How different hermetic bag brands and maize varieties affect grain damage and loss during smallholder farmer storage

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Abstract

Smallholder farmers in sub-Saharan Africa store harvested maize to provide food stocks between harvest seasons, which may be up to 12 months apart. Stored maize is highly susceptible to insect pest damage, hence the need for stored grain protection technologies such as hermetic bags. The current study evaluated the efficacy of five brands of hermetic bags in storing three maize varieties under two contrasting agro-ecologies in Guruve and Mbire districts of Zimbabwe, for two storage seasons. The hermetic bag treatments evaluated included: GrainPro Super Grain bag (SGB) IVR™, PICS bag, AgroZ® Ordinary bag, AgroZ® Plus bag and ZeroFly® hermetic bag, which were compared to grain stored in a polypropylene bag either untreated (negative control) or following admixture with a synthetic pesticide treatment, Actellic Gold Dust® (positive control). The maize varieties included a white hybrid, a pro-vitamin A biofortified orange and a local variety. All the hermetic bag treatments out-performed the synthetic pesticide in limiting grain damage and weight loss during storage. No significant difference in grain damage or weight loss was observed among the hermetic bags. However, rodents punctured some hermetic bags; therefore rodent control is recommended. A positive correlation with grain damage and weight loss for all three maize varieties was found for *Sitophilus zeamais*, *Sitotroga cerealella*, *Tribolium castaneum* and *Cryptolestes* spp adult numbers. Significantly higher insect damage and weight loss ($P<0.001$) occurred in the white hybrid maize than in the other two varieties. The results confirmed that regardless of brand, all the hermetic bags tested can be recommended for smallholder farmer

use to limit postharvest storage losses, avoid pesticide use, and support food and nutrition security.

Keywords: Hermetic grain storage, on-farm smallholder storage, hermetic bag perforation, biofortified maize storage, stored maize losses, storage insect pests

1. Introduction

Maize is a major source of daily calories and is vital for the food security of millions of people across the world (Afzal et al., 2009; Garbaba et al., 2017; Nuss and Tanumihardjo 2010). However, stored maize is host to a wide range of insect pests including the maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae); the red-rust flour beetle, *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae); the Angoumois grain moth, *Sitotroga cerealella* Olivier (Lepidoptera: Gelechiidae) and the larger grain borer (LGB), *Prostephanus truncatus* Horn (Coleoptera: Bostrichidae) (Stathers et al., 2002; Mvumi et al., 2003; Mlambo et al., 2017). In many African countries, *P. truncatus* and *S. zeamais* are the most destructive stored maize insect pests (Abass et al., 2014; Midega et al., 2016), with the former pest estimated to result in twice the grain weight loss of that caused by *S. zeamais* during storage (Hodges, 2002). These insects lead to considerable quantitative and qualitative losses postharvest, posing a serious threat to food and nutrition security of smallholder farmers.

There is a range of grain protection methods commonly used by smallholder farmers in sub-Saharan Africa (SSA) including the admixing of synthetic pesticides with grain (Mvumi and Stathers, 2003; Collins, 2006; Stathers et al., 2020a). However, despite the use of synthetic pesticides and other techniques, average maize postharvest losses (PHLs) are estimated to be 10-20% in SSA (World Bank et al. 2011; APHLIS, 2019). Various factors can reduce the efficacy of synthetic pesticides, including the development of resistance by pests (Arthur, 1996; Collins, 2006; Harish et al., 2014), degradation due to high temperatures (Mlambo et al., 2018) or pesticide adulteration (Stathers et al., 2013). Environmental and health concerns are driving demands amongst some stakeholders to minimize the use of synthetic pesticides on stored food. However, to achieve that, effective, safe and affordable alternative storage methods are required.

Recent developments include the use of hermetic bags, polypropylene bags with synthetic pesticide incorporated into the fabric, and metal silos. Several brands of hermetic storage bags are now being marketed across SSA countries, including: AgroZ® bag, GrainPro Super Grain bag (SGBs) IVR™, ZeroFly® hermetic storage bag and Purdue Improved Crop Storage (PICS) bag. The hermetic storage technology is based on the principle of the depletion of oxygen and build-up of carbon dioxide inside the hermetically sealed bag of grain, resulting in asphyxiation or desiccation of the insects (Hodges and Stathers, 2012; Murdock et al., 2012).

The efficacy of hermetic storage options has received significant research attention recently in Africa, with a particular focus on hermetic bags and metal silos (Murdock et al., 2012; Baoua et al., 2013; de Groote et al., 2013; Guenha et al., 2014; Singano et al., 2019; Baributsa et al., 2020), as well as the socio-economic aspects (Atibioke et al. 2012; Bokusheva et al. 2012; Villane et al. 2012; Gbénou-Sissinto et al. 2018). However, most studies to-date have evaluated up to two different brands of the bags on just one variety of the focal crop or a mixture of varieties, whereas our study compared five brands of hermetic bags, with each brand being compared for three different maize varieties, under two contrasting agro-ecologies and for two consecutive 8 month long storage seasons. Additionally, many of the previous studies were conducted at research stations or under simulated conditions (Chigoverah and Mvumi, 2016; Chigoverah and Mvumi, 2018; Mutambuki et al., 2019; Baributsa et al., 2020; Bakoye et al., 2020; Mutambuki and Likhayo, 2021) whereas the current study was done under smallholder farmer management.

Most of the previous studies were conducted for storage periods of less than 8 months (Baoua et al., 2013; de Groote et al., 2013) which does not simulate farmers' practice in many locations where storage occurs for at least 8 months to provide food between harvests. Only a few studies which have evaluated small-scale postharvest loss reduction technologies in low and middle-income countries have involved the end-users in testing the technologies (Stathers et al., 2020a). Stathers et al. (2020a) also found that there were very few studies that involved multi-site or multi-year comparisons of postharvest loss reduction interventions. Few studies have investigated the perforating effect of both insects and rodents on hermetic bag liners during storage. The current study sought to close these knowledge gaps. Additionally, given that hermetic storage technology is continuously evolving, it is important to field-test the comparative efficacy of new and existing products under farmer-management, to produce real-world evidence to support promotion and adoption decisions and actions. Our study objective was therefore to evaluate the efficacy of different brands of hermetic bags in preventing insect grain damage using several maize varieties stored under on-farm smallholder management in two agro-climatically contrasting districts of Zimbabwe during two storage seasons.

2. Materials and Methods

2.1 Site description

Storage experiments were conducted in two agro-climatically contrasting districts - Guruve (16° 38'59.99" S and 30°41' 59.99" E, 1180 m; about 150 km North of Harare) and Mbire (16°10'0.60" S 30°34'14.99" E, 446 m; about 381 km North of Harare) (Figure 1) in Zimbabwe, during two grain storage seasons, 2017/18 and 2018/19. Zimbabwe is divided into five agro-ecological regions based on the amount of rainfall received, temperature and, to a lesser extent, the soil type. Region I receives the highest amount of rainfall while region V denotes the most arid parts of the country. Guruve district is located in agro-ecological region III, with annual rainfall of 650-800 mm and mean annual temperature range of 18-35 ^{o}C, whereas Mbire district is in the drier agro-ecological region IV receiving annual rainfall below 450 mm and with a mean annual temperature range of 32-42 ^{o}C (Mugandani et al., 2012) (Figures 1a,b). Wards 15 and 22 for Guruve and Mbire district, respectively, were purposively selected in consultation with district stakeholders, to host the experiments (Figure 2).

2.2 Storage structures, grain preparation and storage

The storage structures used in Ward 22 of Guruve district were constructed from fire-burnt earth bricks, which, together with the floors, were plastered with cement and roofed with asbestos sheets. In Ward 15 of Mbire district, the stores were constructed from fire-burnt earth bricks, plastered with earth mortar and roofed using thatch grass.

Twelve smallholder farmers with similar storage structures were selected as Farmer Learning Centre representatives to host the storage experiments in each of the two districts (Guruve and Mbire) giving a total of 24 hosts. A Farmer Learning Centre is a field-based interactive platform integrating local, conventional and new knowledge to promote farm-level adaptive testing or promotion of technologies and innovations to address complex agricultural production and livelihood problems (Mapfumo et al., 2008, 2013).

The Farmer Learning Centre representatives were selected based on their likelihood of high-interactivity with surrounding farmers in the community, ease of accessibility of their homesteads by fellow farmers and service-providers, security of trial grain during storage, and availability of a suitable storage structure – all factors expected to help in scaling-out technologies found effective during the experiments. To build ownership of the experiments; local farmers, community leadership, agricultural extension staff as well as the researchers participated in trial-setting, grain sampling and analysis of the results.

Three maize varieties; namely white hybrid (SC719), pro-vitamin A (pVA) biofortified orange (ZS242) and local variety (*Kanongo*, an open-pollinated variety (OPV)), harvested in 2017 and 2018 growing seasons, were used for the 2017/18 and 2018/19 storage experiments, respectively. A total of 2800 kg of freshly harvested, sun-dried maize grain which had not been treated to control storage insect pests, was procured locally for each maize variety in each season. In each season, for each variety, the grain was mixed thoroughly to ensure baseline uniformity. The seven treatments (Table 1) were set up approximately three months after harvest with no artificial insect infestation.

