, *S. zeamais* was recorded at very low levels in most treatments except the untreated control at week 40. In Mbire district, *S. cerealella* and *S. zeamais* were dominant from trial setting in August 2015 to week 24 in most treatments. However, in the untreated control, *T. castaneum* also became dominant from week 24 to week 40, whereas in Ngwena yedura® and Super guard®, *P. truncatus* became dominant at week 32 and 40. The total insect numbers per kilogram recorded in Mbire of up to 220 insects per kilogram were much less than those recorded in Hwedza (above 600 insects per kilogram) for the same treatments (Fig. 6).

Across sites, both treatments ($F_{5, 24} = 9.20$; $P < 0.001$) and sites ($F_{1, 24} = 177.91$; $P < 0.001$) were significantly different. Treatment-site interactions were also significant ($F_{5, 24} = 7.01$; $P < 0.001$) hence performance of treatments across sites differed. Actellic gold dust® had the least number of total insects followed by the untreated control for pooled data. Chikwapuro®, Shumba super dust® and Super guard® were in the same range and Ngwena yedura® had the highest number of total insects.

Insert Figure 6 about here

3.4 Insect feeding dust

3.4.1 Season 1 (2014/15)

Very little insect feeding dust or chaff (< 2 % by weight) was generated in any of the pesticide treatments in Hwedza during the 2014/15 storage season, and it only reached 4 % in the untreated control by week 40. In Mbire, Shumba super dust® and the untreated control recorded below 1 % chaff dust, whilst Super guard®, Chikwapuro® and Ngwena yedura® recorded between 2 and 4 % chaff. Only treatment-site interactions were significant ($F_{4, 20}$ = 3.53; P = 0.025) at 40 weeks of storage.

3.4.2 Season 2 (2015/16)

In contrast to the 2014/15 storage season, during the 2015/16 season, large quantities of feeding/boring dust were generated in Hwedza from week 24 onwards, rising to between 10 and 25 % by week 40. Only Actellic gold dust® remained with little chaff. Greater quantities of chaff were generated in the pesticide treatments Chikwapuro®, Super guard®, Ngwena yedura® and Shumba super dust® than the untreated control at week 40. Again, almost no dust/chaff was recorded in the Actellic gold dust®. In the Mbire district, all treatments recorded very low chaff content below 5 % (Fig. 7). Treatments were significantly different ($F_{5, 24}$ = 11.13; P < 0.001) across sites. The two sites also had significant differences ($F_{1, 24}$ = 151.03; P < 0.001) and treatment-site interactions were also significant ($F_{5, 24}$ = 9.23; P < 0.001).

Insert Figure 7 about here

3.5 Grain moisture content, store temperature and relative humidity

3.5.1 Season 1 (2014/15)

In Hwedza district, moisture content of the trial grain ranged from 9 to 12 % during the 40 week trial. Moisture content increased from trial setting in November 2014 to February 2015 before stabilizing at around 11 % from March to June (Fig. 8). Temperatures for Hwedza were consistently below 25 ^{o}C except in January and March 2015. On the other hand, r.h. ranged between 50 and 70 % for most of the season and only dropped below 50 % in June. In Mbire grain moisture content dropped from 10 % to about 9 %, between November 2014 and January 2015 before rising to a peak of 11 % in March 2015 (Fig. 8). During this period temperatures were beyond 30 ^{o}C for most of the time except in January 2015 when heavy rains and flooding occurred in Mbire (13 weeks into the trial). Relative humidity was highly variable in Mbire, rising from as low as 30 % during the hot dry summer in November to above 70 % in the hot wet summer in January 2015. Between February and June of 2015, r.h. decreased gently from about 65 % to 40 %. There were no significant differences in grain moisture content between treatments for across site comparisons. However, the sites were significantly different ($F_{1, 20}$ = 83.66; $P < 0.001$). Treatment-site interactions were also insignificant, statistically. There were significant differences in mean temperatures for Hwedza and Mbire districts (Paired sample t-test: $T = -5.88$; $N = 8$, $P < 0.001$).

Insert Figure 8 about here

Insert Figure 9 about here

3.5.2 Season 2 (2015/16)

In the 2015/16 season, grain moisture content in Hwedza district decreased from 12 % in September 2015 to about 9.6 % in December before rising gently and remaining at around 11 % until the end of the season. During the season steady temperatures of 25 to 27 ^{o}C were recorded, and only dropping below 25 ^{o}C in April and May 2016 (Fig. 9). Relative humidity decreased from 40 to 35 % between September and October 2015 before rising steadily to above 50 % from January 2016 onwards. In Mbire district, grain moisture content decreased steeply from 12 % to about 7 % between September and December 2015 (Fig. 8) in response to high temperatures (Fig. 9) which were consistently high above 30 ^{o}C during that period. Grain moisture content then increased between December 2015 and January 2016, then remained constant at just below 10 % until the season's end in May 2016. The hot dry spells of Mbire resulted in r.h. falling below 30 % in September and October 2015 before a rapid rise to slightly above 50 % between November and December. Beginning 2016, r.h. remained steady above 50 % until April, when it dropped to about 42 % in May. No significant differences in grain moisture content between treatments were recorded for across site comparisons. Treatment-site interactions were also not significant. However, sites were significantly different ($F_{1, 24} = 71.96$; $P < 0.001$) at 40 weeks. Significant differences were also confirmed for the mean temperatures (Paired sample t-test: $T = -5.22$; $N = 9$; $P < 0.001$) of the two sites.

