Field efficacy of hermetic and other maize grain storage options under smallholder farmer management

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Abstract

Household grain storage continues to be of paramount importance in improving food security in sub-Saharan Africa (SSA) where maize post-harvest losses of 10 - 20 % are reported. On-farm trials to compare alternative solutions for reducing household maize storage losses were conducted in the 2014/15 and 2015/16 storage seasons in two contrasting agro-ecological zones in the Hwedza district of Zimbabwe. A wide range of treatments including a commercial synthetic pesticide composed of fenitrothion 1 % and deltamethrin 0.13 %[1], unregistered but commonly used botanical pesticides (*Aloe* ash, *Colophospermum mopane* leaves, *Eleusine coracana* (rapoko) chaff, and *Ocimum gratissimum*), hermetic storage facilities (metal silos, GrainPro Super Grain Bags (SGB) IVR™, Purdue Improved Crop Storage (PICS) bags), and storage bags with deltamethrin incorporated into their fabric, were evaluated. The results demonstrated the superiority of hermetic storage facilities (PICS bags, SGBs, and metal silos) in suppressing insect pest build-up, insect grain damage and weight loss in stored maize grain. A newly introduced synthetic pesticide on the Zimbabwean market which has pirimiphos-methyl 1.6 % and thiamethoxam 0.36 % was also evaluated in the 2015/16 season and was found to be highly effective. The following grain storage technologies: hermetic metal silos, SGB bags, PICS bags, and the pesticide formulation of pirimiphos-methyl 1.6 % and thiamethoxam 0.36 % are therefore recommended for smallholder farmer use to reduce stored grain losses due to insect pests.

[1] Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the University of Zimbabwe or Natural Resources Institute and does not imply its approval to the exclusion of other products that may also be suitable.

Key words: food security, unregistered botanical pesticides, maize grain storage, synthetic pesticides, storage insect pests

1. INTRODUCTION

Maize is a staple food in much of sub-Saharan Africa (SSA) where it is grown mainly by resource poor farmers (Phiri and Otieno, 2008). Most SSA countries experience tropical climatic conditions with distinct uni or bimodal rainfall seasons, and a hot dry season (Gordon, 2009; Besada and Sewankambo, 2009). Consequently, in many areas, a rain-fed crop is harvested once per year; and the grain dried and stored for gradual household consumption until the next harvest arrives or kept for sale later in the season (Mvumi and Stathers, 2003).

In unimodal rainfall areas, smallholder farmers will typically store their maize grain for periods of up to eight or twelve months (Mvumi and Stathers, 2003). During this storage period, grain is vulnerable to attack by insect pests resulting in considerable losses. Average maize postharvest losses of 18.6 % have been estimated across SSA (APHLIS, 2014), and the World Bank's Missing Food study reports grain postharvest losses of 10 - 20 % in the same region; with an annual value of US$ 4 billion (World Bank et al., 2011). Insect pests of economic importance in stored maize in SSA include the maize weevil (*Sitophilus zeamais* Motschulsky, 1855 (Coleoptera; Curculionidae) (Stathers et al., 2002; Midega et al., 2016); the red-rust flour beetle (*Tribolium castaneum* (Herbst, 1797) (Coleoptera; Tenebrionidae) (Stathers et al., 2002; Mvumi and Stathers, 2003); the Angoumois grain moth (*Sitotroga cerealella* (Olivier, 1789) (Lepidoptera; Gelechiidae) (Stathers et al., 2002; Mvumi and Stathers, 2003; Midega et al., 2016) and the larger grain borer (LGB) *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) (Nyagwaya et al., 2010; Abass et al., 2014). The introduction and establishment of the LGB in the late 1970s increased the magnitude of grain storage losses in Africa (Boxall, 2002; Mutambuki and Ngatia, 2012). Storage insect pest problems are likely to be exacerbated by global warming as most of these pests multiply faster under higher temperatures (Gornall et al., 2010; Stathers et al., 2013).

While many farmers in SSA rely on synthetic pesticides to control grain storage insect pests, many others who cannot afford or access synthetic pesticides use methods such as "botanical leaf powders" (Mvumi and Stathers, 2003). Botanical pesticides are products derived directly from plants that have pesticidal properties (Ortiz-Hernandez et al., 2013) and are used to protect crops and livestock, crop products, the environment and humans from synthetic pesticide toxicity which has become a global problem (Rozman et al., 2007). Recent studies suggest botanical pesticides have gained enormous research attention as in many cases, smallholder farmers consider them the only economic option for grain storage (Stevenson et al., 2014). Moreover, concerns over pesticide residues in food (Damalas and Eleftherohorinos, 2011) are also driving the need for safer alternative storage technologies. The overzealous use of synthetic pesticides has resulted in unforeseen dangers, leading to increased regulation and focus on alternative pest management methods (Isman, 2006).

In this study, a range of alternative grain storage technologies including unregistered botanical pesticides, synthetic pesticides, air-tight (hermetic) storage as well as polypropylene bags with the synthetic pesticide incorporated in their fabric; were evaluated for efficacy against maize storage insect pest damage. Hermetic storage technologies provide farmers with chemical-free grain protection options (Villers et al., 2010; Mutungi et al., 2014). The hermetic storage facilities tested were GrainPro Super Grain Bags (SGB) IVR™, Purdue Improved Crop Storage (PICS) bags, and metal silos. The PICS bag has two inner liners each made of 80 µm thick polyethylene (Baributsa et al., 2012), and these liners are placed one inside the other in a woven polypropylene bag (Murdock et al., 2012). By contrast, SGBs just have a single polyethylene liner inside a woven polypropylene bag (De Groote et al., 2013). Once the hermetic bags are loaded with well-dried grain and tied shut, the biological activity of the grain and respiration of any insects present, results in depletion of oxygen and build-up of carbon dioxide concentration inside the bag to levels high enough to cause asphyxiation or desiccation of the insects (Murdock et al. 2012; Hodges and Stathers, 2012; Moreno-Martinez et al. 2000). The ZeroFly® technology makes use of woven polypropylene bags with deltamethrin incorporated into the polypropylene fabric and insects are killed when they come into contact with the bag (Baban and Bingham, 2014; Costa, 2014).

Few field studies have comprehensively tested such a range of storage technologies under smallholder farmer circumstances to determine their efficacy and appropriateness, especially where *P. truncatus* occurs. To promote the integration of the new technologies with indigenous knowledge, co-learning and co-innovation; a Learning Centre approach, as described by Mashavave et al. (2011) was used in evaluating the storage options. It is anticipated that the knowledge and hands-on experience of farmers, extensionists and other stakeholders gained through participating together in the trials will facilitate quicker, longer-term and more wide-spread adoption of the most effective grain storage technologies. The current paper reports on the bio-physical findings of the trials, while the results of the farmer and stakeholder interactions are reported separately, elsewhere. The specific objective of the current study was to evaluate the potential of the hermetic storage containers and deltamethrin incorporated polypropylene bags in controlling maize storage insect pests in smallholder farming systems compared to farmers' normal practices and commercial synthetic pesticides.

2. MATERIALS AND METHODS

2.1 Site description

Field trials were conducted in the Hwedza district (18^{o} 41′ S; 31^{o} 42′ E) of Zimbabwe in two consecutive grain storage seasons (2014/15 and 2015/16). The trials were hosted by smallholder farmers in two wards (the administrative unit between district and village levels), namely Makwarimba and Goneso, which differ in their agro-climatic characteristics. Makwarimba ward is mostly located in natural farming region II b, receiving an annual rainfall of 750 - 1000 mm, with a mean annual temperature range of 18 – 30 ˚C while Goneso ward is mostly in natural farming region III, receiving 650 - 800 mm rainfall annually, with a mean annual temperature range of 18 – 35 °C. Zimbabwe is divided into five natural farming regions based on the amounts of rainfall received, prevailing temperatures and to a lesser extend the soil type. Region I receives the highest amounts of rainfall and region V represents the most arid parts of the country.

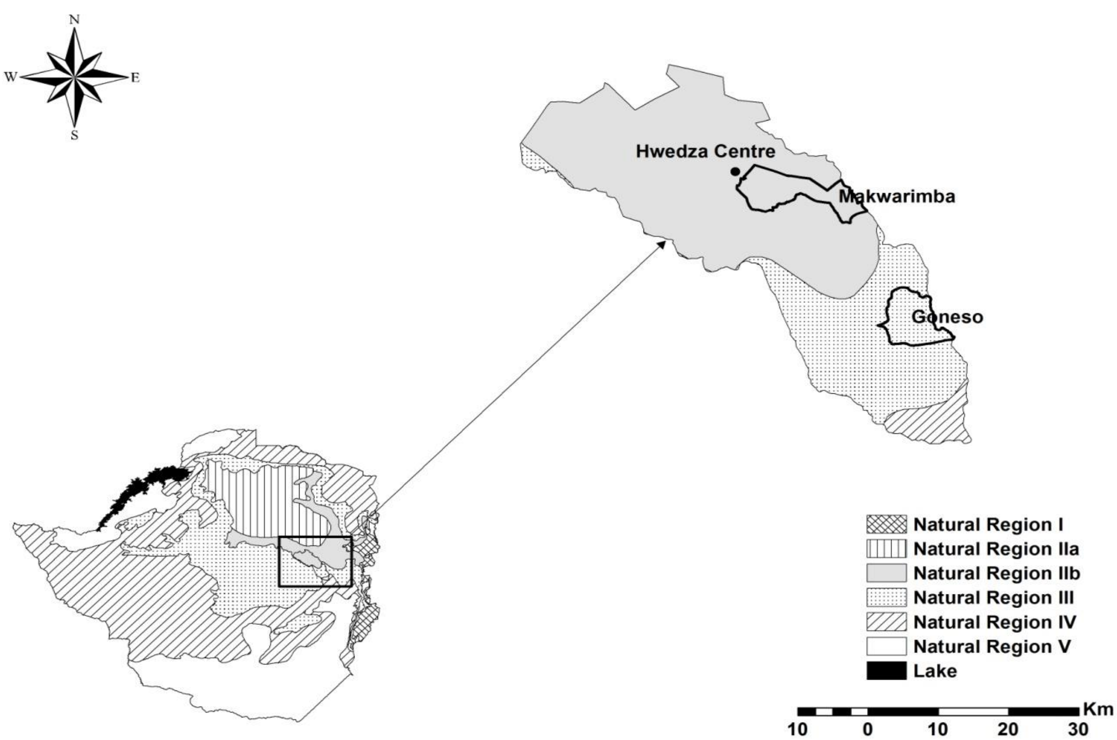

Figure 1: Map of Zimbabwe showing study sites in Hwedza district, Makwarimba ward (Natural Region IIb) and Goneso (Natural Region III).