The 2800 kg of maize grain for each variety was split in two equal batches (i.e. 1400 kg), one for each district. Each batch of maize grain (i.e. 1400 kg of each variety per district) was poured onto a clean plastic sheet and sub-divided into seven 200 kg portions, each of which was further sub-divided into four 50 kg portions. This enabled twelve learning centres in each district (four learning centres for each of the three maize varieties). In the case of the hermetic bags and the untreated control, the grain was loaded into the bags without any chemical treatment. Prior to placing the hermetic bag liners into polypropylene bags, the liners were tested for air tightness by filling them with air to form a pouch before compressing with both hands (Baributsa et al., 2013). A hissing sound indicated that the liner was perforated; thus, only liners without any leakage were used. After loading the grain, hermetic bags were pressed to squeeze out air and then securely tied using elastic rubber strips to ensure airtightness. For the synthetic chemical treatment (positive control), each 200 kg portion of maize grain was thoroughly admixed with Actellic Gold Dust® (pirimiphos-methyl 1.6% and thiamethoxam 0.36%) on plastic sheeting using a shovel, before being packaged into four 50 kg capacity polypropylene bags. All bags were then tightly closed by tying them securely using elastic rubber strips. Each treatment (50 kg of maize grain) was placed on top of fire-burnt earth bricks as per farmer practice, to protect the grain from moisture ingress from the store floor. The experiments were conducted for a 32-week storage period during each storage season.

Temperature and relative humidity data were recorded from selected representative storage facilities in Guruve and Mbire using Extech Instruments® Humidity/Temperature Data Logger Model RHT10 (FLIR Systems, Inc., Nashua, U.S.A) at 30-min intervals from December 2017 to May 2018 and from September 2018 to April 2019. The data were downloaded and saved at bi-monthly intervals.

2.3 Experimental design, trial-setting, sampling and sample analysis

The experiment was set up in two districts (sites), Guruve and Mbire. Three varieties of maize were evaluated which included white hybrid maize (SC719), pro-vitamin A (pVA) biofortified orange maize (ZS242) and local variety (*Kanongo*, an open-pollinated variety (OPV)). Twelve learning centres were set-up in each district, giving a total of twenty-four learning centres for the two districts. Each learning centre housed only one maize variety and all the seven treatments (Figure 3) due to space constraints which prevented the storing of all the treatments for each of the three maize varieties in one structure (Figure 4). The study was therefore unbalanced; thus, the varietal effect was nested in the learning centres. The field experiments were conducted for two storage seasons, 2017/18 and 2018/19. Sampling was done at 8-week intervals for 32 weeks (i.e. 0, 8, 16, 24 and 32 weeks). Each treatment unit was allocated 50 kg of grain.

In the 2017/18 season, the storage experiments were set up in October 2017 and terminated in June 2018 while in the 2018/19 season, the storage experiments commenced in September 2018 and ended in May 2019. Sampling of the stored maize grain was done using a one-metre-long multi-compartmented sampling spear which was gently inserted from the top of the opened bag at 6-10 vertical positions to collect a 1 kg composite sample, and the bag was then immediately closed and tied with a rubber strip. Due care was exercised to avoid puncturing the hermetic liners. The sampling spears were disinfected by cleaning with detergent and drying them between the collection of samples from different treatments to avoid cross-contamination. Samples were placed in labelled plastic bags, kept in the shade before being transported to the University of Zimbabwe laboratory in Harare, where they were immediately analysed for insect grain damage, weight loss, insect-generated grain dust, adult insect counts and moisture content.

2.4 Sample processing, insect population and grain moisture content assessment

Each of the composite samples was weighed, then sieved through a 2-mm sieve (American Scientific Products, McGraw Park, Bloomington, Illinois, USA) to separate adult insects, insect-generated grain dust and grain, and the mass of each was recorded. The grain was then divided into sub-samples for moisture content and insect grain damage analysis. Sub-samples were analysed in triplicate. The live and dead adult insects were counted manually and recorded per species. These figures were then converted per kilogramme number by a simple proportional calculation, based on the sample mass. Grain moisture was measured using a pre-calibrated moisture meter (Model GMK-303CF, GrainPro Inc., Subic Bay, Philippines).

2.5 Insect grain damage and weight loss assessment

Each one kg sample was divided into eight equal parts 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 insect-damaged. Numbers of insect-damaged (Nd) and undamaged (Nu) grains were used to calculate the percentage grain damage. Grain weight loss percentage was calculated using the count and weigh loss assessment method (Boxall, 1986) as shown in equation 1:

$$\text{Weight loss \%} = \frac{(NdxWu)-(WdxNu)}{(Nd+Nu)\times Wu} \times 100 \qquad (1)$$

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.

2.6 Assessment of insect perforation of hermetic bag liners

Each of the hermetic liners were analysed for signs of damage at the end of each storage season by holding them up to the light to see the holes and drawing a circle around each hole using different coloured pens for the different causes. This required counting the number of holes in each liner, and for each hole determining and recording whether it was caused by rodent damage, insect pest damage, seam splitting or sampling spears.

2.7 Data analysis

To analyse the overall treatment, storage time, maize variety, seasonal and site effects, and associated interactions, all the data on grain damage, grain weight loss and moisture content were subjected to repeated measures analysis of variance (rANOVA) in Genstat 18th edition after being tested for conformity to assumptions of ANOVA. The data were subjected to rANOVA because sampling was carried out at five different intervals from the same experimental unit in each of the two seasons. Means were separated by Tukey's test whenever significant differences were detected.

To understand which of the treatments were outperforming the others between the two seasons based on significant interactions detected, further analysis on insect grain damage, grain weight loss and moisture content was conducted per storage season i.e. 2017/18 and 2018/19. The analysis was conducted using repeated measures analysis of variance (rANOVA) in Genstat 18th edition and presented in graphical form. Tukey's test was used to separate means where significant differences were detected. The data on insect perforation of hermetic bag liners were log (x+1) transformed, where x represented the number of holes recorded.

The overall site, variety, treatment, and storage season effects on insect perforation of bags were analysed using one-way ANOVA in Genstat 18th edition. Means were separated by Tukey's test where significant differences were found. Mean temperature and relative humidity were calculated at 4-week intervals (monthly) during the 2017/18 and 2018/19 storage seasons. The data on the total number of insects (live and dead) and specific insect population were correlated with insect grain damage, grain weight loss and moisture content in Genstat 14th edition**.**

3. Results

3.1 Site, season, treatment, storage time and varietal effects on stored grain

Overall, no significant difference between the two districts Guruve and Mbire were found in terms of insect grain damage (P=0.393). However, moisture content was significantly higher in Guruve than Mbire (P<0.001). The grain weight loss was significantly higher in Mbire than Guruve district (P = 0.025) (Table 2).

Insect grain damage, grain weight loss and moisture content were significantly higher in the 2017/18 storage season than the 2018/19 storage season (P<0.001) (Table 2).

The untreated control and Actellic Gold Dust® treatments had significantly higher mean grain damage and mean grain weight loss than the hermetic bag treatments (PICS, SGB, AgroZ® Ordinary bag, AgroZ® Plus and ZeroFly® hermetic storage bag) (P<0.001). The mean insect grain damage and mean weight loss in the untreated control were significantly higher (P<0.001) than in all other treatments (Table 2). There were no significant differences in mean grain damage, mean weight loss and mean moisture content among the hermetic bag treatments (P>0.05). The mean moisture content in the untreated control and Actellic Gold Dust® treatments was significantly higher than in the hermetic bag treatments (P<0.001) (Table 2).

The mean insect grain damage, mean weight loss and mean moisture content increased significantly with storage time (P<0.001) . Mean grain damage increased significantly at 8 and 32 weeks of storage to 33.4% (P<0.001). Mean grain weight loss significantly increased at 24 and 32 weeks of storage to 5% (P<0.001) (Table 2). A significant increase in moisture content was observed at week 16 (P<0.001) (Table 2).

Mean insect grain damage and mean grain weight loss were significantly higher in white hybrid maize than in pVA biofortified orange maize and local variety – *Kanongo* (P<0.001). There was no significant difference in insect grain damage and weight loss between pVA biofortified orange maize and the local variety – *Kanongo* (P>0.05). Among the three maize varieties, no significant difference in mean moisture content was observed (P=0.062) (Table 2).

Site by season, variety, treatment and storage time interactions were significant for insect grain damage and grain moisture content (P<0.001). Site by treatment and site by treatment by variety interactions were not significant for grain weight loss (P=0.473 and P = 0.261), respectively (Table 3). No significant season*treatment, season*site*treatment, season*site*variety and season*site*storage time interactions were found for moisture content (P>0.05) (Table 3).

3.2 Insect grain damage

The baseline mean insect damaged grain for the white hybrid maize, pVA biofortified orange maize and local maize variety - *Kanongo* in the 2017/18 storage season in Guruve district was 26%, 16% and 16%, respectively. Treatment had a significant effect on insect grain damage for white hybrid maize, pVA biofortified orange maize and local variety - *Kanongo* (P<0.001) (Figure 5). In the hermetic treatments (Purdue Improved Crop Storage (PICS) bag, GrainPro Super Grain bag (SGB) IVR™, ZeroFly® hermetic storage bag, AgroZ® ordinary bag and AgroZ® Plus bag), mean insect grain damage of between 28% and 35% occurred at 32 weeks in all maize varieties, while higher damage levels in excess of 70% were recorded in the Actellic Gold Dust® and untreated control treatments (Figure 5). The variety x time interaction was significant (P<0.001). Averaged across treatments, significant differences in mean insect grain damage among maize varieties occurred at 8 (P=0.024), 16 (P<0.001), 24 (P<0.001) and 32 (P<0.001) weeks.