4. DISCUSSION

The study found that the performance of grain storage pesticides differed across the sites and was influenced by the contrasting environmental conditions. This resulted in significant treatment-site interactions. Grain damage and weight losses in the pesticide treated maize grain were higher in Mbire than Hwedza district in the 2014/15 season, although this was not the case for the untreated control. However, in the 2015/16 season, damage and weight losses in all treatments were higher in Hwedza than Mbire district. In the 2014/15 season, Shumba super dust® effectively suppressed damage in treated grain in both districts, and Chikwapuro® was equally as effective but only in Hwedza district. In the 2015/16 storage season, in Hwedza district, grain damage levels were very high in all treatments except Actellic gold dust® after 40 weeks storage. In contrast, in the hotter more arid Mbire district, insect grain damage was suppressed in all pesticide treatments for 32 weeks storage after which high damage levels were recorded in Super guard® and Ngwena yedura® in 2015/16.

Several other recent storage studies from African countries (Mutambuki and Ngatia, 2012, Abass et al., 2014; Midega et al., 2016), also reported grain damage levels as high as those experienced in Hwedza in 2015/16, where over 70 % grain was damaged and 40 % weight losses recorded. In many African countries, *P. truncatus* and *S. zeamais* are ranked as the most destructive stored maize insect pests (Midega et al., 2016), and the former is estimated to cause double the losses caused by *S. zeamais* (Hodges, 2002). Some farmers perceive *P. truncatus* to account for about 56 % and *S. zeamais* up to 36 % of the maize losses (Abass et al., 2014). In the current trial, *P. truncatus* and *S. zeamais* were the main cause of high grain damage and weight losses.

The damage levels and pest populations varied widely between the two seasons in Mbire district, which may be linked to climatic aspects. As in the 2014/15 storage season, flooding occurred in

Mbire between January and February 2015 during which time temperatures dropped to below 30 °C and grain moisture content simultaneously rose to a high of 11 %. In relation to grain damage and pest infestations, there were no sudden fluctuations in response to flooding or environmental conditions as the effects took longer to manifest. Higher damage levels and insect populations did not manifest immediately in response to the flooding and changed environmental conditions, but occurred later on from April to June 2015 (after 32 and 40 weeks storage). Generally, the higher the grain moisture content, the more susceptible the grain is to insects (Rashid et al., 2013).

Another factor which may have caused wide variability in grain damage and pest populations between seasons in the Mbire trials may be the excessively high temperatures experienced during the El-Niño heat wave (WFP, 2016) which affected the 2015/16 season. During this season there was a very slow build-up of insect populations in Mbire trials enabling all the pesticide treatments to perform fairly well for 32 weeks of grain storage. However, a sudden dramatic increase in damage occurred by 40 weeks storage in the untreated control, Super guard® and Ngwena yedura® treatments after temperatures dropped below 30 °C. It is possible that pest build-up was suppressed in the earlier weeks due to the excessively high temperatures experienced during the heat wave. As optimum conditions for life cycle development of most storage insect pests fall in the ranges of 27 – 32 °C at 72 % r.h., excessive temperatures above 35 °C may slow establishment (Mason and McDonough, 2011). It is likely that the heatwave caused pesticide breakdown, leaving insect populations to increase with little restriction when temperatures dropped to optimal levels.

Additionally the different grain moisture content levels experienced in the two districts (9 – 12 % mc in Hwedza, and as low as 8.5 % in Mbire district), which were linked to the high temperatures, may also have influenced insect pest development. When temperatures are high and grain moisture content is so low, it becomes difficult for insects to perforate grain (Rashid et al., 2013) or to breed (Beckett et al., 2007), and hence grain damage is typically lower. There were significant differences between sites for the across site comparisons of grain moisture content confirming that site conditions influenced treatment grain moisture content. Furthermore, the generally higher r.h. (> 50 %) of Hwedza was more favourable for insect pest development compared to the drier conditions (< 30 % r.h.) of Mbire district. Typically, optimum conditions for *S. zeamais* development are 25 ^{o}C at 70 % r.h., 35 ^{o}C at 75 % r.h. for *T. castaneum* and 32 ^{o}C at 80 % r.h. for *P. truncatus* (Haines, 1991; Fields, 1992). *Prostephanus truncatus* has, however, higher tolerance to drier conditions (Haines, 1991).

Overall, no general pattern across the two districts for the two storage seasons in terms of pesticide efficacy as measured by grain damage, weight loss, pest prevalence and abundance was found. As noted earlier, in the 2014/15 season, damage, weight loss and *P. truncatus* prevalence were higher in Mbire than Hwedza district. However, in the 2015/16 season, the reverse occurred with higher grain damage, weight loss and *P. truncatus* populations recorded in Hwedza than in Mbire district. Similarly, the pesticides were fairly effective in Hwedza in 2014/15, but less so in Mbire. However, the 2015/16 season's trial found all the pesticides except Actellic gold dust® perfomed poorly. The variabilities in terms of damage, weight levels and *P. truncatus* prevalence across the two seasons may be attributed to the characteristically sporadic occurrence of *P. truncatus* (Boxall, 2003; Hodges et al., 2003; Muantinte et al., 2014). According to Krall (1984), damage and losses caused by *P. truncatus* are difficult to measure due to their often isolated and unpredictable occurrence. The pest's presence is known to be sporadic between treatments, farm stores and storage seasons (Boxall, 2003; Hodges et al., 2003). This was the case across treatments, sites and seasons in both Hwedza and Mbire districts during these trials. Therefore, any pesticide used needs to be able to perform whether *P. truncatus* is present or not that year, because the risk of food shortages is so high if the pest does attack.

In terms of general pesticide efficacy, the grain damage and total insect numbers graphs clearly demonstrate the failure of most of the pesticides in suppressing insect pest development in both study districts. With the exception of Actellic gold dust® which performed very well in both districts, and Shumba super dust® in the 2014/15 season, all the other pesticides succumbed to insect pressure. These studies found that the organophosphate and pyrethroid pesticide combinations failed to control insect pests and only Actellic gold dust® which is composed of an organophosphate (pirimiphos-methyl 1.6 %) and a neonicotinoid (thiamethoxam 0.36 %) performed well across the two contrasting environmental conditions. In this case, the neonicotinoid (thiamethoxam 0.36 %) active ingredient appears to be the differential active ingredient between the poor and high efficacy pesticides. Failure of organophosphate and pyrethroid pesticides can be attributed to either poor pesticide persistence or pesticide tolerance and/ resistance, among other factors.