2.2 Storage structures, grain preparation and storage

Four smallholder farmers with similar brick granaries and roofing materials were selected by the community to host the trials and act as Learning Centre representatives in each of the two wards. The different grain storage treatments were housed within farmers' own brick-built grain storage structures. The storage structures in both wards were constructed from mud bricks and plastered with cement. In Makwarimba ward, the storage structures were roofed using zinc sheets whilst asbestos sheets were used in Goneso ward.

Figure 2: Typical storage structures which housed the trials (view from outside at trial setting and from inside after setting the trials)

The host farmers were selected on the basis of their ease of-interaction with their communities, ease of access to their homes, security of the trial grain during storage, and the availability of a suitable storage structure. Local farmers, agricultural extension staff and the researchers participated in trial-setting, sampling, sample evaluation and ranking of the treatments.

In each ward, the maize grain used to set-up all the treatments was bought locally and mixed thoroughly to ensure baseline uniformity. Two commonly grown hybrid maize varieties, "PHB 30G19" and "Sirda 113", freshly harvested from the 2014/15 growing season, were mixed thoroughly in a ratio of 2:1 in order to homogenise the treatment grain. In the successive 2015/16 storage season, maize varieties; "Pioneer 2859" and "PHB 30G19" mixed in a 3:1 ratio were used. Mixed varieties were used due to the lack of sufficient grain of a single variety as a result of poor harvests. None of the grain was fumigated prior to setting up the experiment and no insect seeding was done.

The grain was then sub-divided into 200 kg portions; (four 50 kg replicates per treatment in each ward) and poured onto different plastic sheets. In the case of the synthetic chemical and botanical treatments, each 200 kg portion of maize grain was thoroughly admixed with the respective treatment/product (as described in Table 1) before loading into 50 kg polypropylene bags. For the hermetic bags, metal silos, untreated bags (negative control) and ZeroFly® bag treatments; grain was loaded into these devices without any chemical treatment.

The bags were tied securely using rubber strips. The inlet and outlet caps of metal silos were also closed and made air-tight by tying rubber strips around the caps. Each treatment replicate was placed on bricks to prevent direct contact with the floor, as that might result in the accumulation of moisture at the bottom of the bags. Metal silos were placed on wooden pallets to prevent moisture accumulation under the base. The trials were conducted over a period of 32 weeks in the 2014/15 storage season. However, in the 2015/16 season the period was extended to 40 weeks to evaluate the performance of the technologies over a longer storage period.

2.3 Experimental designs, trial setting and sampling

Nine different grain storage treatments (Table 1) were set up at each Learning Centre in a randomised complete block design. The four Learning Centres per ward acted as blocks and each held all of the nine different treatments, creating four replicates of each treatment per ward. Polypropylene bags (50 kg) were used for storage of maize grain for both organic and registered pesticide treatments. Shumba super dust®, a formulation of fenitrothion 1 % and deltamethrin 0.13 %, being the most widely used pesticide in Hwedza (according to a community profiling survey conducted prior to the storage trials), was used as a positive control. Moreover, two separate treatments of Shumba super dust® (one bought from a Harare-based agro-dealer (Pesticide 1) and the other from a Hwedza-based stockist (Pesticide 2)) were used to determine if the efficacy of locally-purchased Shumba super dust® pesticide was different from that of the Harare stock. Farmers often allege that the locally-procured product is manipulated by agro-dealers before being sold or that an already expired product is sold; rendering them ineffective in controlling grain storage insect pests. The Actellic gold dust® treatment (Pesticide 3), made up of pirimiphos-methyl 1.6 % and thiamethoxam 0.36 % was introduced in the 2015/16 season as a recent product on the Zimbabwean market. Botanical treatments were also included in the investigation at the request of the farmers since they often rely on such treatments when they cannot access or afford synthetic pesticides. A maximum of two botanical pesticides were evaluated per season; with any poorly performing ones being replaced after the first season, to enable other options from the wide range of botanical materials available within the community to be evaluated.

Table 1: Treatments tested under smallholder farmer management

Category	**Treatment[2] /Trade name**	**Makwarimba ward**		**Goneso ward**	
		2014/15	**2015/16**	**2014/15**	**2015/16**
Local botanical pesticides	*Aloe* ash	✓	✓	-	-
	Maize cob ash	✓	-	-	-
	Ocimum gratissimum leaves	-	✓	-	-
	Mopane (*Colophospermum mopane*) leaves	-	-	✓	-
	Rapoko (*Eleusine corocana*) chaff				
	Rapoko chaff mixed with mopane leaves	-	-	-	✓
Registered pesticides	Harare shumba super dust® (Pesticide 1)	✓	✓	✓	✓
	Hwedza shumba super dust® (Pesticide 2)	✓	-	✓	-
	Actellic gold dust® (Pesticide 3)	-	✓	-	✓
New storage technologies	ZeroFly storage bags	✓	✓	✓	✓
	GrainPro Super Grain bag (SGB) IVR™	✓	✓	✓	✓
	Purdue Improved Crop Storage (PICS) bags	✓	✓	✓	✓
	Metal silo	✓	✓	✓	✓
Control	Untreated	✓	✓	✓	✓

Nine different treatments were evaluated per season in each ward. "✓" shows which treatments were included, while "-" shows the treatment was not included.

The trials were set in September and August and terminated in April and May for the 2014/15 and the 2015/16 storage seasons; respectively. The trial timing coincided with the usual storage season in the trial sites, and enabled the capturing of storage insect pests' prevalence and diversity during the hot dry (August – November), hot wet (December – March) as well as part of the cold dry (April – July) season. Sampling was conducted at 8-weekly intervals. Samples of 1 kg were collected using 1 m long multi-compartmented sampling spears. The sampling spears were disinfected between the collection of samples from the different treatments to avoid cross contamination of treatments. Samples were taken to the laboratory at the University of Zimbabwe in Harare for analysis.

[2]Per 50 kg of grain, botanical rates were *Aloe* ash (3 cups equivalent to 200 g), maize cob ash (3 cups equivalent to 200 g), *Ocimum gratissimum* (62.9 g), *Colophospermum mopane* (mopane) leaves (1 kg of dried leaves), *Eleusine corocana* (Rapoko) chaff (3 cups equivalent to 200 g), rapoko chaff and mopane leaves (150 g rapoko and 150 g mopane leaves). Shumba super dust (Pesticide 1 and 2) is a cocktail of fenitrothion 1 % + deltamethrin 0.13 %, whilst Actellic gold dust (Pesticide 3) contains pirimiphos-methyl 1.6 % + thiamethoxam 0.36 %.

In the laboratory, the samples were weighed first, then sieved to remove insects and chaff before dividing them into sub-samples for grain damage analysis. Grain moisture was measured using a pre-calibrated GrainPro® moisture meter model GMK- 303CF (GrainPro® Inc, Philippines). Grain was filled into the tester slot, crushed and grain moisture recorded. Chaff dust generated from insect feeding was sieved though a 2-mm test sieve (American Scientific Products, McGraw Park IL 60085) and the mass recorded. Chaff content was expressed as a percentage of the total mass of the sample. The 2-mm test sieve was also used to separate insects and chaff dust from whole grain. Counts of live and dead adult insects were recorded per species and converted to numbers per kilogram by simple proportion using sample mass. The trial relied on natural infestation which assumes that some insects have infested the grain whilst in the field or before storage (Golob and Hanks, 1990) and then continue to develop, breed and feed during grain storage, while other insects may arrive during the trial period and then attack the stored grain (Hodges et al., 1998; Stathers et al., 2008; Njoroge et al., 2014).

2.4 Grain damage and weight loss assessment

The 1 kg sample was divided into equal portions using a riffle divider. Three sub-samples representing three-eighths of the total sample were analysed for grain damage, manually separating the insect damaged from undamaged grains. Grains that had been perforated by insect pests were considered as insect damaged. Numbers of insect damaged (*Nd*) and undamaged (*Nu*) grain were used to calculate percentage grain damage using the equation: Grain damage (%) = $Nd/ (Nd + Nu) * 100$. Grain weight loss percentage was calculated using the count and weigh method (Harris and Lindbald, 1978; Boxall, 1986).

2.5 Data analysis

One way analysis of variance in randomised blocks, adjusted for covariate (baseline sampling) in Genstat version 14 (VSN International, 2011), was applied to test for statistical significance on mean % insect damaged grain, percentage weight loss, and % grain moisture content data at each sampling interval per ward. Square root transformations were done to compress the large values (Kirchner, 2001) and stabilize the variance (Velleman and Hoaglin, 1981) on grain damage, weight loss and chaff data. Tukey's test at 95 % probability was used for treatment mean separation where statistical significance among the means were found.

3. RESULTS

3.1. Grain damage

3.1.1. Storage season 1 (2014/15)

Baseline grain damage averaged 2.5 % and 5 % across all treatments in Makwarimba and Goneso wards respectively. In Makwarimba, the hermetic treatments demonstrated their superiority over conventional treatments by maintaining much lower levels of grain damage (Fig 3). Significant differences were observed at 8 ($F_{8, 23} = 15.93$; $P < 0.001$), 16 ($F_{8, 23} = 37.01$; $P < 0.001$), 24 ($F_{8, 23} = 47.97$; $P < 0.001$) and 32 weeks ($F_{8, 23} = 46.70$; $P < 0.001$) of storage. While all the hermetic treatments (metal silos, PICS bags and SGBs) recorded less than 10 % insect grain damage over the 32 weeks of storage, the pesticide 1 and 2 treatments recorded at least 40 % insect grain damage at 32 weeks storage. ZeroFly® bags, botanical treatments and the untreated control had the highest grain damage of between 60 and 80 % at 32 weeks storage.

Similarly for Goneso ward, significant differences emerged at 8 ($F_{8, 22} = 28.21$; $P < 0.001$), 16 ($F_{8, 22} = 132.65$; $P < 0.001$), 24 ($F_{8, 21} = 120.12$; $P < 0.001$) and 32 weeks ($F_{8, 21} = 68.64$; $P < 0.001$). Metal silos and PICS bags recorded the least damage below 13 % over 32 weeks of grain storage. SGBs also maintained damage below 10 % up to 24 weeks after which rodents attacked one of the treatment replicates allowing oxygen to permeate and the level of damage rapidly increased to about 32 % (Fig 4). Grain damage of nearly 100 % was recorded in pesticides 1 and 2 as well as in botanicals and untreated grain. ZeroFly® bags also suffered high damage of approximately 65 %.