Similarly, for Mbire district in the 2017/18 season, significant differences among treatments were observed for white hybrid maize, pVA biofortified orange maize and local variety – *Kanongo* (P<0.001) (Figure 5). In addition, varietal effect on mean insect grain damage was significant (P<0.001). White hybrid maize showed significantly higher damage than other varieties (P<0.001) . Hermetic treatments maintained significantly lower insect grain damage (<35%) (P<0.001), than Actellic Gold Dust® and untreated control in which at least 60% of grains were damaged by 32 weeks' storage in all the maize varieties.

In the 2018/19 season, mean insect grain damage in the Guruve district baseline samples ranged from 9 to 14%. Treatment x time interaction for insect grain damage was significant for all the three maize varieties (P<0.001) . The variety x time interaction for insect grain damage was significant (P<0.001) (Figure 6). Untreated control and Actellic Gold Dust® experienced significantly higher insect damage (48-90%) during the 32-week storage period than the hermetic treatments (5-12%) (P<0.001) (Figure 6). In the 2018/19 storage season, insect grain damage in the hermetic bags was significantly lower than in 2017/18 (P<0.001).

3.3 Grain weight loss

In the 2017/18 storage season, grain weight loss significantly increased from an average baseline of 4% to 10-19% (P<0.001) in the untreated control and Actellic Gold Dust® treatments in all maize varieties as storage duration increased. The hermetic bag treatments maintained the baseline grain weight (Supplementary material, Fig. A1). The baseline grain weight loss in Guruve and Mbire for the 2018/19 storage season ranged between 1 and 2%. The treatment x time interaction on grain weight loss was significant for white hybrid maize, pVA biofortified orange maize and local variety - *Kanongo* in Guruve (P<0.001) (Supplementary material Fig. A2). Similarly, significant difference (P<0.001) among treatments was recorded in Mbire at 8, 16, 24 and 32 weeks for all the maize varieties. Hermetic treatments maintained grain weight loss at 2-3% throughout the 32-week storage period, while significantly higher (P<0.001) grain weight loss of 9 – 22% occurred in the untreated control and Actellic Gold Dust® (Supplementary material Fig. A2). The grain weight loss in the hermetic bag treatments was lower in the 2018/19 storage season than in 2017/18.

3.4 Adult insect pest and natural enemy spectra in stored maize

In Guruve and Mbire districts, the insect pest species recorded were *Sitophilus zeamais*, *Sitotroga cerealella*, *Prostephanus truncatus*, *Rhyzopertha dominica*, *Tribolium castaneum* and the parasitoid *Pteromalus cerealellae* (Ashmead) (Hymenoptera: Pteromalidae). *Sitophilus zeamais* was the dominant insect species in the 2017/18 storage season and was observed in all treatments, while *S. cerealella* was most abundant in Actellic Gold Dust® treatment for white hybrid maize, orange maize and local variety, reaching 901, 806 and 308 insects per kg, respectively, from a baseline of 0 insects per kg (Supplementary material, Fig. A3). In the untreated control, *T. castaneum* (15 to 30 insects per kg) were observed only at 32 weeks of storage in all maize varieties. The hermetic bag treatments suppressed *P. truncatus, S. cerealella, T. castaneum* and *S. zeamais* proliferation and low insect numbers were maintained (< 10 insects per species per kg). *Prostephanus truncatus* numbers were generally low (<10 insects per kg) in all the treatment samples (Supplementary material, Fig. A3).

In Guruve, *S. zeamais* was the dominant insect species at the start of the 2018/19 season. *Pteromalus cerealellae* were suppressed in hermetic bag and Actellic Gold Dust® treatments during the 32-week storage period. *Sitotroga cerealella* population increased over 32-week storage period in the Actellic Gold Dust® treatment to 1030 and 56, 552 insects per kg in white hybrid maize, pVA biofortified orange maize and local variety – *Kanongo*, respectively. The most abundant insect species in the untreated control at 32 weeks were *S. zeamais* (140 to 160 insects per kg), *C. ferrugineus* (20 to 44 insects per kg) and *T. castaneum* (40 to 100 insects per kg) in all maize varieties (Supplementary material, Fig. A4). The same trends were observed in Mbire district, although the insect numbers were higher than in Guruve. Hermetic bag treatments generally maintained low insects counts (<30 insects per species per kg) in both districts (Supplementary material, Fig. A4).

3.5 Grain moisture content

The initial grain moisture content in the 2017/18 storage season in Guruve district for white hybrid, pVA biofortified orange and the local maize variety - *Kanongo* was 10.9%, 10.7% and 10.4%, respectively (Supplementary material, Fig. A5). Grain moisture content fluctuated in the Actellic Gold Dust® and untreated control treatments of the three maize varieties, resulting in significant differences in moisture content among treatments at 8, 16, 24 and 32 weeks of storage (P<0.001). However, the moisture content remained below 13% throughout the 32 weeks. In Mbire district, the baseline moisture content for hybrid white maize, pVA biofortified orange maize and local variety - *Kanongo* was 10.4%, 10.3% and 10.5% respectively (Supplementary material, Fig. A5). The trends in Mbire district were similar to those observed in Guruve district, although in the untreated control treatments for all maize varieties, mean moisture content at 32 weeks' storage period was lower than for Guruve district. The hermetic bag treatments maintained constant grain moisture (<11%), while untreated control increased to 12.2% at week 8 following the January 2018 rains (Supplementary material, Fig. A5).

The baseline moisture content in 2018/19 storage season for Guruve district was 10.5%, 10.3% and 10.3% for hybrid white maize, pVA biofortified orange maize and local variety – *Kanongo*. Hermetic bag treatments maintained moisture content throughout the 32 weeks of storage, while fluctuations were observed in the untreated control and Actellic Gold Dust® (Supplementary material, Fig. A6). Significant differences in moisture content among treatments were observed at week 8, 16, 24 and 32 (P<0.001). In Mbire district, the initial moisture content for hybrid white maize, pVA biofortified orange maize and local variety – *Kanongo* was 10.1%, 10.1% and 10% respectively. Fluctuations in moisture content among the untreated and Actellic Gold Dust® were observed leading to significant differences among treatments at weeks 8, 16, 24 and 32 (Supplementary material, Fig. A6).

3.6 Correlations between insects and grain damage, weight loss and moisture content.

In the 2017/18 storage season in Guruve district, total insect population had a significant (P<0.001) and positive correlation with insect grain damage (r = 0.65 and 0.76) and weight loss (r = 0.51 and 0.66) for white hybrid and pVA biofortified orange maize, respectively (Supplementary material, Table A1). *Sitotroga cerealella* population (live and dead) had a significant (P<0.001) and positive relationship with increased grain damage (r = 0.63 and 0.73) for white hybrid and pVA biofortified orange maize, respectively and weight loss (r = 0.67) for pVA biofortified orange maize. Total population of *S. zeamais* had a significant (P<0.001) and positive correlation with insect grain damage (0.50) for the local variety - *Kanongo*, while white hybrid and pVA biofortified orange maize had a significant (P<0.001) and weak correlation (r = 0.14 and 0.36), respectively. *Tribolium castaneum* population had a significant (P<0.001) and positive correlation with insect grain damage for all three maize varieties. In

Mbire district, a significant (P<0.001) and positive correlation of total insect population with moisture content was recorded for the local variety - *Kanongo* (r = 0.61).

In the 2018/19 storage season in Guruve district, total insect population had a significant (P<0.001) and positive correlation with insect grain damage (r = 0.69, 0.64 and 0.80) for white hybrid, pVA biofortified orange and the local maize variety - *Kanongo*, respectively (Supplementary material, Table A2). Total insect population had a positive correlation (r = 0.78 and 0.67) with grain weight loss and moisture content, respectively for the local variety - *Kanongo*. A correlation with moisture content (r = 0.67) was recorded for the local variety - *Kanongo. Sitotroga cerealella* population (live and dead) had a significant (P<0.001) and positive relationship with insect grain damage (r = 0.74, 0.54 and 0.60) for white hybrid, pVA biofortified orange and the local maize variety - *Kanongo*, respectively. The total population of *S. zeamais* had a significant (P<0.001) and positive correlation with insect grain damage (r = 0.72) for the local variety – *Kanongo*. *Tribolium castaneum* population had a significant (P<0.001) and positive correlation with insect grain damage for all three maize varieties. In Mbire district, the total insect population had a significant (P<0.001) and positive correlation with insect grain damage (r = 0.39, 0.40 and 0.42) and weight loss (r = 0.47, 0.40 and 0.41) for white hybrid, pVA biofortified orange and the local maize variety - *Kanongo*, respectively. *Cryptolestes* population had a significant (P<0.001) and positive correlation with insect grain damage (r = 0.51) for white hybrid maize (Supplementary material, Table A2).