Earlier laboratory studies of pirimiphos-methyl (organophosphate) in stored-maize under hot-humid conditions (30 ^{o}C, > 50 % relative humidity) showed that it was effective for a short duration of four months after which efficacy was greatly reduced (Richter et al., 1997). Pirimiphos-methyl and fenitrothion (organophosphates) have also been categorised as less persistent pesticides at 30 ^{o}C temperatures, whilst deltamethrin and permethrin (pyrethroids) showed higher persistence over a nine months storage period (Morton et al., 2001). Therefore considering the 40 weeks storage duration (≈ 10 months) of this current trial and the high temperatures experienced in both districts, it might have been too long a period for effective storage, especially considering the pesticides' low persistence. Although deltamethrin and permethrin have in previous studies shown higher persistence (Morton et al., 2001), in the current study the effectiveness of products in which they were included barely lasted 24 weeks.

Besides the poor persistence, poor efficacy of synthetic pesticides may also be a result of pesticide dilution by high chaff dust. The dust generated due to extensive tunneling by *P. truncatus* has the potential to dilute the pesticidal dust, making it ineffective (Mlambo et al., 2017). This is also one of the reasons why delayed pesticide application results in pesticide failure (Mutambuki and Ngatia, 2012). At the same time, it was also noted in some cases that untreated grain suffered less damage and weight loss than pesticide- treated grain which can be due to the high sensitivity of natural enemies to synthetic pesticides (Stathers et al., 2008). Studies done by Stathers et al., (2008) indicate that natural enemies (parasitic wasps) numbers were higher in untreated grain compared to pesticide treatments, showing how natural enemies can be killed in treated grain but survive in untreated grain and help to regulate insect populations and hence lower damage.

Pesticide resistance world-wide is being fueled by the over-reliance on synthetic pesticides, mainly organophosphates and pyrethroids for grain storage (Pereira et al., 2009). "Low levels of resistance" in the case of *S. zeamais* have been reported in South America (Pereira et al., 2009). Strains of *R. dominica* with "normal" and "intermediate" tolerance as well as high resistance factors have also been screened (Lorini and Galley, 1999; Chen and Chen, 2013). Resistance of *S. zeamais* and *T. castaneum* to pirimiphos-methyl and fenitrothion has also been reported

(Lorini and Galley, 1999). It is concerning that even laboratory cultures of the *S. zeamais* and *T. castaneum* species showed resistance to these pesticides without any obvious selection pressure (Lorini and Galley, 1999). Furthermore, Collins (1998) postulated that elimination of weaker insects due to rapid field selection will make it even more difficult to control insect pests. The dominant insect species in this trial *P. truncatus* and *S. zeamais,* may therefore have developed some form of resistance to some of these pesticides and this calls for further studies to investigate pest resistance to organophosphate and pyrethroid pesticides in Zimbabwe and the SSA subcontinent as a whole.

Due to the novelty of the neonicotinoid, thiamethoxam as a grain protectant (Khan et al., 2016), development of resistance may be minimal compared to the more commonly applied organophosphates and pyrethroids. To manage the development of pesticide resistance, the poorly performing pesticides should be withdrawn from the market to avoid continuous selection for resistant insect species.

5. CONCLUSION

Our study demonstrates the generally poor efficacy of the organophosphate and pyrethroid grain protectant combinations currently commercially available in Zimbabwe, under both cooler and hotter climatic conditions. This study confirms frequent reports by farmers that the synthetic insecticidal dusts on the market are not effective. Only Actellic gold dust®, which contains a neonicotinoid (thiamethoxam 0.36 %) active ingredient suppressed insect pest build-up, minimising insect grain damage and grain weight losses in both districts. These findings highlight the need for further research to investigate why the efficacy of these organophosphate and pyrethroid grain protectants is poor. The very high temperatures and minimal grain moisture conditions experienced in Mbire district during the 2015/16 season appear to have suppressed insect development in the stored grain compared to the more favourable insect-developmental temperature ranges of Hwedza district. The study showed that the general efficacy of synthetic pesticide on stored maize grain varies across different climatic conditions and only Actellic gold dust® was efficacious under both the hotter and cooler climatic areas, suggesting it can be widely recommended. Nevertheless, as documented by Blacquière et al. (2012), the neonicotinoid components of the pesticide also negatively affect pollinator bees so the search for effective and safer (to both humans and the environment) alternatives to synthetic pesticides needs to continue.

The simultaneous effects of multiple insect stressors such as pesticides, and extreme temperatures, especially high temperature, and low relative humidity (hence low grain moisture content) on both pests and natural enemies needs further investigation.

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Highlights

- High grain damage and weight loss occurred in stored maize treated with most organophosphate-pyrethroid combinations
- The organophosphate-neonicotinoid-based pesticide restricted grain damage and losses below 5 % for 40-weeks storage
- Poor pesticide efficacy occurred in both cool and hot climatic locations
- *Prostephanus truncatus* prevalence increased the magnitude of weight losses recorded
- Extremely high ambient temperatures suppress insect pest development and grain damage

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List of tables

Table 1: Treatments used in the experiment

Trade name	Active ingredients	Application rate (g/25kg grain)*	Pesticide groups combined in product			Hwedza district		Mbire district	
			Organophosphates	Pyrethroids	Neonicotinoids	2014/15 season	2015/16 season	2014/15 season	2015/16 season
Shumba super dust	Fenitrothion 1% + deltamethrin 0.13%	12.5	●	●		✓	✓	✓	✓
Actellic gold dust	Pirimiphos-methyl 1.6% + thiamethoxam 0.36%	12.5	●		●	x	✓	x	✓
Chikwapuro	Pirimiphos-methyl 2.5% + deltamethrin 0.1%	10	●	●		✓	✓	✓	✓
Ngwena yedura	Pirimiphos-methyl 2.5% + deltamethrin 0.2%	10	●	●		✓	✓	✓	✓
Super guard	Pirimiphos-methyl 1.6% + permethrin 0.4%	13.9	●	●		✓	✓	✓	✓
Untreated control	N/A	N/A				✓	✓	✓	✓