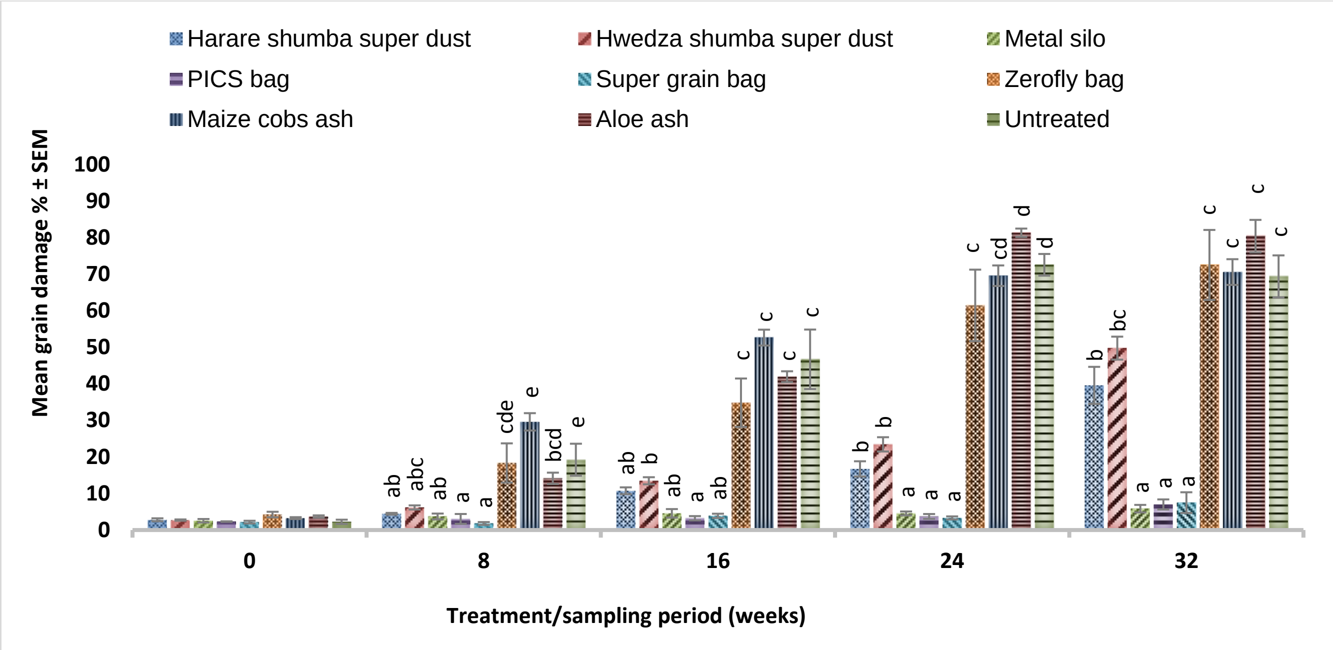

Figure 3: Mean percentage grain damage (± SEM) recorded under different treatments in Makwarimba ward during the 2014/15 storage season (n = 4).

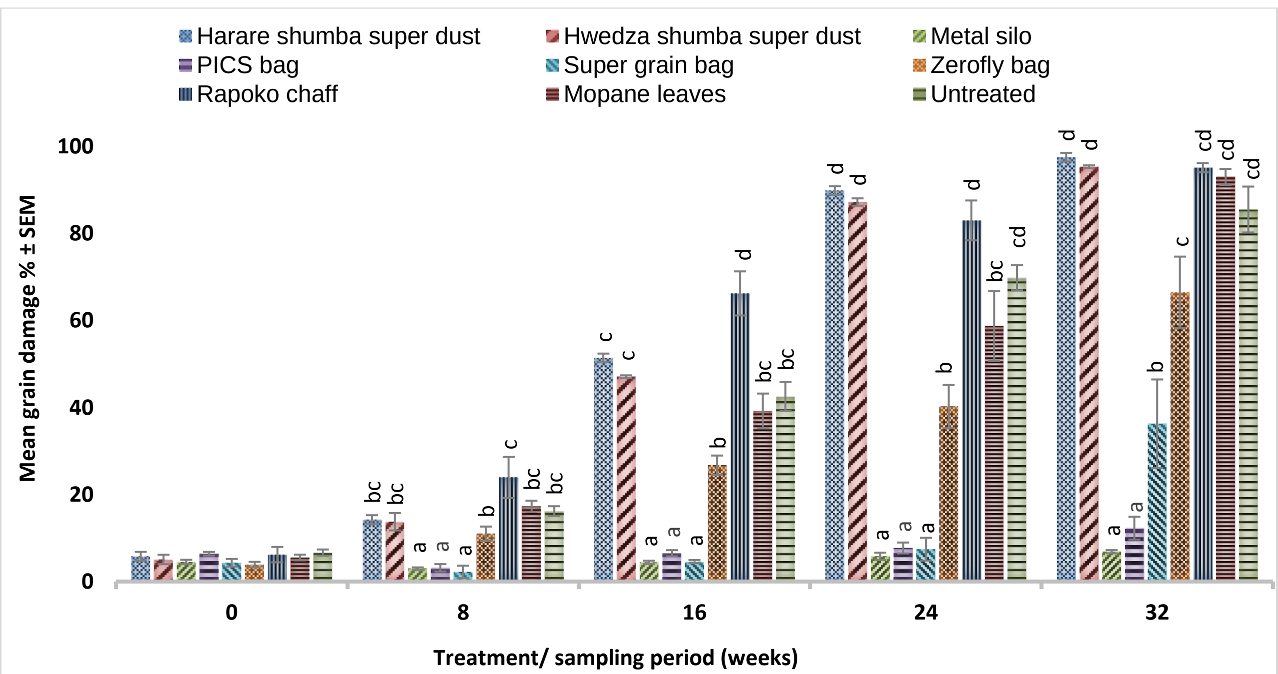

Figure 4: Mean percentage grain damage (± SEM) recorded under different treatments in Goneso ward during the 2014/15 storage season (n = 4).

3.1.2. Storage season 2 (2015/16)

During season 2, grain damage was almost nil (averaging 0.1 %) at trial setting in all treatments for both Makwarimba and Goneso wards. Significant differences were observed at 8 ($F_{8, 23}$ = 9.72; P < 0.001), 16 ($F_{8, 23}$ = 13.99; P < 0.001), 24 ($F_{8, 23}$ = 37.06; P < 0.001), 32 ($F_{8, 23}$ = 27.26; P < 0.001) and 40 weeks ($F_{8, 23}$ = 34.44; P < 0.001). A swift increase was observed at week 32 in Makwarimba (Fig 5). On average, metal silos, PICS bags, SGBs and pesticide 3 recorded damage of 25 % or below. On the other hand, pesticide 1 as well as ZeroFly® bags, botanical treatments and untreated recorded the highest damage levels between 65 and 90 %. The damage recorded in pesticide 3 and the hermetic treatments was significantly lower than that in pesticide 1, botanical treatments and untreated.

In Goneso, the newly introduced pesticide 3 recorded the least grain damage of less than 5 % over the 40 weeks of storage which was superior to the rest of the treatments. This was followed by the hermetic treatments and pesticide 1 which recorded between 15 and 35 % damage over the 40 weeks of storage. ZeroFly® bags, botanical treatments and the untreated control recorded the highest grain damage of between 70 and 80 % (Fig 6). Significant differences in grain damage were observed at 8 ($F_{8, 23}$ = 9.12; P < 0.001), 16 ($F_{8, 23}$ = 15.00; P < 0.001), 24 ($F_{8, 23}$ = 11.77; P < 0.001), 32 ($F_{8, 23}$ = 28.23; P < 0.001) and 40 ($F_{8, 22}$ = 24.91; P < 0.001) weeks. Pesticide 3 was the most effective treatment followed by the hermetic treatments and pesticide 1 respectively. The highest insect damage (> 70 %) occurred in the ZeroFly® storage bags, botanical treatments and untreated grain.

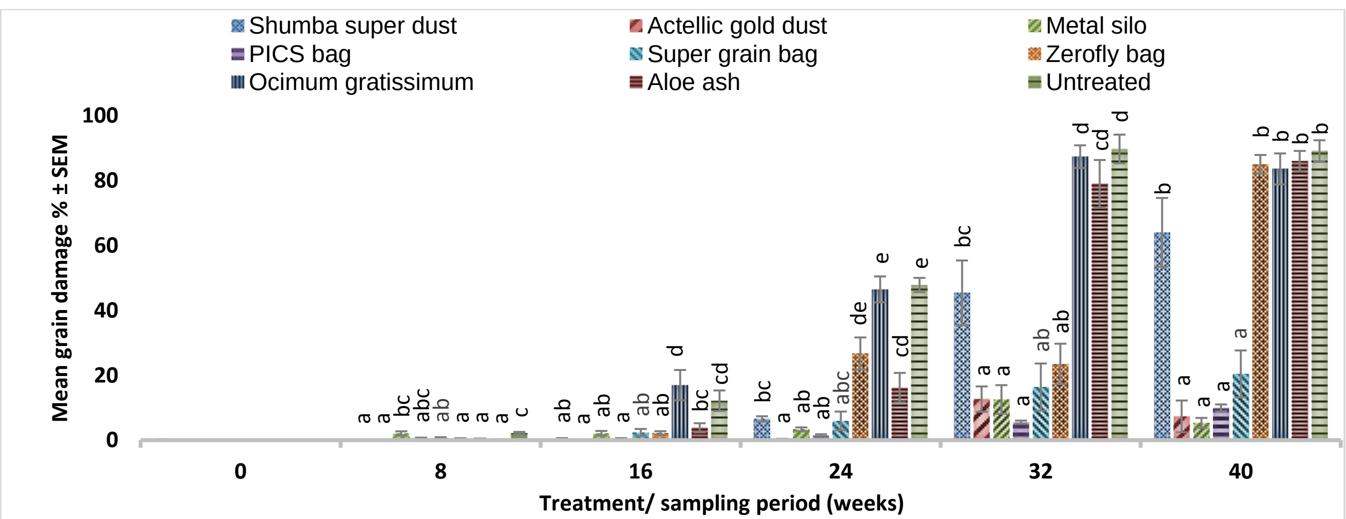

Figure 5: Mean percentage grain damage (± SEM) recorded under different treatments in Makwarimba ward during the 2015/16 storage season (n = 4).