3.7 Site, season, treatment and varietal effects on insect perforation holes in different hermetic bag brands liners after 32 weeks' storage

Site and variety had a significant effect on the number of insect-perforated holes in hermetic bag liners (P<0.001) (Table 4). The mean number of insect-perforated holes per hermetic bag liners was significantly higher in Mbire (12.6 holes) than Guruve (0.3 holes) district (P<0.001) (Table 4). The bags containing the local variety – *Kanongo* had significantly higher numbers of insect-perforated holes than those containing pVA biofortified orange maize and white hybrid maize (P<0.001). Treatment and storage season had no influence on the number of insect perforation holes in the hermetic bag liners (P=0.192) and (P=0.996), respectively (Table 4).

3.8 Rodent and sampling spear perforation of hermetic bag liners

During the 2017/18 storage season, in Guruve, no rodent damage was recorded on the liners of any of the hermetic bag treatments for any of the three maize varieties. However, at one of the four households, a PICS bag liner containing white hybrid maize, had two holes arising from accidental piercing by the sampling spear during sampling activities. In Mbire district, rodents damaged one PICS bag and one ZeroFly® hermetic storage bag at separate households.

In the 2018/19 storage season, no rodent damage occurred to the liners of any treatments in Guruve. In Mbire district, for white hybrid maize, rodent damage to bags was recorded at only one Learning Centre where PICS bag and ZeroFly® hermetic storage bags liners had two and three large holes, respectively. In Mbire, two holes caused by accidental sampling spear piercing during sampling, were recorded at two Learning Centres for PICS and AgroZ® Plus bag liners.

3.9 Environmental temperature and relative humidity (RH)

The mean temperature inside the farmers' storage room for the 2017/18 storage season from storage weeks 16 to 32, ranged from 20 to 24^{o}C and 26 to 30^{o}C for Guruve and Mbire districts, respectively. During this period, temperature decreased as storage time progressed in both districts. Relative humidity of 57-78% and 50-68% was recorded from storage weeks 16 to 32 in Guruve and Mbire, respectively (Figure 7a). The highest relative humidity was recorded in weeks 16 to 24 (December 2017 – January 2018) for both districts. Mbire district recorded lower relative humidity than Guruve (Figure 7a).

In the 2018/19 storage season, the temperature inside the farmers' storage room ranged from 20 to 26^{o}C and 26 to 31^{o}C in Guruve and Mbire districts, respectively. The highest mean temperatures of 26^{o}C and 31^{o}C were recorded in week 0-8 (September – October 2018) and week 8-16 (November – December 2018) for Guruve and Mbire districts, respectively (Figure 7b). Relative humidity ranged between 38-75% and 31-71% for Guruve and Mbire districts, with the highest levels being recorded in the 16 to 24 weeks' storage period (January – February 2019) (Figure 7b).

4. Discussion

All five hermetic bag brands evaluated (PICS, SGB, AgroZ® Ordinary bag, AgroZ® Plus and ZeroFly® hermetic storage bag) were more effective in protecting maize grain from insect damage during 32 weeks of storage under smallholder farming systems than admixture of the commercial synthetic pesticide Actellic Gold Dust® with the grain or grain that was left untreated. The lower efficacy of the synthetic pesticide Actellic Gold Dust® in the current study, could have been due to poor persistence and/or pesticide tolerance and resistance as was suggested by Mlambo et al. (2017) who found similar results in their 40-week long work on smallholder maize storage in Zimbabwe. In our study, the 2017/18 storage season experiments were set 3 months after harvest when insect proliferation had already started. This reflects farmers’ common practices in these districts, where they leave their grain drying for several months before shelling and treating. This delay in applying the pesticide may have contributed to the subsequent low performance of the pesticide. Delayed application of pesticide is not recommended for smallholder farmer storage, as pest populations can then build up inside the grains before treatment with contact pesticides (Mutambuki and Ngatia, 2012).

Significantly higher numbers of insect perforation holes were observed in hermetic bag liners containing the local variety – *Kanongo*, than the other maize varieties. We observed that this local variety has kernels with sharper tips that could have pierced the bag liners, creating holes similar to those made by insects. However, this aspect needs further study. The hermetic bag liners in Mbire district were significantly more perforated by insects than those in Guruve district. This could have been due to rodents observed in Mbire puncturing the bags, allowing air ingress, resulting in increased insect proliferation and subsequent perforation of the bags. The hermetic bag brand had no influence on insect perforations as all the bags had equal chances of being perforated.

Insect-induced perforations were also recorded on the liners of PICS bags used to store maize grain for 6.5 months in West Africa (Baoua et al., 2014). However, laboratory studies by Garcia-Lara et al. (2013) on the SGB concluded that it could not be perforated from the inside by insect pests resident in the grain, although they found it could be perforated by insects arriving from the outside of the bags. Faulty base seams which split open during the storage period were observed on two AgroZ® Plus bags in Mbire. This highlights the importance of minimising the handling and movement of the grain-loaded bags and suggests opportunities for manufacturers to improve the quality and strength of the bag seams.

The population of *S. cerealella, S. zeamais, T. castaneum* and *Cryptolestes* showed a strong positive relationship with grain damage and weight loss for the three maize varieties causing high levels of grain damage (>70%) in the untreated control and Actellic Gold Dust®. Despite the presence of an initial insect population in the grain, hermetic bag treatments managed to suppress insect pest populations and the parasitic wasp *P. cerealellae*, preventing the grain from sustaining high storage insect damage. This can likely be attributed to the modified atmosphere created within the closed bag resulting in the cessation of insect metabolism (Murdock et al., 2012).

However, a weak correlation with grain damage, weight loss and moisture content in all maize varieties was observed for *P. truncatus, R. dominica* and *P. cerealellae* wasp populations. *Prostephanus truncatus* populations were generally low in both districts and storage seasons hence its low contribution to insect damage, as this pest is notorious for its characteristically sporadic occurrence (Boxall, 2002; Hodges et al., 2003; Muatinte et al., 2014; Muatinte et al., 2019). In addition, the low levels may be attributed to cool weather conditions during weeks 24 to 32 (April to May), which are unfavourable for *P. truncatus* whose optimum temperature for growth is 32^{o}C (Hodges, 1986; Hodges et al., 2003).

The moisture content of stored maize grain needs to be controlled for safe storage. In Zimbabwe, ≤12.5% moisture content is recommended by the Grain Marketing Board Zimbabwe, since the higher the moisture content, the more susceptible the grain is to insects and therefore deterioration (Rashid et al., 2013). In the current study, grain moisture content fluctuated between 10% and 12% in the untreated control and Actellic Gold Dust® treatments due to interaction with the environment, i.e., responding to changes in ambient relative humidity, unlike the hermetic bag treatments which maintained fairly constant moisture content levels (<11%).

Of the three maize varieties studied, white hybrid maize was more heavily damaged by storage insects than pVA biofortified orange maize or the local maize variety - *Kanongo*. This agrees with conclusions by Giga and Mazarura (1991) that hybrid maize varieties tend to be more susceptible to storage insect pests than open pollinated varieties. Some hybrid maize varieties had higher yields but were softer with poorer husk cover, making them more susceptible to storage insect pests and diseases resulting in higher storage losses (Schulten, 1975; Tyler, 1982, Golob, 1984; Giga et al., 1998; Boxall, 2001). The three maize varieties used in the current trial have different kernel sizes and colour. White hybrid maize has the largest kernel, local variety – *Kanongo* (white) is medium sized, and pVA biofortified maize (orange) was the smallest. The kernel dimensions (length x width x height) for the maize varieties were as follows: white hybrid maize – 14 mm x 10mm x 4mm, local variety - *Kanongo* – 12 mm x 9 mm x 4 mm and pVA biofortified orange maize – 9 mm x 8 mm x4 mm.

Laboratory studies conducted in Kenya for a 2-month storage period found that *S. zeamais* and *P. truncatus* preferentially fed on smaller, rather than larger grains, and on coloured rather than normal creamy white grains (De Groote et al., 2017). This preference was more pronounced in *S. zeamais*, which was able to distinguish between different colours, and preferred the green-dyed maize kernels. These findings contrast with our study findings in which the maize variety with the largest kernel size had significantly higher damage and weight loss than the others. The composition and softness of hybrid white maize may influence its susceptibility to insect damage. In addition, the pVA biofortified orange maize was less damaged in our study. The opposite was found in a laboratory study with the same white hybrid and pVA biofortified orange maize grain varieties. After four months' storage, following the addition of four *S. zeamais* and four *P. truncatus* insects to 300g of grain, 69% of the biofortified grains were damaged compared to 37% of the white hybrid grains (Stathers et al., 2020b). A laboratory study that evaluated the resistance of five maize cultivars to attack by *S. zeamais* showed that the presence of lectin in the grains contributed to resistance (Frazão et al., 2018). The current study focused on quantitative losses of maize during smallholder farmer-managed storage and further study on the effect of storage on nutritional and anti-nutritional composition and germination potential is recommended.

Of the five hermetic bags evaluated in the current study, only GrainPro Super Grain bag (SGB) IVR™ and Zerofly® hermetic storage bags are currently available on the Zimbabwean market, costing USD$1.50 and $2.00 in 2019, respectively. None of the hermetic bags are manufactured locally in Zimbabwe. However, AgroZ bags and PICS bags are manufactured in Africa while the others are manufactured outside Africa. Local manufacturing and wide availability of all the bags may help lower the retail price and in turn, promote adoption of the technologies by smallholder farmers in low and middle-income countries.