** For pesticides, manufacturer's label application rates were used. The symbols (✓) and (x) show which treatments were included or not included, respectively*

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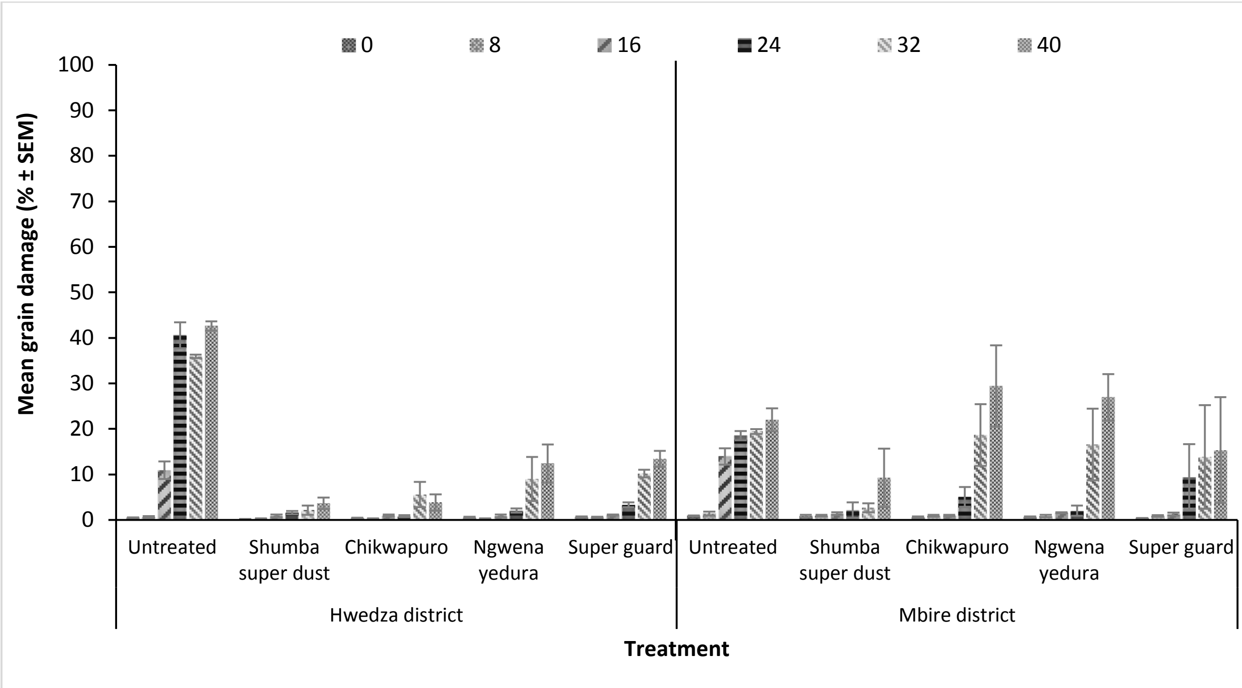

Figure 1: Mean insect grain damage (% ± SEM) recorded in maize stored under different treatments in Hwedza and Mbire districts during the 2014/15 storage seasons (n = 3). The legend 0, 8, 16 etc. represent the sampling period in weeks