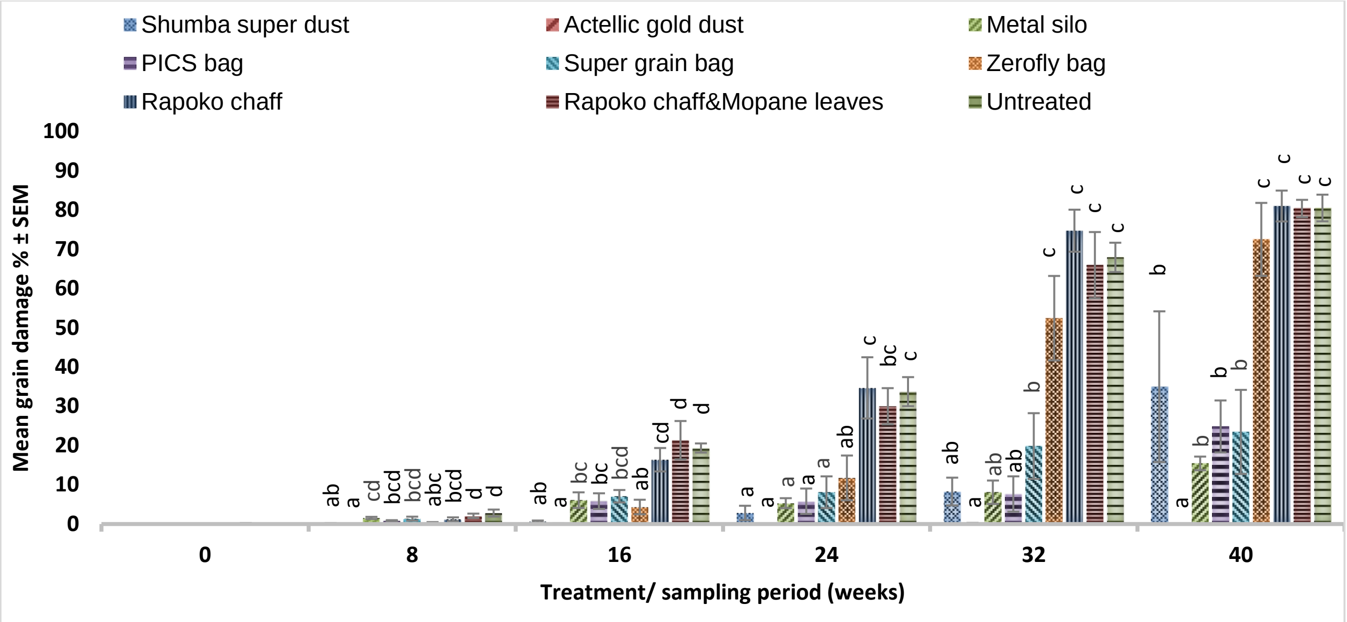

Figure 6: Mean percentage grain damage (± SEM) recorded under different treatments in Goneso ward during the 2015/16 storage season (n = 4).

3.2. Grain weight loss

3.2.1. Storage season 1 (2014/15)

In Makwarimba, grain damage levels (Fig 3) relate well to the weight loss (Table 2) with the most damaged treatments recording the highest losses on a weight basis. Metal silos, PICS and SGBs, pesticide 1 and 2 recorded the lowest weight loss of below 5 %. Significant differences in weight loss were recorded at 8 ($F_{8, 24} = 5.52$; $P < 0.001$), 16 ($F_{8, 23} = 9.33$; $P < 0.001$), 24 ($F_{8, 23} = 15.53$; $P < 0.001$) and 32 weeks ($F_{8, 23} = 12.78$; $P < 0.001$). The highest losses of approximately 23 % on average were recorded in ZeroFly® storage bags as highlighted in Table 2.

For Goneso ward, grain weight losses (Table 2) corresponded well to the damage levels observed in Fig 4; the case of which is similar with Makwarimba ward. The highest losses rounding off to 50 % and above were recorded for pesticides 1 and 2 and rapoko chaff followed by mopane leaves, untreated grain and ZeroFly® bags respectively. Significant differences ($P < 0.001$) in weight loss among treatments were recorded at week 16 ($F_{8, 22} = 10.11$; $P < 0.001$), 24 ($F_{8, 21} = 29.06$; $P < 0.001$) and 32 ($F_{8, 21} = 31.71$; $P < 0.001$) weeks. Average losses were lowest in the hermetic storage facilities, remaining below 10 % despite rodents perforating one of the four replicates of SGBs between week 24 and 32.

3.2.2. Storage season 2 (2015/16)

In the 2015/16 season, weight losses below 5 % were recorded in pesticide 3 and the hermetic treatments over the 40 weeks of storage whereas average weight losses above 15 % to 35 % were recorded in pesticide 1, ZeroFly® bags, botanical treatments as well as the untreated control in Makwarimba ward (Table 3). Statistically significant differences in weight loss were observed at 8 ($F_{8, 23}$ = 2.74; P < 0.0028), 16 ($F_{8, 23}$ = 4.99; P < 0.001), 24 ($F_{8, 23}$ = 6.40; P < 0.001), 32 ($F_{8, 23}$ = 10.47; P < 0.001) and 40 weeks ($F_{8, 23}$ = 32.87; P < 0.001) of grain storage. The highest weight losses of between 18 and 32 % were recorded in the pesticide 1, ZeroFly® bags, *O. gratissimum*, *Aloe* ash and the untreated control treatments.

In the drier ward of Goneso, weight losses below 5 % were recorded in the pesticide 3 and hermetic treatments over the 40 weeks of storage, whereas losses of above 15 % to 35 % were on average recorded in pesticide 1, ZeroFly® bags, botanical treatments as well as the untreated control (Table 3). Statistical differences in weight loss were observed at 8 ($F_{8, 23}$ = 3.98; P < 0.004), 16 ($F_{8, 23}$ = 9.49; P < 0.001), 24 ($F_{8, 23}$ = 10.46; P < 0.001), 32 ($F_{8, 23}$ = 7.46; P < 0.001) and 40-week ($F_{8, 22}$ = 11.96; P < 0.001) sampling intervals. Pesticide 3 and hermetic treatments produced the least weight loss below 3 % compared to pesticide 1, ZeroFly® bags, botanical treatments and untreated grain which recorded between 12 and 31 % weight loss within the 40 week storage period.

3.3. Insect species composition and abundance

3.3.1. Season 1 (2014/15)

The insect species recorded in both Makwarimba and Goneso during season 1 were *Sitophilus zeamais* Motschulsky, (Coleoptera; Curculionidae), *Sitotroga cerealella* Olivier, 1789 (Lepidoptera; Gelechiidae), *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae), *Rhyzopertha dominica* (Fabricius) (Coleoptera; Bostrichidae), *Tribolium castaneum* Herbst, 1797 (Coleoptera; Tenebrionidae) and predator wasps of the order hymenoptera. The most dominant species were *S. zeamais* which were recorded in all treatments and *S. cerealella* which was most abundant in the botanical treatments, untreated control and pesticide 1 and 2 respectively. *Prostephanus truncatus* was also recorded in all treatments although in low numbers. The hermetic treatments outperformed the other treatments in maintaining the lowest numbers of insect pests (Fig 7).

Table 2: Mean percentage grain weight loss (± SEM) recorded under different treatments in Makwarimba and Goneso wards during the 2014/15 storage season (n = 4).

Treatment	Makwarimba ward 2014/15				Goneso ward 2014/15			
	8 wks	16 wks	24 wks	32 wks	8 wks	16 wks	24 wks	32 wks
Harare shumba super dust (Pesticide 1)	0.38 ± 0.00**a**	1.77 ± 0.26**ab**	1.45 ± 0.87**ab**	2.93 ± 1.28**ab**	1.68 ± 0.57	8.57 ± 1.57**cd**	36.05 ± 1.94**de**	53.32 ± 2.26**c**
Hwedza shumba super dust (Pesticide 2)	0.47 ± 0.06**a**	1.90 ± 0.30**ab**	1.64 ± 0.42**ab**	4.14 ± 2.07**ab**	2.86 ± 0.35	7.97 ± 2.86**cd**	40.13 ± 6.12**e**	49.06 ± 2.85**c**
Metal silo	0.32 ± 0.17**a**	0.23 ± 0.16**a**	0.78 ± 0.10**a**	3.03 ± 0.20**a**	1.18 ± 0.07	0.95 ± 0.22**a**	1.85 ± 0.05**a**	2.15 ± 0.11**a**
PICS bag	0.48 ± 0.42**a**	0.03 ± 0.08**a**	0.48 ± 0.06**a**	2.65 ± 0.33**a**	0.66 ± 0.13	0.98 ± 0.21**a**	1.50 ± 0.10**a**	2.27 ± 0.43**a**
Super Grain bag	0.21 ± 0.11**a**	0.08 ± 0.02**a**	0.64 ± 0.05**a**	3.38 ± 0.63**a**	0.53 ± 0.09	1.08 ± 0.50**ab**	1.57 ± 0.29**a**	7.97 ± 3.18**ab**
ZeroFly bag	2.04 ± 1.33**ab**	5.46 ± 1.44**b**	14.86 ± 9.12**c**	17.61 ± 9.06**bc**	1.08 ± 0.25	3.36 ± 0.09**abc**	4.65 ± 1.22**ab**	19.98 ± 7.55**b**
Maize cobs ash	3.47 ± 1.09**b**	5.53 ± 1.24**b**	12.26 ± 2.25**c**	14.34 ± 1.97**bc**	-	-	-	-
Aloe ash	1.49 ± 0.83**ab**	6.68 ± 2.59**b**	15.90 ± 0.39**c**	23.55 ± 2.05**c**	-	-	-	-
Rapoko chaff	-	-	-	-	1.31 ± 2.35	17.14 ± 1.62**d**	32.78 ± 7.11**de**	53.21 ± 2.28**c**
Mopane leaves	-	-	-	-	2.61 ± 1.70	6.54 ± 1.40**bcd**	13.31 ± 5.37**bc**	45.24 ± 4.03**c**
Untreated	1.88 ± 1.25**ab**	4.59 ± 1.88**b**	10.43 ± 6.52**bc**	15.60 ± 3.50**bc**	1.85 ± 0.61	11.30 ± 4.85**cd**	19.69 ± 2.67**cd**	39.88 ± 7.17**c**
P-value	<0.001	<0.001	<0.001	<0.001	0.065	<0.001	<0.001	<0.001
CV%	28.8	26.8	30.1	26.3	33.8	24.4	19.5	15.8

Figures presented are the original averages of each treatment. "-" means treatment was not included. Means within a column are compared and separated using Tukey's test at P < 0.05 and different alphabetic letters indicate significant differences

Table 3: Mean percentage grain weight loss (± SEM) recorded under different treatments in Makwarimba and Goneso wards during the 2015/16 storage season (n = 4).