5. Conclusion

The current study showed the superiority of hermetic bags over the synthetic pesticide, Actellic Gold Dust®, in protecting stored maize grain from insect attack under smallholder farming conditions and management. The hermetic bags also maintained grain moisture content better than the non-hermetic methods studied. There was no significant difference in efficacy between any of the five hermetic bag brands that were trialled. Location affected the maize grain weight loss, with Mbire district experiencing higher weight loss than Guruve district. *Sitotroga cerealella*, *S. zeamais*, *T. castaneum* and *Cryptolestes* were the main insects that contributed to high grain damage and weight loss for the three maize varieties in the untreated control and Actellic Gold Dust®. The white hybrid maize was significantly more insect-damaged than pVA biofortified orange maize and local maize variety – *Kanongo* in the untreated control and Actellic Gold Dust® treatments. The development of varieties less susceptible to storage insect pest infestation could help reduce postharvest losses. Location and variety had a significant effect on insect perforation holes in hermetic bag liners. Some of the hermetic bags were punctured by insects and rodents, presenting a challenge to hermetic bag efficacy, re-usability and life-span. The findings highlighted the critical importance of practicing good storage and homestead hygiene, rodent-proofing and control in storage facilities to reduce the likelihood of the hermetic bags being perforated and rendered ineffective. Repeated handling of some hermetic bag brands led to the bags splitting along their base seams and thus reduced their efficacy. Early treatment of grain with grain protectants as soon as possible after drying and shelling is recommended to optimize their effectiveness and retreatment may be necessary though it has cost and labour implications. The hermetic bag storage technology can be an effective and sustainable chemical-free alternative to synthetic pesticides to ensure food and nutrition security and is suitable for use by smallholder farmers in SSA in different agroecologies.

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Tables

Table 1. Maize storage treatments evaluated under smallholder farmer management in Guruve and Mbire districts, Zimbabwe

Category	Treatment/Trade Name	Description
Positive control (Registered synthetic pesticide)	Actellic Gold Dust®	A cocktail of pirimiphos-methyl 1.6% and thiamethoxam 0.36%; applied at 0.5 g/kg.
Hermetic storage technologies	Purdue Improved Crop Storage (PICS) bag	Two high-density polyethylene (HDPE) liners with 80 mm thickness fitted inside a third woven polypropylene bag. Oxygen transmission rate (OTR) not available.
	GrainPro Super Grain bag (SGB) IVR™	Low-density polyethylene (LDPE) multi-layered single plastic liner with 78 ± 2 mm thickness used, fitted inside a polypropylene bag. Oxygen transmission rate (OTR) <3 cc/m^2 per day.
	ZeroFly® hermetic storage bag	Insecticide-incorporated (deltamethrin applied at 3 mg/kg) polypropylene bags with hermetic HDPE liner inside with 65 mm thickness. OTR <1.5 cc/m^2 per day.
	AgroZ® Ordinary bag	A polypropylene outer bag and a multi-layer inner liner (co-extruded combining HDPE and metallocene linear low density polyethylene - MLLDPE) with 90 mm thickness. OTR 2.2 cc/m^2 per day.
	AgroZ® Plus bag	A polypropylene outer bag and a multi-layer inner liner. The multi-layer liner with 90 mm thickness includes a central layer incorporating a repellent insecticide (alpha-cypermethrin at 3 mg/kg) sandwiched between two barrier layers. OTR 2.2 cc/m^2 per day.
Negative control	Untreated	Untreated grain in a polypropylene bag

Table 2. Overall site, season, treatment, storage time and varietal effects on mean insect grain damage, grain weight loss-and moisture content

Factor		Mean grain damage (%±SEM)	Mean grain weight loss (%±SEM)	Mean grain moisture content (%±SEM)
Site (n=840)	Guruve	25.5±0.72a	2.7±0.16a	10.7±0.60b
	Mbire	24.6±0.69a	3.2±0.15b	10.4±0.02a
	P value	0.393	0.025	<0.001
	$F_{1,1665}$	0.73	5.06	112.92
Season (n=840)	2017/18	34.6±0.60b	4.0±0.14b	10.9±0.02b
	2018/19	15.5±0.65a	1.8±0.15a	10.2±0.02a
	P value	<0.001	<0.001	<0.001
	$F_{1,1665}$	469.52	113.78	546.64
Treatment (n=240)	Actellic Gold Dust®	39.0±1.70b	4.9±0.38b	10.7±0.05b
	ZeroFly® hermetic storage bags	19.2±0.89a	1.9±0.13a	10.5±0.03a
	AgroZ® Plus bag	17.8±0.78a	1.9±0.12a	10.5±0.03a
	AgroZ® Ordinary bag	18.5±0.87a	1.9±0.14a	10.5±0.03a
	Purdue Improved Crop Storage (PICS) bag	18.2±0.87a	1.8±0.13a	10.5±0.03a
	GrainPro Super Grain bag (SGB) IVR™	18.7±0.89a	2.0±0.14a	10.5±0.03a
	Untreated control	44.7±1.53c	6.2±0.50c	11.3±0.05b
	P value	<0.001	<0.001	<0.001
	$F_{6,1665}$	104.08	48.25	7.80
Storage time (weeks) (n=336)	0	15.8±0.56a	2.2±0.18a	10.4±0.03a
	8	22.4±0.89b	2.1±0.12a	10.3±0.03a
	16	27.2±1.11c	2.4±0.20ab	10.5±0.03b
	24	25.8±1.13c	2.9±0.19b	10.6±0.04b
	32	33.4±1.44d	5.0±0.39c	10.6±0.03b
	P value	<0.001	<0.001	<0.001
	$F_{4,1665}$	37.33	25.78	25.01
Variety (n=560)	White hybrid (SC719)	30.5±0.90b	3.6±0.18b	10.5±0.02a
	pVA biofortified orange (ZS242)	21.3±0.76a	2.5±0.17a	10.6±0.03a
	Local variety - *Kanongo*	23.4±0.87a	2.6±0.20a	10.6±0.03a
	P value	<0.001	<0.001	0.062
	$F_{2,1663}$	32.91	11.50	2.79

Data were presented as means±standard error of the means n* is the product of interactions between all the factors analysed. For each factor, means within a column were compared and separated using Tukey's test at p<0.05 and different letters indicate significant differences.

Table 3. Factor interactions of mean insect grain damage, grain weight loss and moisture content

Interaction	P and F Values		
	Grain damage	Weight loss	Moisture Content
Site x season	<0.001; $F_{1,1251}$=310.63	0.022; $F_{1,1251}$=5.29	<0.001; $F_{1,1251}$=70.17
Site x variety	<0.001; $F_{2,1251}$=428.53	<0.001; $F_{2,1251}$=57.21	<0.001; $F_{2,1251}$=117.32
Site x treatment	<0.001; $F_{6,1251}$=74.92	0.473; $F_{6,1251}$=0.93	<0.001; $F_{6,1251}$=23.99
Site x storage time	<0.001; $F_{4,1251}$=6.05	<0.001; $F_{4,1251}$=8.33	<0.001; $F_{4,1251}$=17.79
Season x variety	<0.001; $F_{2,1251}$=216.65	<0.001; $F_{2,1251}$=20.74	<0.001; $F_{2,1251}$=87.48
Season x treatment	<0.001; $F_{6,1251}$=3.92	0.002 $F_{6,1251}$=3.41	0.949; $F_{6,1251}$=0.28
Season x storage time	<0.001; $F_{4,1251}$=52.30	0.003; $F_{4,1251}$=4.06	<0.001; $F_{4,1251}$=9.03
Season x site x treatment	<0.001; $F_{6,1251}$=5.54	0.020; $F_{6,1251}$=2.52	0.782; $F_{6,1251}$=0.53
Season x site x variety	<0.001; $F_{2,1251}$=45.33	0.001; $F_{2,1251}$=6.87	0.462; $F_{2,1251}$=0.77
Season x site x storage time	<0.001; $F_{4,1251}$=11.74	0.031; $F_{4,1251}$=2.67	0.528; $F_{4,1251}$=0.80
Site x time x variety	<0.001; $F_{8,1251}$=14.20	0.018; $F_{8,1251}$=2.33	<0.001; $F_{8,1251}$=16.07
Site x treatment x variety	<0.001; $F_{12,1251}$=14.62	0.261; $F_{12,1251}$=1.22	0.013; $F_{12,1251}$=2.13

Table 4. Overall site, season, treatment and varietal effects on mean number of insect perforation holes on different hermetic bag brands liners after 32 weeks' storage

Factor			Mean number of insect perforating holes *
Site	Guruve		0.07±0.16a (0.3)
	Mbire		0.59±0.63a (12.6)
		P value	<0.001
		$F_{1,216}$	103.09
Season	2017/18		0.33±0.08b (0.3)
	2018/19		0.33±0.23a (0.3)
		P value	0.996
		$F_{1,216}$	0.00
Treatment	ZeroFly® hermetic storage bags		0.37±1.16a (9.9)
	AgroZ® Plus bag		0.34±0.43a (3.5)
	AgroZ® Ordinary bag		0.24±0.48a (4.9)
	Purdue Improved Crop Storage (PICS) bag - Inner		0.44±0.52a (12.2)
	Purdue Improved Crop Storage (PICS) bag - Outer		0.32±0.65a (5.6)
	GrainPro Super Grain bag (SGB) IVR™		0.25±0.40a (2.5)
		P value	0.192
		$F_{5,216}$	1.50
Variety	White hybrid (SC719)		0.21±0.62a (5.2)
	pVA biofortified orange (ZS242)		0.20±0.34a (1.4)
	Local variety - *Kanongo*		0.58±0.50b (12.6)
		P value	<0.001
		$F_{2,216}$	24.23

Data were presented as means±standard error of means. For each factor, means within a column were compared and separated using Tukey's test at $p<0.05$ and different letters indicate significant differences.