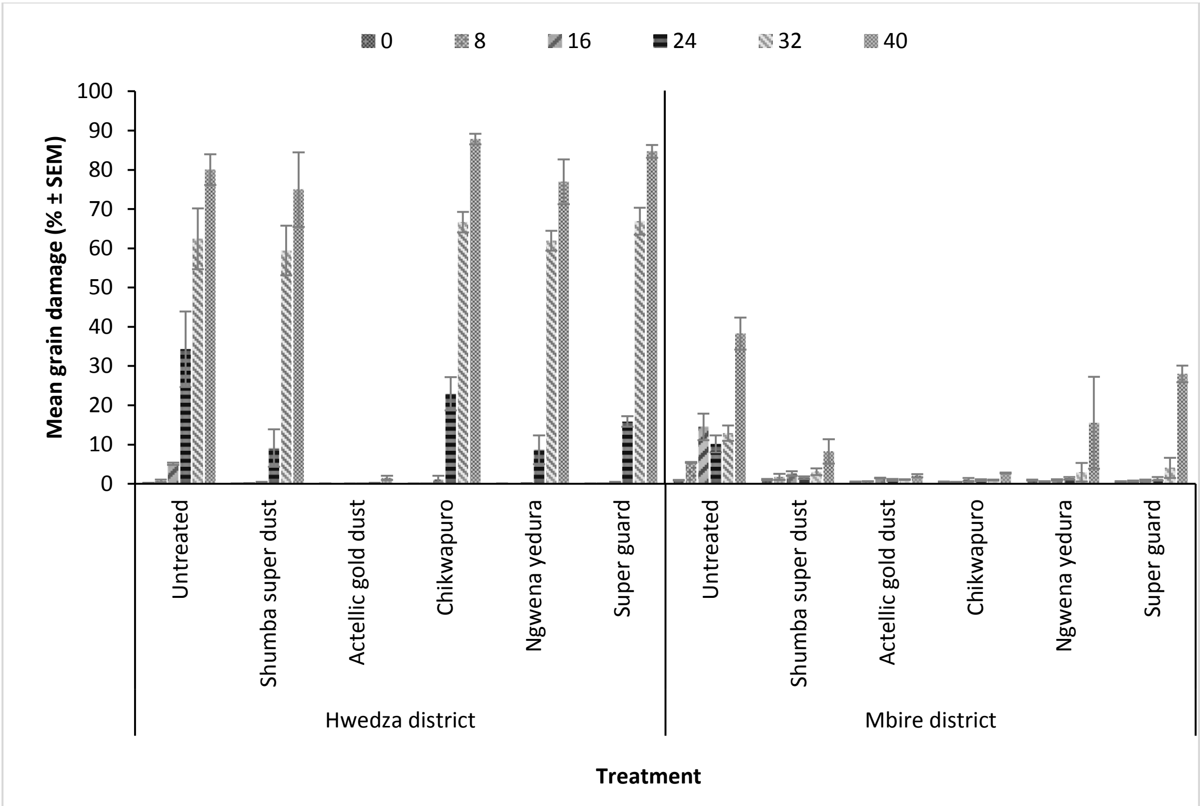

Figure 2: Mean maize insect grain damage (% ± SEM) recorded under different treatments in Hwedza and Mbire districts during the 2015/16 storage seasons (n = 3). The legend 0, 8, 16 etc. represent the sampling period in weeks

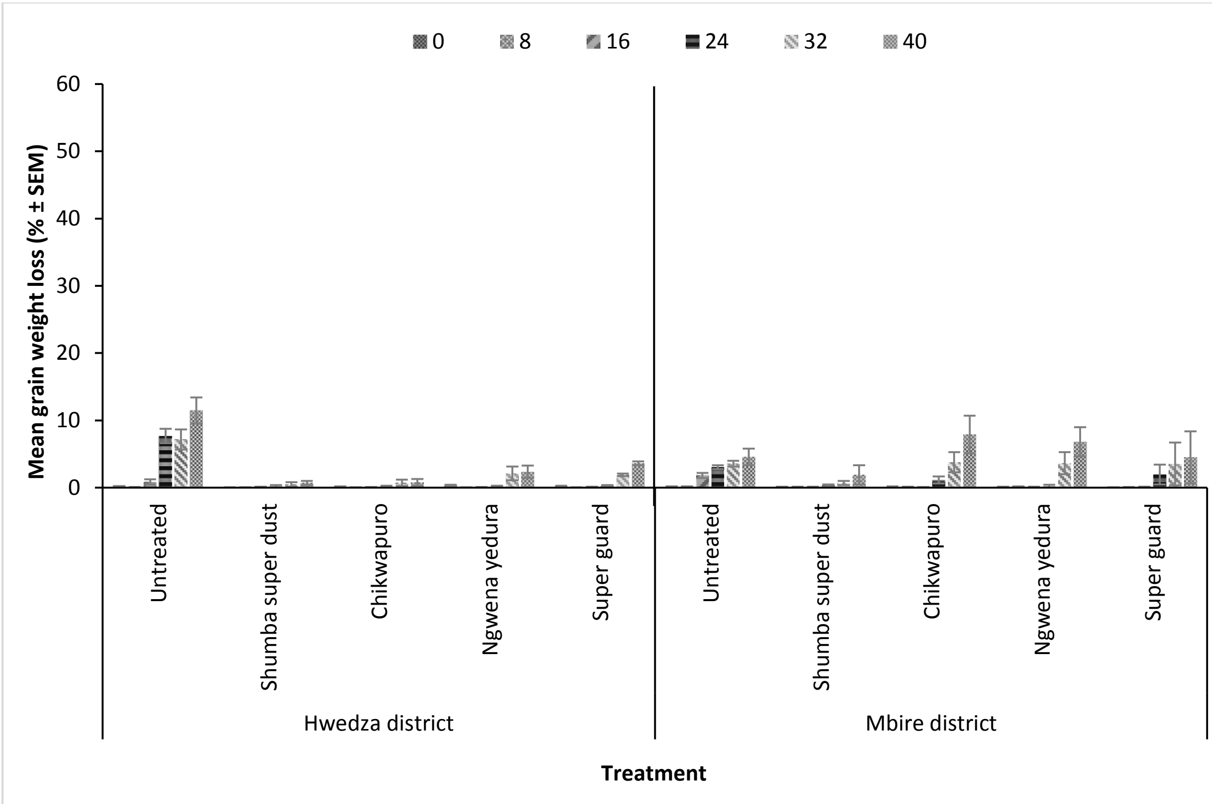

Figure 3: Mean maize grain weight loss (% ± SEM) recorded under different treatments in Hwedza and Mbire districts during the 2014/15 storage seasons (n = 3). The legend 0, 8, 16 etc. represent the sampling period in weeks