	Makwarimba ward 2015/16					Goneso ward 2015/16				
Treatment	**8 wks**	**16 wks**	**24 wks**	**32 wks**	**40 wks**	**8 wks**	**16 wks**	**24 wks**	**32 wks**	**40 wks**
Shumba super dust (Pesticide 1)	0.02 ± 0.01**a**	0.21 ± 0.05**a**	0.92 ± 0.21**ab**	7.70 ± 2.46**ab**	18.21 ± 4.45**b**	0.06 ± 0.03**ab**	0.07 ± 0.03**a**	0.43 ± 0.32**abc**	0.88 ± 0.34**a**	12.38 ± 9.61**cd**
Actellic gold dust (Pesticide 3)	0.00 ± 0.01**a**	0.16 ± 0.00**a**	0.03 ± 0.04**a**	0.13 ± 0.16**a**	0.16 ± 0.33**a**	0.01 ± 0.00**a**	0.02 ± 0.02**a**	0.03 ± 0.01**a**	0.24 ± 0.05**a**	0.39 ± 0.00**a**
Metal silo	0.12 ± 0.12**ab**	0.14 ± 0.21**a**	0.28 ± 0.28**a**	0.87 ± 0.34**a**	0.08 ± 0.22**a**	0.11 ± 0.08**b**	0.20 ± 0.13**a**	0.11 ± 0.08**ab**	0.13 ± 0.22**a**	2.32 ± 0.18**abc**
PICS bag	0.06 ± 0.03**ab**	0.01 ± 0.02**a**	0.04 ± 0.02**a**	0.18 ± 0.19**a**	0.77 ± 0.16**a**	0.08 ± 0.01**ab**	0.14 ± 0.07**ab**	0.12 ± 0.07**ab**	2.07 ± 1.49**ab**	2.21 ± 1.62**abc**
Super Grain bag	0.08 ± 0.03**ab**	0.37 ± 0.14**a**	0.34 ± 0.13**ab**	1.17 ± 0.17**a**	2.17 ± 0.65**a**	0.17 ± 0.08**b**	0.21 ± 0.10**ab**	0.20 ± 0.11**ab**	1.60 ± 1.03**ab**	0.18 ± 1.02**a**
ZeroFly bag	0.05 ± 0.01**ab**	0.34 ± 0.09**a**	1.94 ± 0.34**b**	4.56 ± 0.73**ab**	24.50 ± 2.60**b**	0.04 ± 0.03**ab**	0.61 ± 0.33**abc**	1.83 ± 1.14**bcd**	16.97 ± 8.98**c**	31.05 ± 10.20**d**
Ocimum gratissimum leaves	0.02 ± 0.01**a**	3.77 ± 1.83**b**	1.53 ± 0.50**b**	20.33 ± 7.63**b**	19.43 ± 3.11**b**	-	-	-	-	-
Aloe ash	0.02 ± 0.03**a**	0.20 ± 0.14**a**	1.94 ± 0.72**b**	17.43 ± 4.04**b**	31.60 ± 1.94**b**	-	-	-	-	-
Rapoko chaff	-	-	-	-	-	0.03 ± 0.03**ab**	1.74 ± 0.29**c**	3.15 ± 0.63**d**	10.44 ± 2.56**bc**	23.16 ± 6.14**d**
Rapoko chaff & mopane leaves	-	-	-	-	-	0.12 ± 0.01**b**	1.64 ± 0.33**c**	2.25 ± 0.45**d**	10.29 ± 3.54**bc**	19.40 ± 2.66**d**
Untreated	0.16 ± 0.06**b**	1.09 ± 0.41**ab**	1.817 ± 0.66**b**	19.64 ± 5.16**b**	32.31 ± 8.50**b**	0.13 ± 005**b**	1.16 ± 0.32**bc**	1.71 ± 0.19**cd**	1.32 ± 0.62**ab**	14.52 ± 2.79**cd**
P value	0.028	0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	<0.001
CV%	18	42.5	28.8	35.8	21.6	15.4	23.4	26.6	43.7	31.2

Figures presented are the original averages of each treatment. "-" means treatment was not included. Means within a column are compared and separated using Tukey's test at P < 0.05 and different alphabetic letters indicate significant differences

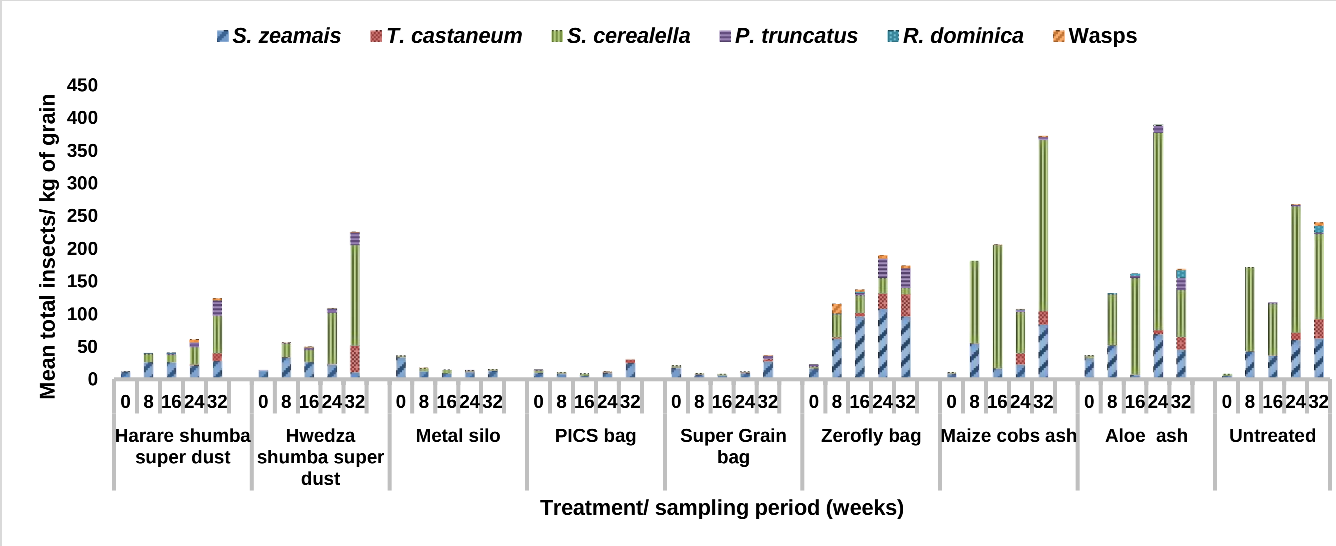

Figure 7: Total adult insects recorded under different stored maize grain treatments in Makwarimba ward during the 2014/15 storage season (n = 4).

In Goneso ward, the maize weevil, *S. zeamais* was the dominant insect species at the beginning of the season. However, between week 24 and 32 of storage, *P. truncatus* and *T. castaneum* populations exceeded those of *S. zeamais* (Fig 8). Pesticide treatments, including ZeroFly® bags succumbed to the insect pressure as did the botanical treatments and untreated control grain, recording between 200 and 400 insects per kilogram of sample. Hermetic storage facilities recorded between 50 and 100 insects per kilogram which was notably lower than in the other treatments. Predator wasps of the Hymenoptera order were also recorded in many of the samples. Insect pressure began to rise gently in the rainy months of November and December before reaching a peak in February.

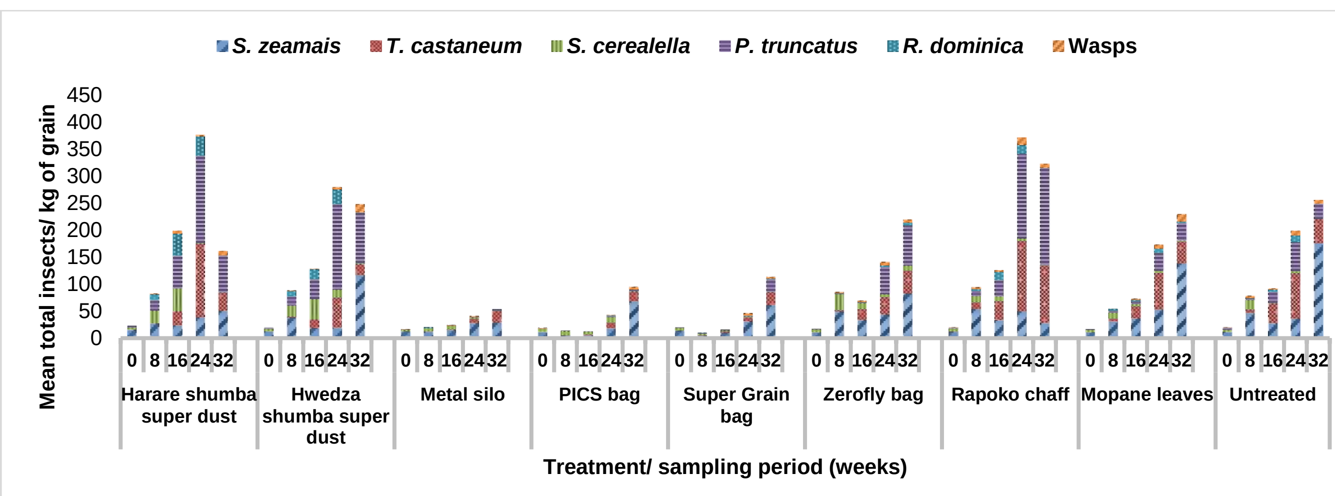

Figure 8: Total adult insects recorded under different stored maize grain treatments in Goneso ward during the 2014/15 storage season (n = 4).