Key: Data in parenthesis denote means of untransformed data. *All data were transformed using log (x+1)

Figures

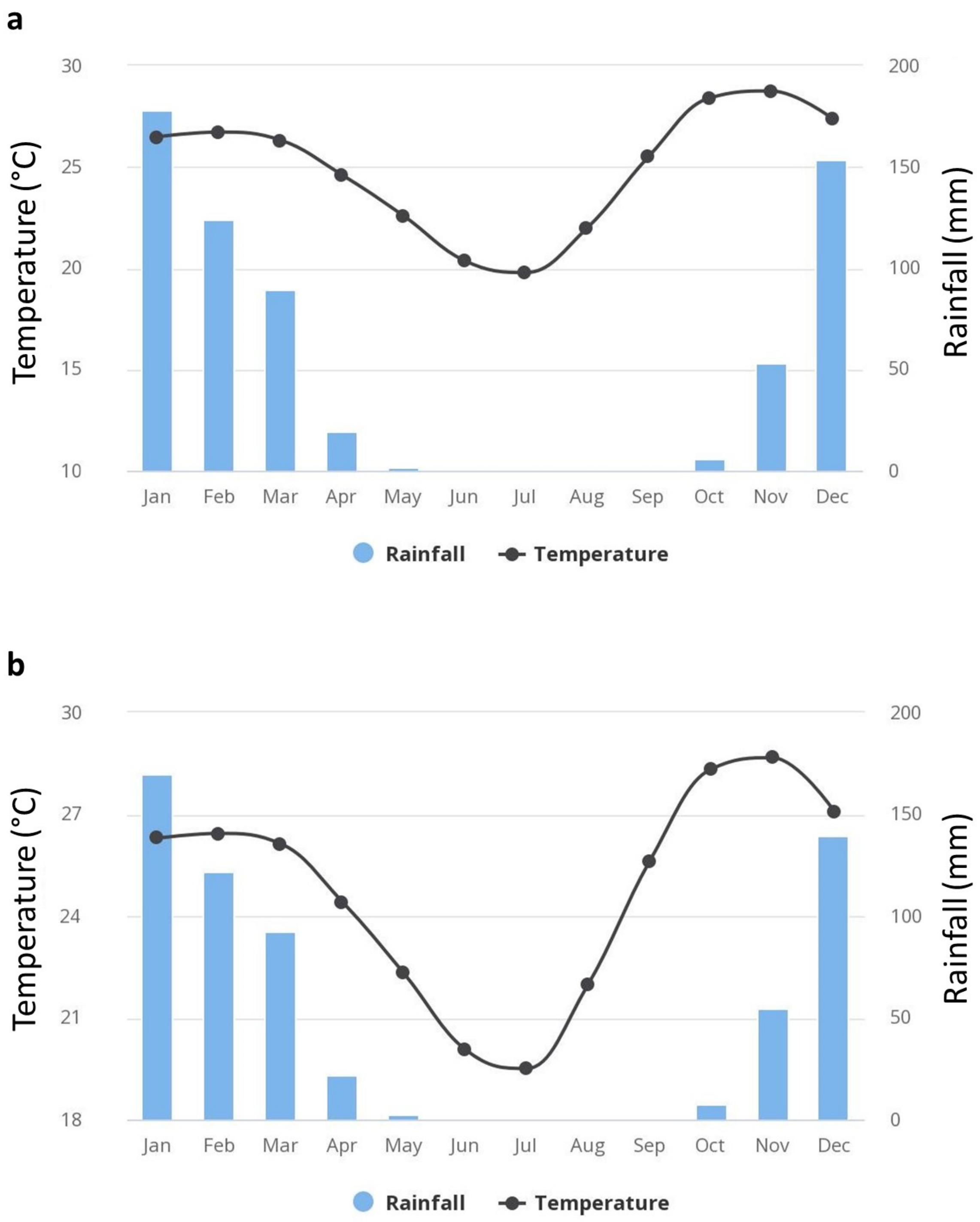
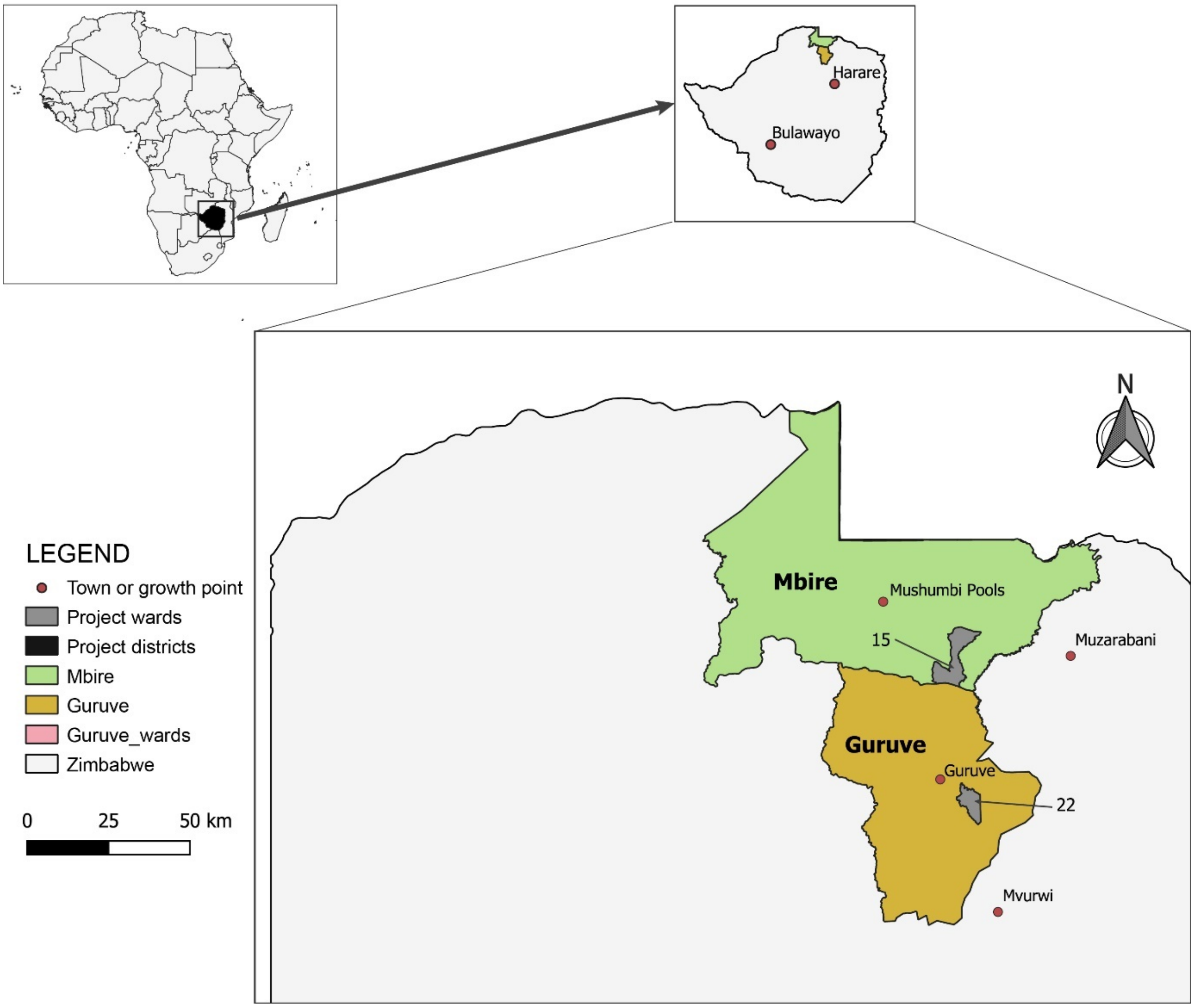


Figure 1: Average monthly temperature and rainfall in the trial locations in Zimbabwe: (a) Mbire district and (b) Guruve district for 1991-2016 (Source: World Bank Group Climate Change Knowledge Portal, 2021)



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824 **Figure 2: Map showing Guruve (Ward 22) and Mbire (Ward 15) districts; the focal study**
825 **areas in Zimbabwe**