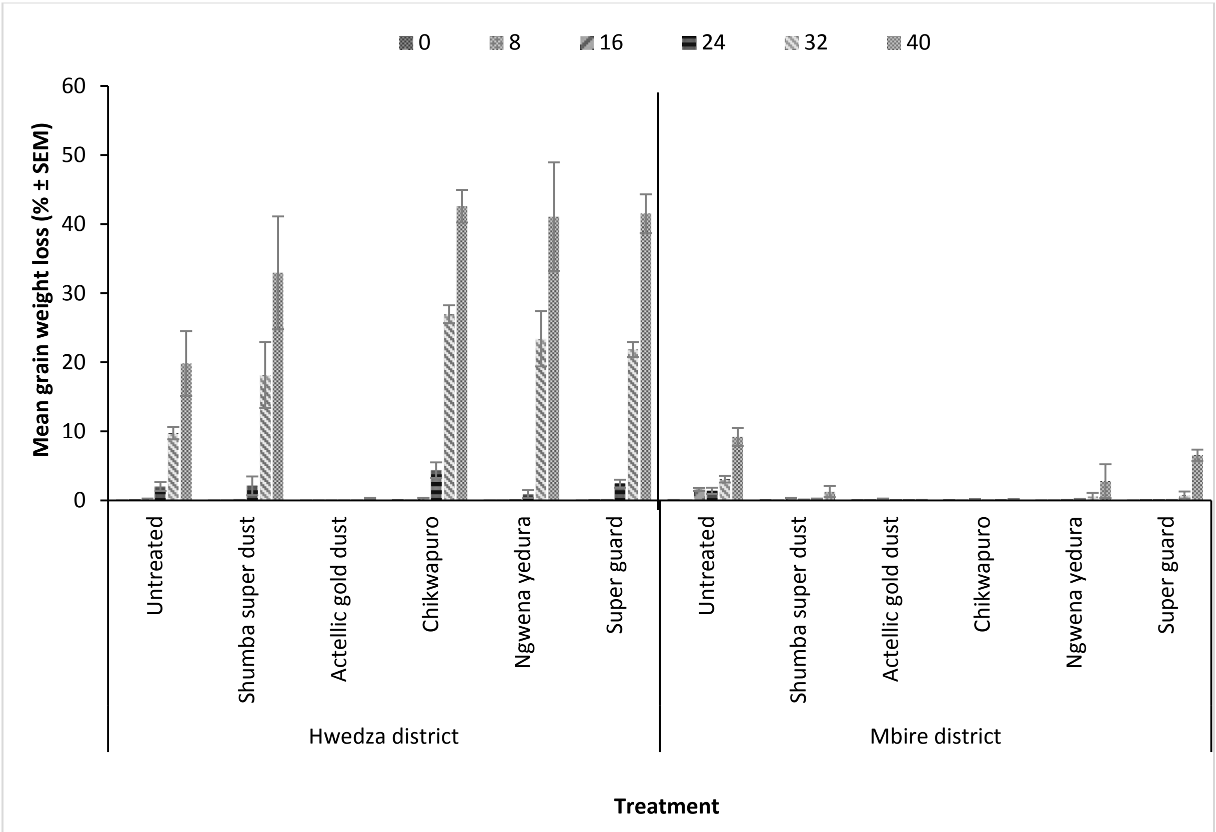

Figure 4: Mean maize grain weight loss (% ± SEM) recorded under different treatments in Hwedza and Mbire districts during the 2015/16 storage season (n = 3). The legend 0, 8, 16 etc. represent the sampling period in weeks

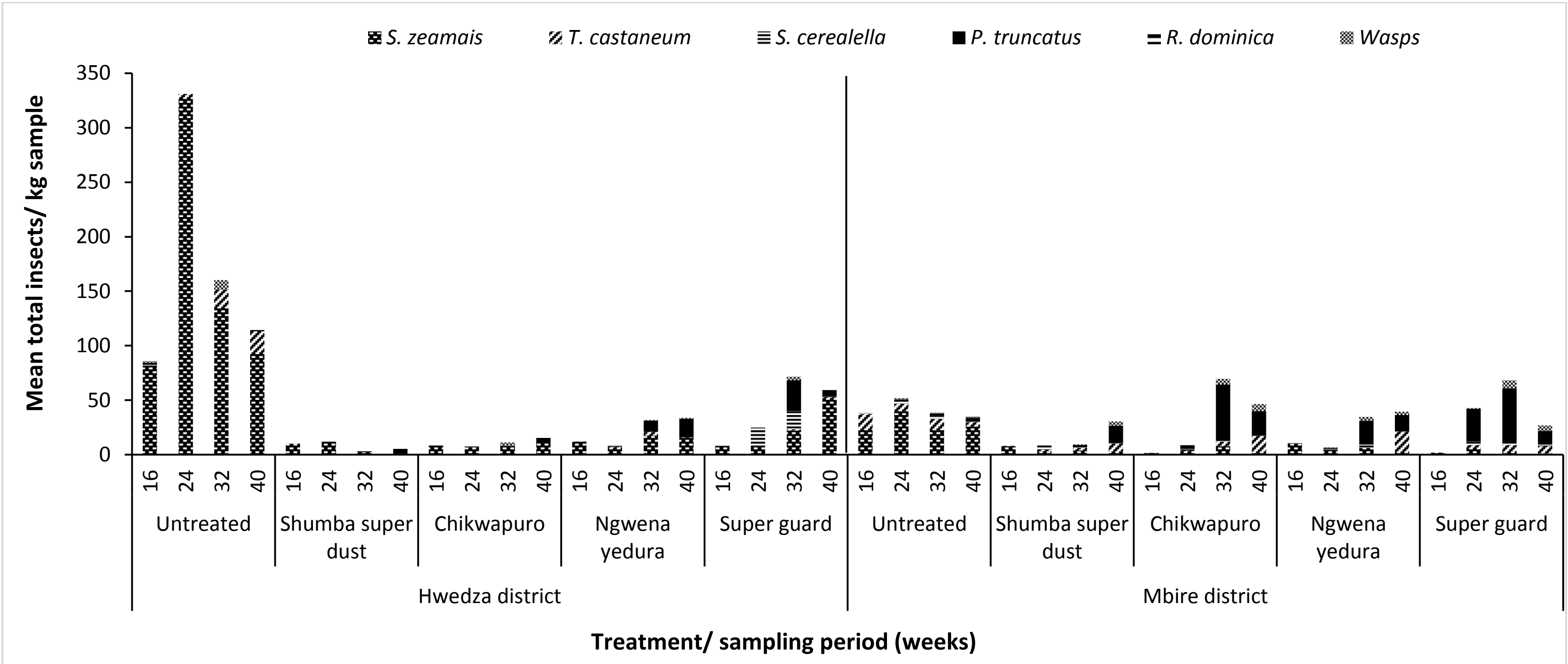

Figure 5: Mean total insects recorded in maize grain stored under different treatments in Hwedza and Mbire districts during the 2014/15 storage season (n = 3). The legend shows insect species recorded