3.3.2. Storage season 2 (2015/16)

Prostephanus truncatus and *S. cerealella* dominated in Makwarimba in the 2015/16 season (Fig 9) as opposed to *S. zeamais* and *S. cerealella* in the 2014/15 season (Fig 7). However, a significant number of *S. zeamais* and *T. castaneum* were also recorded. The highest number of insects was recorded at week 32 and 40 when populations exceeding 200 insects per kilogram were recorded in pesticide 1, ZeroFly® bags, botanical treatments as well as untreated grain. Pesticide 3 and hermetic treatments managed to suppress insect populations below 100 insects per kilogram except for SGBs which recorded a slightly above number at week 40. In both wards, the highest number of insects (close to 700/kg) was recorded in Makwarimba in untreated control in the 2015/16 season (Fig 9).

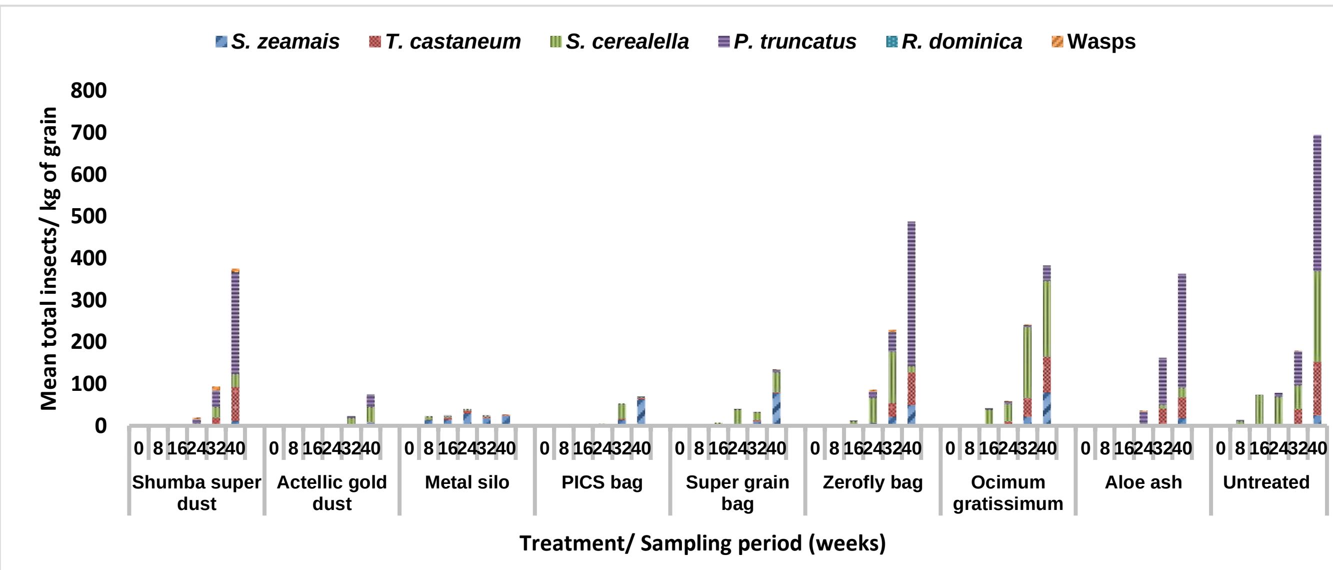

Figure 9: Total adult insects recorded under different stored maize grain treatments in Makwarimba ward during the 2015/16 storage season (n = 4).

In Goneso, the lowest insect pest numbers (< 20/kg) were recorded in pesticide 3, demonstrating its efficacy in suppressing pest build up. However, metal silos and PICS bags also recorded below 100 insects per kilogram whereas the rest had higher insect populations. *Prostephanus truncatus* was the dominant pest in pesticide 1, Zerofly® bags and botanical treatments. On the other hand, *S. cerealella* dominated in untreated grain and botanical treatments as well. Between 24 and 40 weeks of storage, *T. castaneum* was also a major pest in most treatments except pesticide 3 treatment (Fig 10).

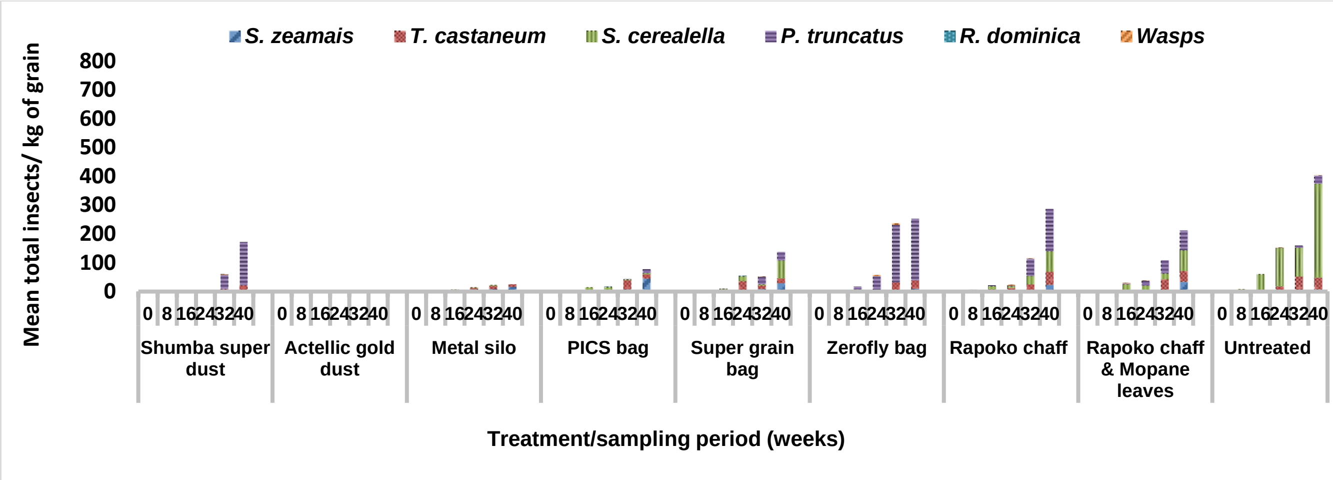

Figure 10: Total adult insects recorded under different stored maize grain treatments in Goneso ward during the 2015/16 storage season (n = 4).

3.4. Chaff generated

3.4.1. Storage season 1 (2014/15)

The amount of chaff generated due to insect feeding and/or boring activities over the 32 weeks of grain storage in the 2014/15 season, was generally low in Makwarimba. The highest amount of chaff (close to 7 %) was recorded in the ZeroFly® treatment followed by slightly more than 4 % in the *Aloe* ash (Table 4). The other treatments recorded below 2 % chaff for the 32 weeks of storage. Significant differences were recorded at 8 ($F_{8, 23}$ = 5.21; P < 0.001), 16 ($F_{8, 23}$ = 4.79; P = 0.001), 24 ($F_{8, 23}$ = 3.60; P = 0.007) and 32 weeks ($F_{8, 23}$ = 5.34; P < 0.001).

In Goneso, due to high insect infestation pressure especially *P. truncatus* (Figure 8), very high amounts of chaff dust were generated under different treatments in the 24th and 32nd weeks of storage as observed in Table 4. The greatest amount of chaff dust (between 40 and 50 % of total sample weight at 32 weeks storage) was generated in the pesticide 1 and 2 as well as in rapoko chaff. Between 18 and 30 % chaff was also recorded in the Mopane leaves and untreated control treatments, whereas ZeroFly® and hermetic treatments recorded below 10 % chaff dust (Table 4). Highly significant differences in chaff percentage were recorded at 8 ($F_{8, 22}$ = 28.63; P < 0.001), 16 ($F_{8, 22}$ = 107.71; P < 0.001), 24 ($F_{8, 21}$ = 13.34; P < 0.001) and 32 weeks ($F_{8, 21}$ = 63.21; P < 0.001).

3.4.2. Storage season 2 (2015/16)

The highest amount of chaff dust generated by storage insect pests in Makwarimba was recorded in the untreated control (19.9 %) followed by *Aloe* ash (15.2 %), pesticide 1 (7.6 %) and ZeroFly® (8.1 %) treatments. Pesticide 3 and all the hermetic treatments recorded the least chaff dust, less than 2 % throughout the 40 weeks of grain storage (Table 5). Significant differences were recorded at 8 ($F_{8, 23}$ = 2.88; P = 0.02), 16 ($F_{8, 23}$ = 2.70; P = 0.0029), 24 ($F_{8, 23}$ = 4.65; P = 0.002), 32 ($F_{8, 23}$ = 8.00; P < 0.001) and 40 weeks ($F_{8, 23}$ = 7.16; P < 0.001).

For Goneso ward, treatments generally recorded lower chaff levels than in the 2014/15 season. The highest was generated in rapoko chaff (19.4 %), rapoko chaff plus mopane leaves (12.9 %), ZeroFly® (13.4 %) and pesticide 1 (6.6 %). A sudden increase in chaff generation in the above treatments was seen at 32 weeks which is also the point at which infestation pressure was high especially for *P. truncatus* and *T. castaneum*. It was notable that the untreated control had little chaff despite the high numbers of insects. Significant differences in chaff content were recorded at 16 ($F_{8, 23}$ = 4.83; P = 0.001), 32 ($F_{8, 23}$ = 6.77; P < 0.001) and at 40 weeks ($F_{8, 22}$ = 6.63; P < 0.001) when pesticide 3, hermetic treatments and the untreated control recorded significantly lower amounts (< 3 %) of dust as compared to ZeroFly®, rapoko chaff, pesticide 1 and rapoko chaff plus with mopane leaves (Table 5).

3.5. Grain moisture content

3.5.1. Storage season 1 (2014/15)

In Makwarimba ward, grain moisture content was approximately 10 % at trial setting. As the storage season progressed, grain moisture content in some treatments fluctuated in response to changes in environmental conditions. The hermetic treatments maintained constant grain moisture of ≤ 11 %, whereas grain moisture content in conventional treatments increased up to 13.5 % following the January to April 2015 rains. Significant differences in grain moisture content between treatments were recorded at 8 ($F_{8, 23}$ = 4.34; P = 0.003), 16 ($F_{8, 23}$ = 10.15; P < 0.001), 24 ($F_{8, 23}$ = 3.77; P = 0.006) and at 32 weeks ($F_{8, 23}$ = 2.85; P = 0.024). In Goneso ward, grain moisture content dropped from 10 to 8 % in conventional treatments while hermetic storage facilities closely maintained 10 % moisture content in the first eight weeks of storage. A general rise in grain moisture content to between 11 and 12 % was then recorded in conventional treatments from week 24 to 32. However, differences in grain moisture content between different treatments were only significant at week 8 ($F_{8, 22}$ = 13.98; P < 0.001).