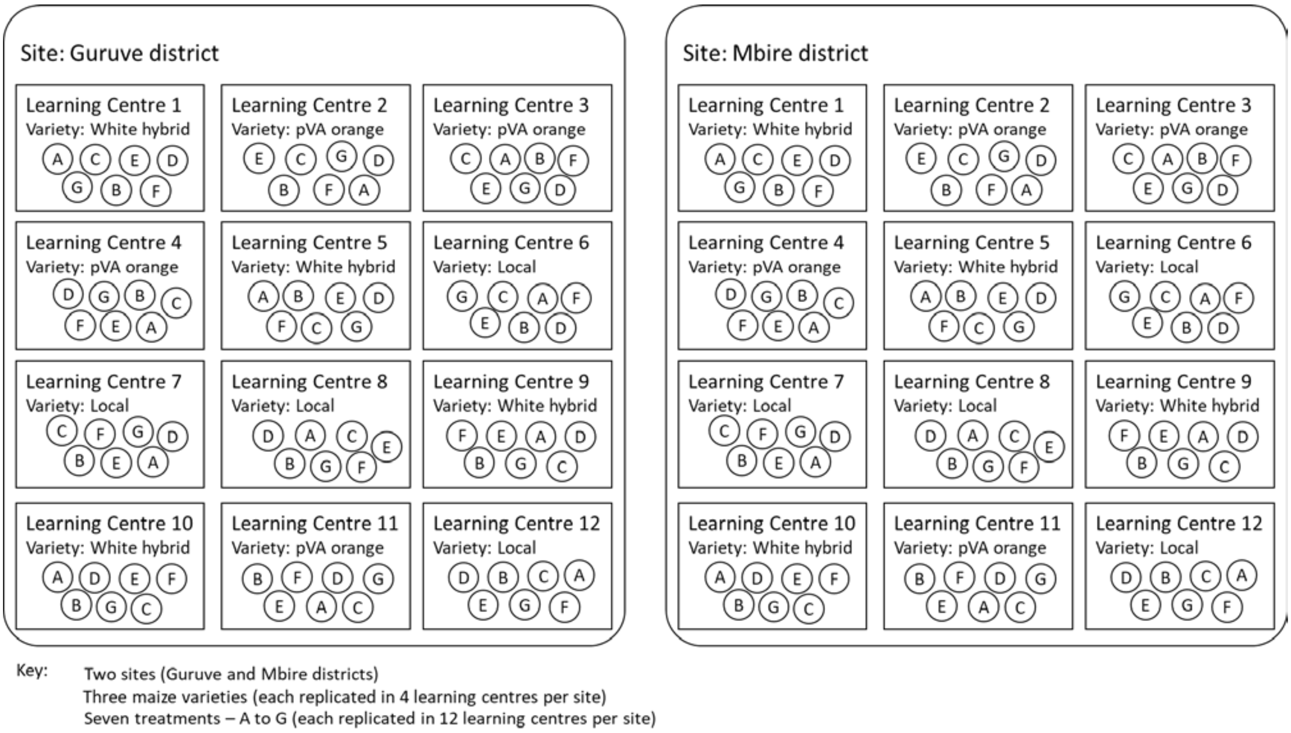


Figure 3: Experimental layout of the study

Figure 4: Typical store used in the field study: (a) Interior of the store and layout of the treatments (b) full view of the structure of the store also showing learning together with farmers and local agricultural extension staff.

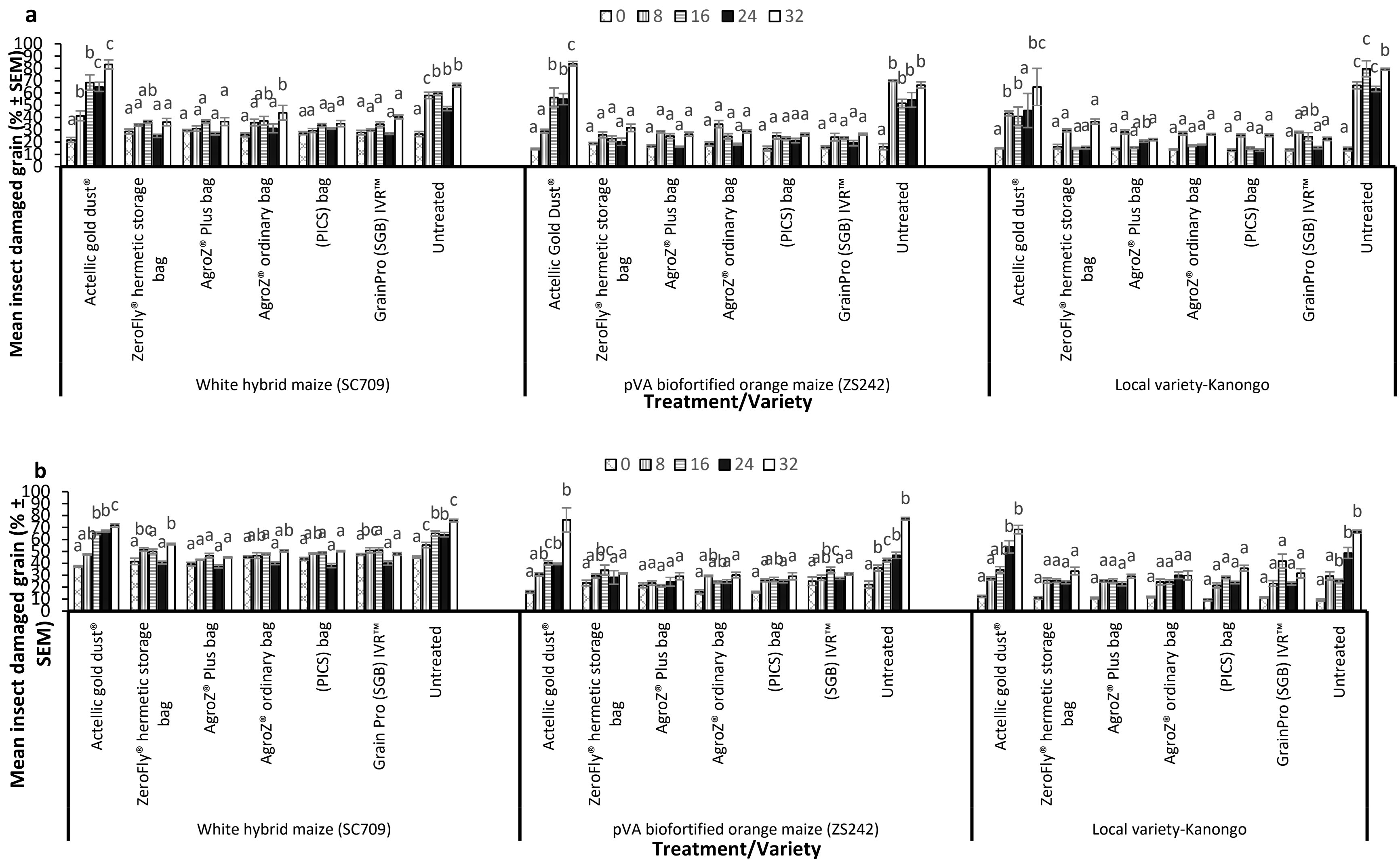
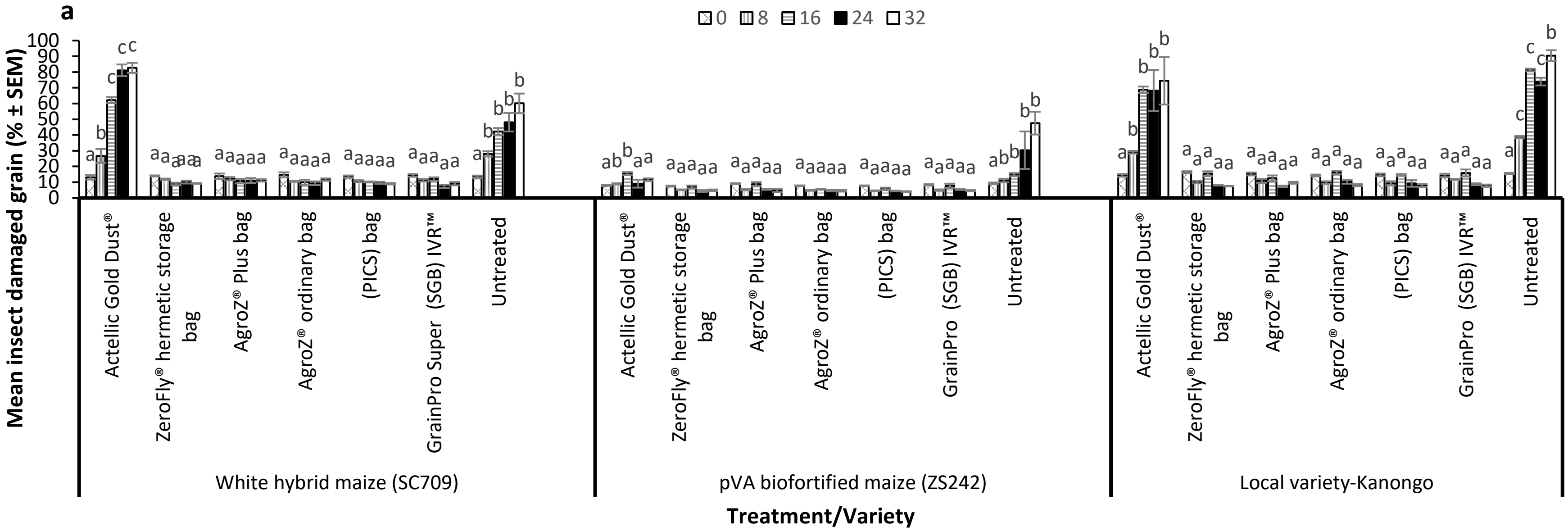