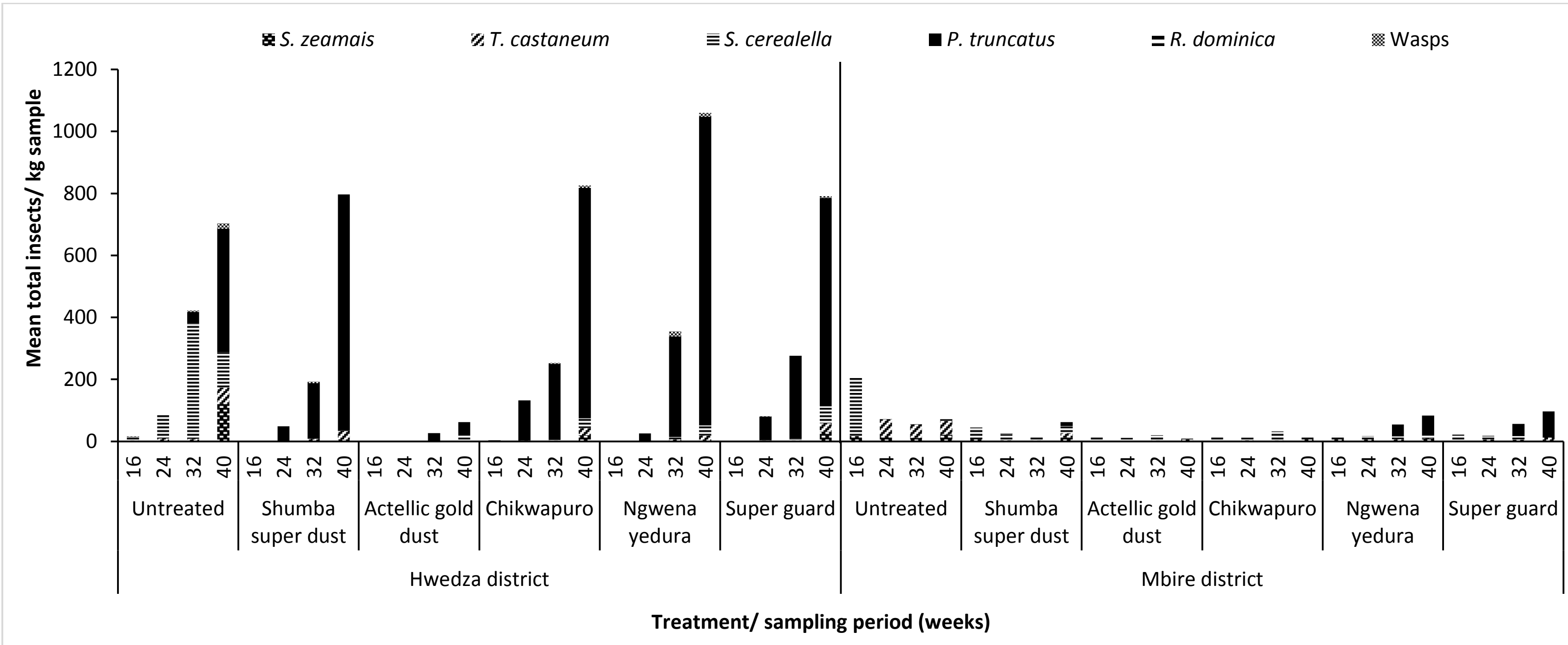

Figure 6: Mean total insects recorded in maize grain stored under different treatments in Hwedza and Mbire districts during the 2015/16 storage season (n = 3). The legend shows insect species recorded

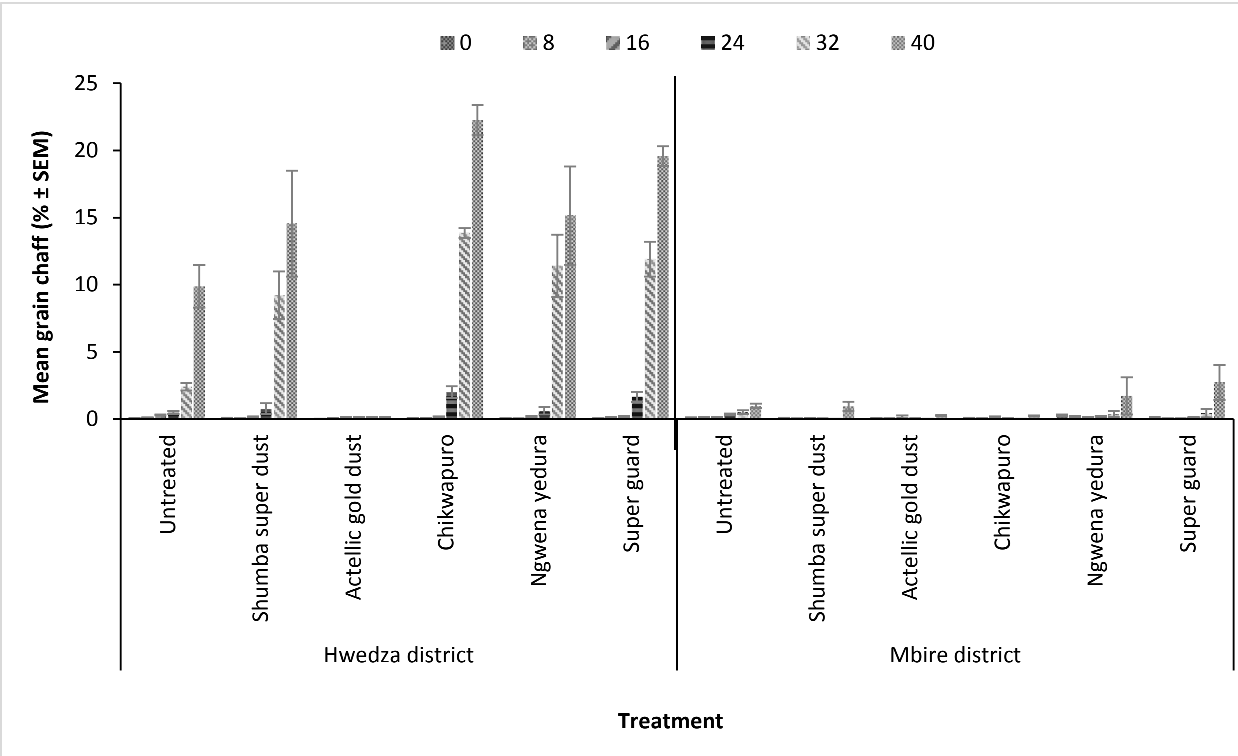

Figure 7: Mean chaff (% ± SEM) recorded in maize grain stored under different treatments in Hwedza and Mbire during the 2015/16 season (n = 3). The legend 0, 8, 16 etc. represent the sampling period in weeks