Table 4: Mean percentage insect generated chaff (± SEM) recorded under different treatments in Makwarimba and Goneso wards during the 2014/15 storage season (n = 4).

Treatment	Makwarimba ward 2014/15				Goneso ward 2014/15			
	8 wks	16 wks	24 wks	32 wks	8 wks	16 wks	24 wks	32 wks
Harare shumba super dust (Pesticide 1)	0.07 ± 0.02**a**	0.27 ± 0.06**ab**	1.86 ± 0.25**ab**	1.40 ± 0.59**ab**	1.36 ± 0.06**cd**	4.62 ± 0.97**d**	24.27 ± 4.12**c**	43.50 ± 5.17**de**
Hwedza shumba super dust (Pesticide 2)	0.10 ± 0.04**ab**	0.25 ± 0.02**ab**	1.35 ± 0.05**ab**	1.93 ± 0.41**ab**	1.21 ± 0.27**cd**	4.32 ± 0.57**d**	23.07 ± 7.95**bc**	49.19 ± 2.62**e**
Metal silo	0.05 ± 0.01**a**	0.09 ± 0.03**a**	0.14 ± 0.01**a**	0.09 ± 0.02**a**	0.06 ± 0.09**a**	0.33 ± 0.01**a**	0.49 ± 0.08**a**	0.66 ± 0.02**a**
PICS bag	0.05 ± 0.02**a**	0.06 ± 0.01**a**	1.53 ± 0.02**ab**	0.08 ± 0.05**a**	0.00 ± 0.01**a**	0.06 ± 0.01**a**	0.06 ± 0.07**a**	0.14 ± 0.05**a**
Super Grain bag	0.02 ± 0.00**a**	0.05 ± 0.01**a**	0.99 ± 0.01**a**	0.13 ± 0.08**ab**	0.04 ± 0.01**a**	0.26 ± 0.01**ab**	0.80 ± 0.08**a**	3.57 ± 1.95**ab**
ZeroFly bag	0.67 ± 0.37**b**	1.52 ± 0.92**b**	6.38 ± 3.26**b**	6.72 ± 4.27**b**	0.30 ± 0.01**ab**	0.48 ± 0.15**b**	1.86 ± 1.26**a**	5.68 ± 2.04**b**
Maize cobs ash	0.28 ± 0.03**ab**	0.41 ± 0.05**ab**	1.06 ± 0.08**ab**	1.56 ± 0.07**ab**	-	-	-	-
Aloe ash	0.09 ± 0.03**ab**	0.36 ± 0.07**ab**	0.74 ± 3.29**a**	4.15 ± 1.17**ab**	-	-	-	-
Rapoko chaff	-	-	-	-	2.41 ± 0.54**d**	9.50 ± 0.54**e**	20.99 ± 6.69**bc**	48.78 ± 2.64**e**
Mopane leaves	-	-	-	-	0.85 ± 0.24**bc**	1.68 ± 0.69**c**	5.89 ± 2.79**ab**	26.29 ± 3.84**cd**
Untreated	0.12 ± 0.03**ab**	0.38 ± 0.08**ab**	2.72 ± 0.25**ab**	1.05 ± 0.32**ab**	0.85 ± 0.10**bc**	1.57 ± 0.37**c**	7.29 ± 1.93**abc**	23.34 ± 6.30**c**
P-value	<0.001	0.001	0.007	<0.001	<0.001	<0.001	<0.001	<0.001
CV%	19.6	25.1	41.9	33.7	15	11.3	34	15.6

Figures presented are the original averages of each treatment. "-" means treatment was not included. Means within a column are compared and separated using Tukey's test at P < 0.05 and different alphabetic letters indicate significant differences.

Table 5: Mean percentage insect generated chaff (± SEM) recorded under different treatments in Makwarimba and Goneso wards during the 2015/16 storage season (n = 4).

Treatment	Makwarimba ward 2015/16					Goneso ward 2015/16				
	8 wks	16 wks	24 wks	32 wks	40 wks	8 wks	16 wks	24 wks	32 wks	40 wks
Shumba super dust (Pesticide 1)	0.18 ± 0.04**b**	0.19 ± 0.05**ab**	0.68 ± 0.11**ab**	2.38 ± 0.75**ab**	7.69 ± 2.41**ab**	0.06 ± 0.02	0.11 ± 0.02**ab**	0.07 ± 0.67	0.77 ± 0.60**ab**	6.64 ± 6.83**ab**
Actellic gold dust (Pesticide 3)	0.11 ± 0.03**ab**	0.06 ± 0.02**ab**	0.04 ± 0.03**a**	0.07 ± 0.01**a**	0.03 ± 0.03**a**	0.06 ± 0.01	0.11 ± 0.02**ab**	0.01 ± 0.01	0.03 ± 0.01**a**	1.55 ± 0.01**a**
Metal silo	0.16 ± 0.06**ab**	0.22 ± 0.06**b**	0.07 ± 0.06**a**	0.13 ± 0.04**a**	0.45 ± 0.03**a**	0.04 ± 0.01	0.09 ± 0.01**a**	0.04 ± 0.01	0.07 ± 0.02**a**	2.01 ± 0.01**a**
PICS bag	0.08 ± 0.03**ab**	0.14 ± 0.06**ab**	0.08 ± 0.05**a**	0.04 ± 0.03**a**	0.15 ± 0.05**a**	0.11 ± 0.04	0.11 ± 0.03**ab**	0.02 ± 0.02	0.07 ± 0.06**a**	1.60 ± 0.47**a**
Super Grain bag	0.06 ± 0.01**ab**	0.07 ± 0.01**ab**	0.02 ± 0.02**a**	0.05 ± 0.08**a**	0.11 ± 0.09**a**	0.08 ± 0.02	0.14 ± 0.02**ab**	0.04 ± 0.04	0.83 ± 0.83**ab**	2.26 ± 0.27**a**
ZeroFly bag	0.07 ± 0.01**ab**	0.15 ± 0.02**ab**	0.54 ± 0.21**ab**	3.39 ± 0.55**b**	8.17 ± 0.74**ab**	0.05 ± 0.00	0.19 ± 0.08**ab**	0.86 ± 0.76	7.40 ± 3.51**b**	13.46 ± 4.57**ab**

Ocimum gratissimum leaves	0.14 ± 0.01**ab**	0.13 ± 0.02**ab**	0.39 ± 0.07**ab**	1.79 ± 0.54**ab**	2.79 ± 0.92**ab**	-	-	-	-	-
Aloe ash	0.00 ± 0.01**a**	0.07 ± 0.02**a**	1.47 ± 0.40**b**	6.52 ± 1.41**b**	15.26 ± 1.28**b**	-	-	-	-	-
Rapoko chaff	-	-	-	-	-	0.18 ± 0.03	1.24 ± 0.26**c**	1.91 ± 0.21	4.35 ± 0.75**ab**	19.47 ± 5.40**b**
Rapoko chaff & mopane leaves	-	-	-	-	-	0.08 ± 0.03	0.56 ± 0.07**bc**	1.37 ± 0.21	3.45 ± 0.93**ab**	12.97 ± 1.92**ab**
Untreated	0.07 ± 0.03**ab**	0.12 ± 0.05**ab**	0.31 ± 0.11**ab**	3.07 ± 1.61**ab**	19.96 ± 10.70**b**	0.06 ± 0.01	0.14 ± 0.01**ab**	0.18 ± 0.02	0.13 ± 0.05**ab**	1.29 ± 0.42**a**
P value	0.022	0.029	0.002	<0.001	<0.001	0.131	0.001	0.31	<0.001	<0.001
CV%	11.3	12.7	21.4	27.5	40.7	9.6	12.6	25.7	34.4	44.1

Figures presented are the original averages of each treatment. "-" means treatment was not included. Means within a column are compared and separated using Tukey's test at $P < 0.05$ and different alphabetic letters indicate significant differences.

3.5.2. Storage season 2 (2015/16)

Grain moisture content for hermetic treatments in Makwarimba ranged between 10 and 12 % whilst moisture content in conventional treatments went up to 13 % during the 40 weeks of storage. These fluctuations in moisture content resulted in significant differences being observed at 8 ($F_{8, 23} = 11.04$; $P < 0.001$), 16 ($F_{8, 23} = 4.49$; $P = 0.002$) and 24 weeks ($F_{8, 23} = 39.14$; $P < 0.001$). Similarly, in Goneso ward, hermetic treatments managed to maintain constantly higher moisture content at 12 % resulting in significant differences being observed at 8 ($F_{8, 23} = 72.37$; $P < 0.001$), 16 ($F_{8, 23} = 4.62$; $P = 0.002$), 24 ($F_{8, 23} = 61.17$; $P < 0.001$) and 32 weeks ($F_{8, 22} = 5.79$; $P < 0.001$), while in the conventional treatments moisture content dropped to between 8 and 10 %.

3.6. Environmental temperatures and Relative Humidity (RH)

Temperatures in Makwarimba were between 20 and 30 ^{o}C, coupled with fluctuations in relative humidity of 30 – 60 % up to the ninth week in 2016. Thereafter, temperature decreased to below 25 ^{o}C and relative humidity increased to 70 %. While in Goneso, temperatures were higher than in Makwarimba throughout the seasons. Temperatures between 25 and 35 ^{o}C were recorded in Goneso with relative humidity ranging from 30 % to 55 %. A decline in temperatures in Goneso in 2016 corresponded with an increase which saw relative humidity slightly exceed 60 % (Fig. 11).