Figure 5: Mean percentage insect grain damage (±SEM) for three different maize varieties stored on-farm using different treatments for a 32-week period in a) Guruve district during 2017/18 storage season (n=4), b) Mbire district, 2017/18 (n=4).
Key: PICS = Purdue Improved Crop Storage; GrainPro (SGB) IVR™ = GrainPro Super Grain Bag IVR™


a
0
8
16
24
32
Mean insect damaged grain (% ± SEM)
Actellic Gold Dust®
ZeroFly® hermetic storage bag
AgroZ® Plus bag
AgroZ® ordinary bag
(PICS) bag
GrainPro Super (SGB) IVR™
Untreated
White hybrid maize (SC709)
pVA biofortified maize (ZS242)
Local variety-Kanongo
Treatment/Variety

837

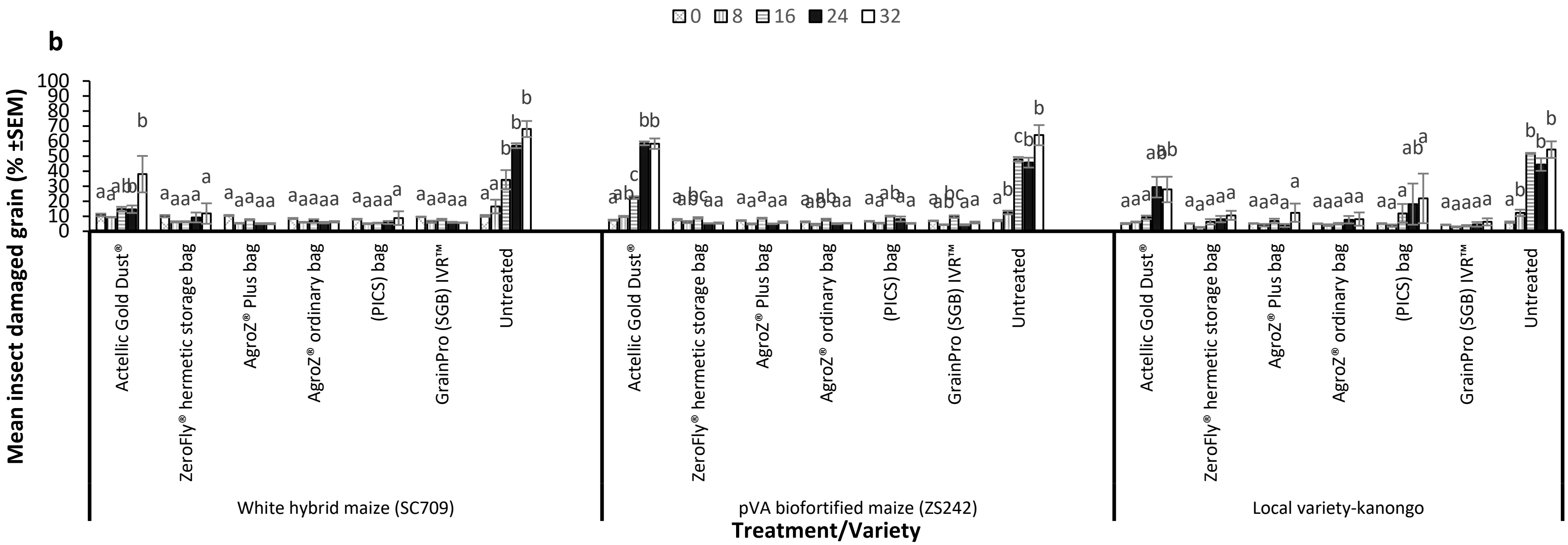
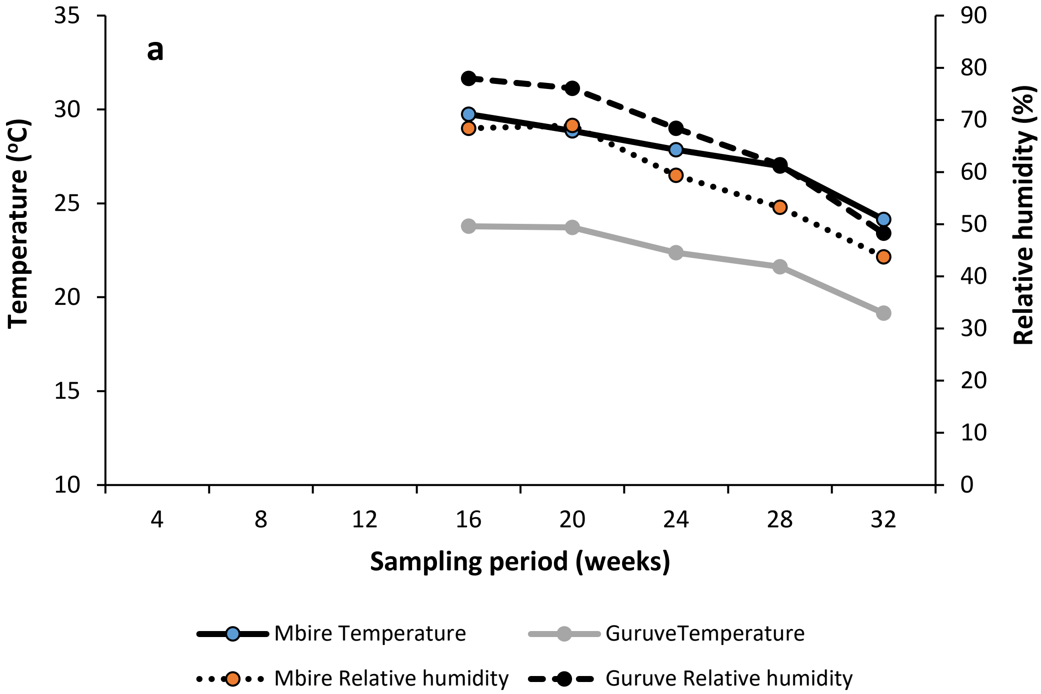


Figure 6: Mean percentage insect grain damage (±SEM) for three different maize varieties stored on-farm using different treatments during a 32-week period in a) Guruve district, 2018/19 (n=4), b) Mbire district, 2018/19 (n=4).



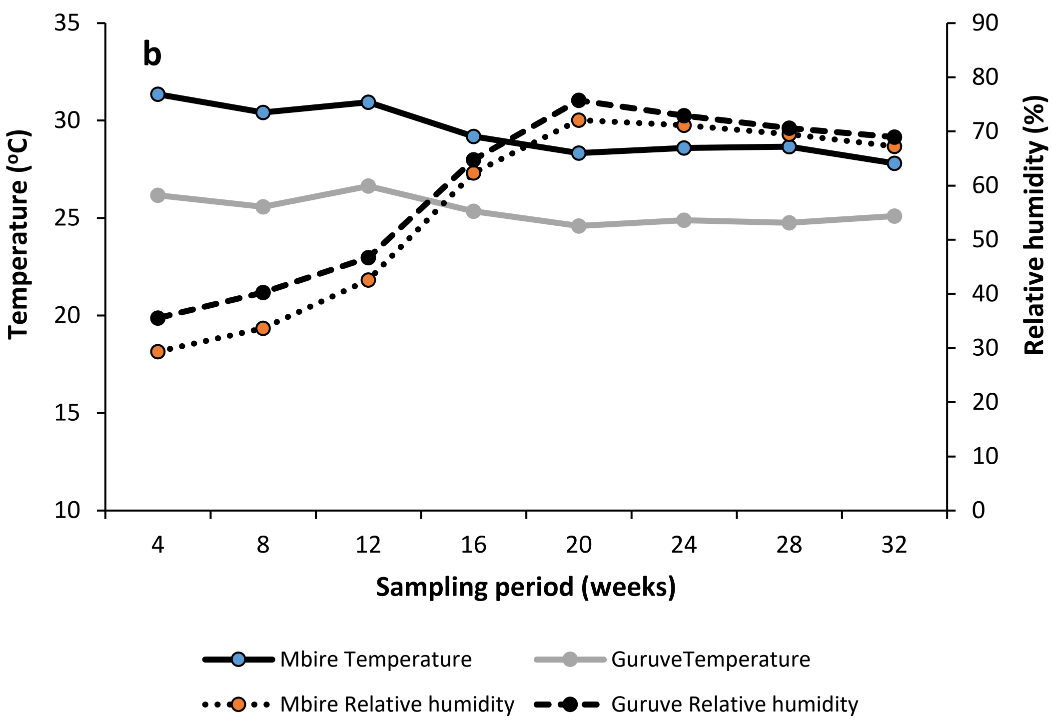


Figure 7: Mean temperatures (º C) and relative humidity (%) averaged at 4-week intervals, during the (a) 2017/18 and (b) 2018/19 storage seasons in Guruve and Mbire districts of Zimbabwe. During the 2017/18 storage season, it was only possible to take measurements

from week 16 to 32 (December 2017 to May 2018) whereas in the 2018/19 storage season measurements were from 0 to 32 weeks (September 2018 to April 2019)