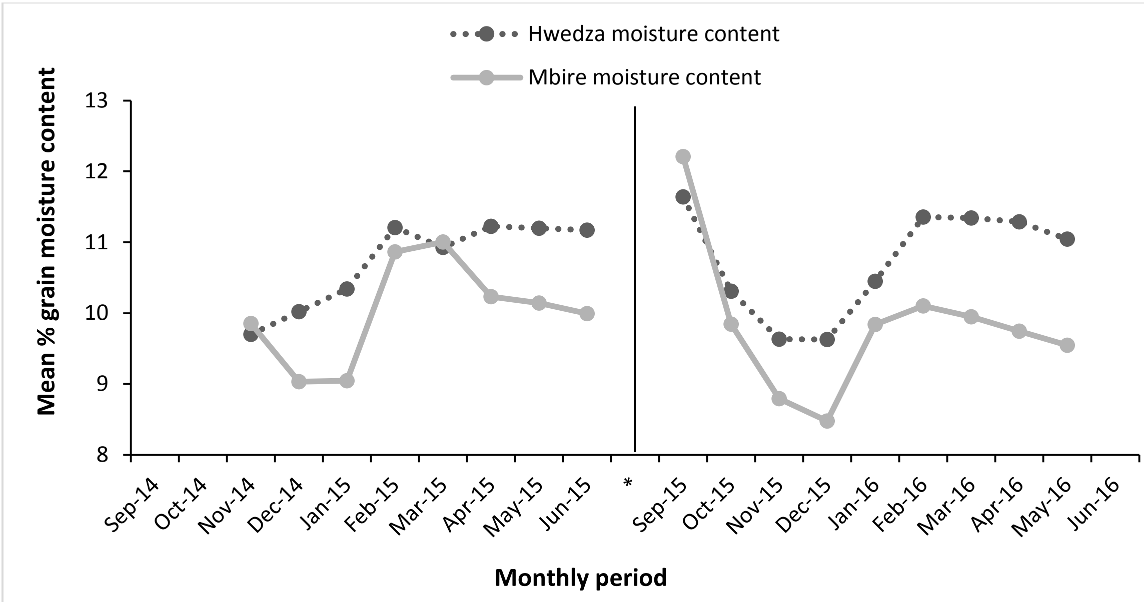

Figure 8: Mean moisture content recorded on maize grain samples in Hwedza and Mbire districts during the 2014/15 and 2015/16 season

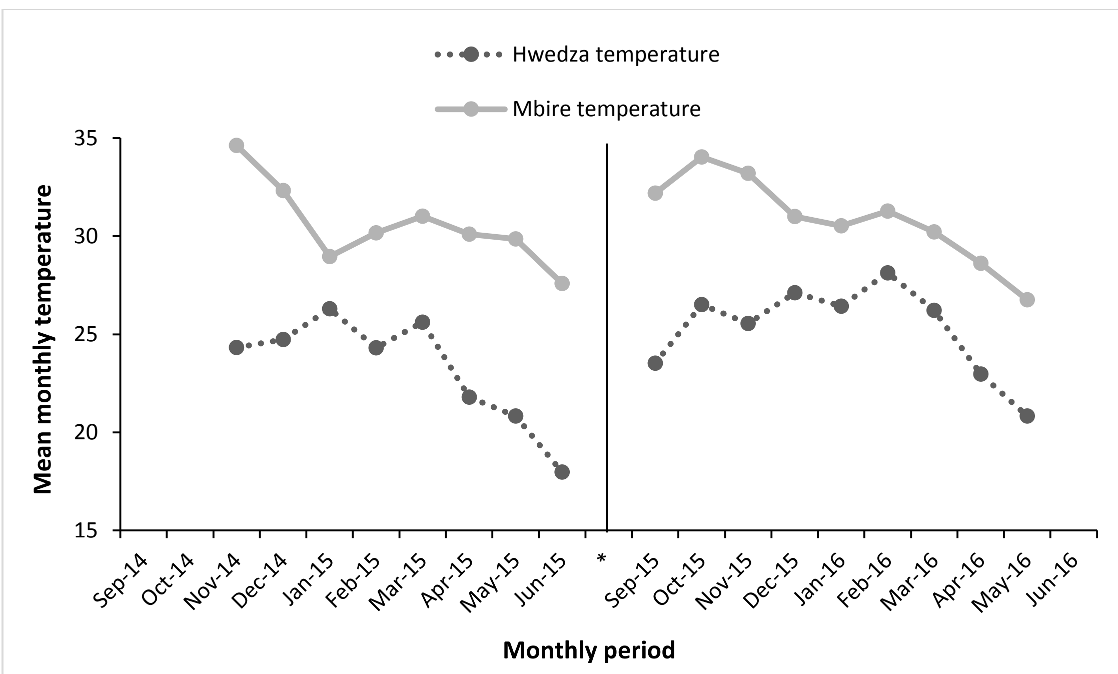

Figure 9: Mean monthly store temperatures recorded in Hwedza and Mbire districts during the 2014/15 and 2015/16 seasons