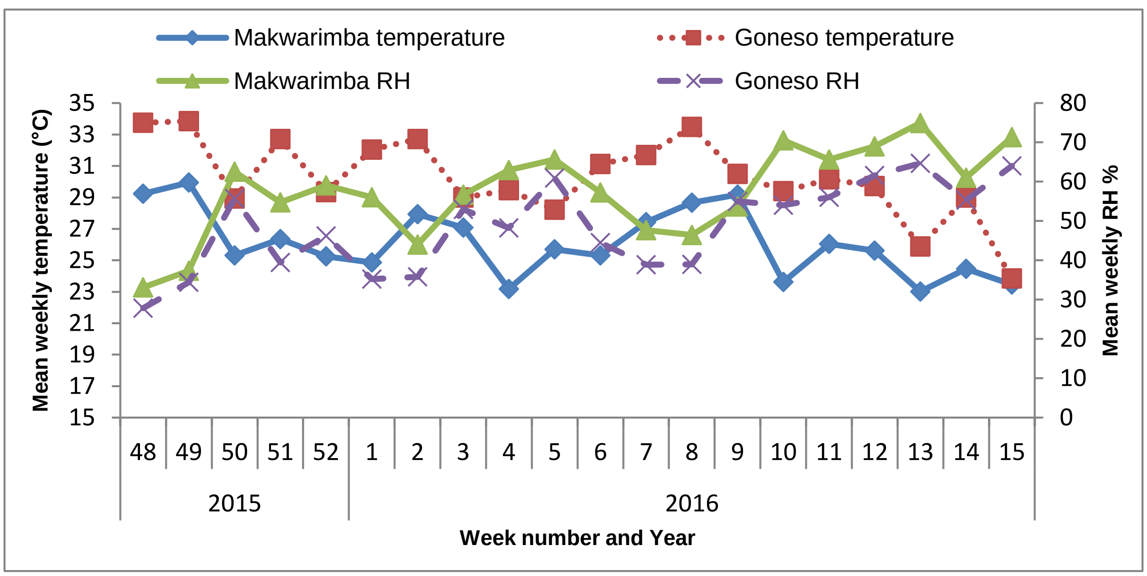

Figure 11: Mean weekly temperatures (^{o}C) recorded for Makwarimba and Goneso wards, Hwedza district, Zimbabwe.

4. DISCUSSION

These results provide evidence that hermetic storage facilities can be highly effective in protecting stored maize for extended storage periods of up to 40 weeks under smallholder farming systems. Whereas grain damage levels of 70 to 90 % and weight losses of 15 % to 60 % were recorded for conventional storage treatments in both Makwarimba and Goneso wards, the hermetic storage facilities performance was consistently superior with grain damage and weight losses below 30 % and 15 % respectively, except in one case when rodents damaged SGBs at the one site. In Makwarimba ward though, in the 2014/15 season, the losses recorded were lower than those recorded in Goneso ward. This was mainly due to the combined activity of *S. zeamais*, *P. truncatus* and *T. castaneum*, all being notorious pests of stored maize resulting in the higher damage and weight losses in Goneso as compared to Makwarimba ward which was highly populated with *S. cerealella*. The 2015/16 season was more similar across the two wards with *P. truncatus* being the dominant pest in both wards.

High weight losses of over 30 % as well as damage levels around 70 – 80 % have also been reported by Boxall (2002) and Tefera (2011) depending on the duration of grain storage and the presence or absence of the LGB. Losses due to LGB have been reported to be 2 - 3 times more than losses due to *Sitophilus* spp. and *S. cerealella* (Mutambuki and Ngatia, 2012). LGB damage is characterised by extensive tunneling, generating extensive dusts resulting in whole kernels 'being lost' (Tefera, 2011), as opposed to just being perforated as is typically seen with *S. cerealella* (Akter, 2013). The adult grain moth usually does not produce heavy amounts of dust as adults do not feed and are mainly involved in mating and egg-laying. Most of the damage is done by the larvae which hatch and start feeding inside kernels (Akter, 2013).

While *P. truncatus* is typically more prevalent in hot and dry agro-ecologies where droughts may even be common (Munyuri and Tabu, 2013), by contrast *S. cerealella* thrives well between temperatures of 18 - 30 ^{o}C (Akter, 2013). Therefore, greater losses are incurred under tropical compared to subtropical conditions (Bergvinson, 2001). Temperatures above 30 ^{o}C are not favourable for *S. cerealella* development (Hansen et al., 2004) and this may explain the different pest distribution observed between the two wards due to their location in different agro-climatic regions. *Sitophilus zeamais* and *T. castaneum* typically thrive under conditions of between 28 - 35 ^{o}C (IRRI, 2013) and were observed to be well distributed across both wards. In terms of arthropod spectrum, in field trials previously conducted in

Zimbabwe in Buhera (NR-III) and Harare (NR-IIb) (Stathers et al., 2002), a wide range of arthropods including *Corcyra cephalonica*, *Plodia interpunctella*, *Cryptolestes ferrugineus,* and *Anisopteromalus calandrae* were found on maize samples (Stathers et al., 2002). This was not the case in the current trial. On the other hand, *P. truncatus* which was not recorded at that time, has since then become a major threat to smallholder maize storage and household food security in Zimbabwe and many other SSA countries.

In some parts of Africa and Mexico where grain weight losses of at least 25 % were reported during storage, hermetic storage facilities have been used resulting in weight loss reduction to about 10 % (Villers et al., 2010; Tefera et al., 2011). Without the addition of any pesticide, hermetic metal silos can be extremely effective in controlling *S. zeamais* and *P. truncatus* (De Groote et al., 2013). Hermetic bags and metal silos have also been evaluated under simulated smallholder farmer conditions in Zimbabwe (Chigoverah and Mvumi, 2016) using both natural and artificial introductions of storage insect pests. In both cases, hermetic storage was much more effective than synthetic pesticides. Similarly, in the current trials, hermetic treatments were highly effective compared to other conventional options, with the exception of pesticide 3 which was not yet available on the local market during the 2014/15 season trials. However, despite their efficacy, hermetic bags (PICS and SGB) can be damaged by rodents, chickens and rough handling as well as perforation by LGB resulting in gaseous exchange and thus the loss of their efficacy. In the current study, perforation of one SGB bag by rodents in Goneso during the 2014/15 season was recorded. This contributed to a general rise in grain damage and weight losses in SGB treatment of which rodent damage contributed the most due to larger holes. LGB perforations on both PICS and SGBs were also recorded in both wards for the two storage seasons. This demonstrates that hermetic storage bags require careful handling and sound postharvest management to get the best results. Similar conclusions were drawn by Ndegwa et al. (2015).

Pesticide 1 and 2 succumbed to pest build up in both wards resulting in high grain damage and weight losses being recorded. There were no significant differences in performance between pesticide 1 and 2. Studies by De Groote et al. (2013) and Mutambuki et al. (2014) in Kenya indicate that seeded LGB also thrived in grain treated with Actellic super dust (*Pirimiphos-methyl* 16 g/kg and *Permethrin* 3 g/kg) with grain damage over 50 % in a six months storage period. A similar case in which synthetic pesticide treated grain recorded higher grain damage and weight losses compared to untreated grain, as was observed in this current study was also reported in the case of Actellic super in De Groote et al. (2013). Possibly, the

LGB might have some tolerance to synthetic pesticides or its chances of being in contact with pesticides are reduced as the pest spends more time feeding inside grains. Its survival may also be attributed to the high amounts of dust generated through its feeding which dilutes the pesticide and other insect species would survive. It is also possible that natural enemies are effective in reducing pest numbers in the untreated controls, resulting in lower losses compared to pesticide treatments in which natural enemies are sensitive (Stathers et al., 2008). Further studies are, however, required to better understand these unexpected observations, including deepening understanding of the effect of climatic variables on the performance of synthetic pesticides. Arthur et al. (1992) hypothesised that increased temperatures accelerate the breakdown of synthetic pesticides. In the 2015/16 season however, pesticide 3 was as effective in protecting stored maize as the hermetic treatments.

The ZeroFly® storage bags used with un-fumigated grain recorded high damage and weight losses in both storage seasons. In some instances where the bags are used, grain is fumigated first before storage. However, in Zimbabwe fumigation at smallholder level is not recommended since it is considered risky to human health and the environment especially when used by people who have not been properly trained in professional grain fumigation and if used close to or within residential areas. Findings by Baban and Bingham (2014) concluded that ZeroFly® bags are highly effective in controlling both incoming as well as hidden infestation which comes with grain from the fields at harvest and manifest during storage though this was when grain was fumigated first. Similarly, Paudyal et al. (2017) concluded that ZeroFly® bags are very effective in controlling storage insects in pre-fumigated maize. The current study's findings, however, contradict those results, and did not find ZeroFly® bags appropriate and effective under smallholder grain storage in Zimbabwe considering that most smallholder farmers do not fumigate their grain prior to storage. The company has since released a new ZeroFly® hermetic storage bag to complement fabric pesticidal activity of ZeroFly® bags with desiccation by the inner hermetic system. Similar farmer-managed tests are needed to evaluate the efficacy of this new product.

Botanical pesticides, since they are readily available, smallholder farmers find it easy to use them for their grain storage when they cannot afford or access other options (Mvumi and Stathers, 2003; Dubey et al. (2008)). However, most of the botanical pesticides and combinations as used in this trial are not well-documented. A few botanical pesticides reported being effective against storage insect pests include *Eucalyptus* leaves against *Sitophilus* spp. and *T. castaneum* (Tinkeu et al., 2004; Negahban and

Moharramipour, 2007) and *Aloe* spp. against storage moths (Kareru et al., 2013). Botanical pesticides are regarded as attractive alternatives to synthetic pesticides (Isman, 2006) not due to their efficacy but because they are perceived by farmers as being relatively safe to human health and the environment, and locally available. As demonstrated in this research, there is still more work to be done if botanical pesticides are to significantly contribute to improved grain storage under typical smallholder farming conditions. More research is needed to determine which botanical species, and using what application methods and dosage are effective against which storage pests.

The current trial clearly demonstrates the contribution hermetic storage facilities can make to reducing grain storage losses amongst smallholder farmers. However, for PICS and SGBs, their prices may not be affordable for smallholder farmers since there are no manufacturers in Zimbabwe; local stockists have to import the bags. There is need therefore to up-scale awareness and training from a multi-dimensional approach including the private sector, government and research institutions on the best practices for using these storage options for the benefit of, not only end-users (farmers) but also for the region in terms of improving food security. The current trials were conducted using a Learning Centre approach comprised of farmers, researchers, national extension services and interested stakeholders to encourage co-learning and innovation, full and equal participation allowing farmers to embrace the effective storage options at the same time encouraging the private sector to up-scale delivery and availability of effective storage options.

In conclusion, hermetic storage facilities were shown to be more effective than the other treatments tested, providing an alternative to synthetic pesticide use for extended grain storage under smallholder farming conditions. Actellic gold dust® pesticide also performed well, providing significantly greater grain protection than Shumba super dust®. The efficacy of ZeroFly® storage bags when used on non-fumigated grain was low suggesting in their current form they are not suitable for smallholder grain storage systems as found in Zimbabwe. Further efficacious trials of pesticide Shumba super dust® need to be conducted to determine whether its failure to control storage insect pests is due to resistance development or poor pesticide formulation properties or climatic conditions. Similarly, more research on botanicals for grain storage is required to establish effective botanical species; their preparation and application rates as well as optimization strategies.

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