Effectiveness of grain storage facilities and protectants in controlling stored-maize insect pests in a climate-risk prone area of Shire Valley, southern Malawi

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Abstract

Shire Valley is one of Malawi's most vulnerable areas to climate change (CC). In addition to other impacts, CC is expected to affect storage insect pest status, and the efficacy of grain storage facilities and protectants. On-farm grain storage trials were therefore conducted in Shire Valley to assess the performance of storage facilities and grain protectants against storage insect pests. Eight smallholder farmers hosted the trials in Thyolo and Chikwawa districts. Seven grain storage treatments were evaluated for 32 weeks during two storage seasons: Neem leaf powder (NM), Actellic Super dust (ASD), ZeroFly® bag (ZFB), Purdue Improved Crop Storage bag (PICS), Super Grain Bag (SGB), hermetic metal silo (MS) and untreated grain in a polypropylene bag (PP). Insect pest populations and grain damage increased with storage duration and differed significantly between treatments (p □ 0.05). Grain stored in hermetic bags (PICS, SGB) sustained significantly lower ($p < 0.05$) insect damage and weight loss compared to other treatments across sites and seasons. The hermetic bags also outperformed the other treatments in suppressing insect numbers. However, germination rates of undamaged grains stored in the hermetic storage facilities (MS, PICS, SGB) for 40 weeks were extremely low (<15 %) compared to that of undamaged grains from NM treatment (53-58 %) and the other treatments (>75 %) at both sites. The hermetic MS, ZFB bags, ASD and NM treatments did not effectively protect grain from insect damage. High in-store mean temperature (35.6 °C) and high initial grain moisture content (13.7 %) may have negatively affected efficacy of some treatments and seed germination. *Tribolium castaneum* survival in the MS requires further investigation. The hermetic storage bags (PICS, SGB) can be recommended for long-term maize grain storage (≥32 weeks) by smallholder farmers in Shire Valley and other similar climate change-prone areas in sub-Saharan Africa.

Key words: hermetic storage facilities; grain protectants; storage insect pests; insect grain damage and weight loss; germination rate; climate change

1. Introduction

Maize is the main staple food crop for the majority of people in sub-Saharan Africa (SSA) where over 70 % of the crop is produced by smallholder farmers. Over 60 million tonnes of maize is produced annually in SSA, excluding South Africa (FAOSTAT, 2017). Although published data on quantity of grain retained is scarce, anecdotal evidence suggests that 60-80 % is stored on-farm by smallholder farmers. Grain storage is a key household food security strategy practised by the smallholder farmers but storage insect pests are a major problem causing grain damage and economic losses. Additionally, climate change (CC) is another factor expected to negatively affect grain storage in SSA, a region that is highly vulnerable to the effects of CC (Boko et al., 2007; Stathers et al., 2013). Projections are that there will be an increase in global mean surface temperature by the end of the 21st century (2081–2100) in the range of 0.3 °C to 1.7 °C (IPCC, 2014). The strongest warming is projected to occur on the land surface in tropical and Northern Hemisphere subtropical regions (Mastrandrea *et al.,* 2010). Projections for some areas such as Shire Valley in southern Malawi suggest that temperature will increase by 3 °C by the year 2065 with monthly mean temperature predicted to be above 32 °C (Matiya et al., 2011).

Global warming is likely to affect populations of stored product insect pests, increase degradation rates of storage insecticides and reduce the efficacy of storage technologies such as hermetic bags (Delcour et al., 2014). A 2 °C increase in ambient temperature is estimated to have the potential to increase the number of insect life cycles up to five times during the cropping season (Bale et al., 2002). Laboratory studies showed that the duration of Larger Grain Borer (LGB), *Prostephanus truncatus* Horn. (Coleoptera: Bostrichidae) life cycle stages (egg, larva and pupa) decreased with an increase in temperature up to 31 °C at a RH range of 50–80 %, but increased at a temperature of 35 °C (Markham et al., 1991; Subramanyam and Hagstrum, 1991; Hodges, 1994). *Prostephanus truncatus* is among the most devastating pests of stored maize, and was accidentally introduced to East Africa in the late 1970s from Central America and Mexico (Markham et al., 1991; Hodges, 1994) and is now endemic in SSA.

Postharvest (PH) losses of maize are estimated to be 10 to 20 % annually in SSA, mainly caused by storage insect pests (World Bank et al., 2011). Losses of these magnitudes, are an important contributing factor to food insecurity in many African countries including Malawi (Christensen, 1982; FAO, 2009). In Malawi, as across much of SSA, maize was traditionally stored in outdoor woven-basket style granaries (Tyler, 1995). However, Malawian farmers are now increasingly storing their maize grain in polypropylene bags inside their homes (Singano et al., in prep.). The majority (65.5 %) of smallholder farmers in Malawi , typically admix synthetic pesticides, either dust or liquid formulations, with their grain prior to storage, or add ash (3.0 %) or plant materials (12.6 %) to manage storage insect pests (Golob, 1981a; Jayas et al., 1995; Paliani et al., 2001). The increasing demand for alternative pest management options to storage synthetic pesticides (Cooper and Dobson, 2007), has led to the development of several new technologies including modern hermetic storage facilities such as the Super Grain Bag (SGB), Purdue Improved Crop Storage (PICS) bag and the metal silo (MS). The ZeroFly® bag (ZFB), a woven polypropylene grain bag with the insecticide deltamethrin incorporated into the fabric so as to kill any stored insect pests coming into contact with it is another recently introduced technology (Baban and Bingham Zivanovic, 2014). However, performance of these modern storage technologies under smallholder management in different climate-risk prone areas has not been widely tested. Therefore, the current study assessed the performance of a range of storage facilities and grain protectants in protecting stored maize grain against storage insect pests in Shire Valley; a climate-risk prone area in southern Malawi.

2. Materials and methods

2.1. Study site and description

The studies were conducted in Shire Valley, southern Malawi for two consecutive storage seasons; 2014/2015 and 2015/2016. The trials were conducted at two sites; Dwale and Livunzu Extension Planning Areas (EPAs) within Thyolo and Chikwawa districts, respectively. Dwale EPA lies at 16^{o} 19 South and 35^{o} 12 East, 222 m above sea level (masl) while Livunzu EPA lies at 16^{o} 11 South and 35^{o} 00 East, 99 masl (National Statistical Office, 2005). The study area is characterized by two main agro-ecological zones; Shire Highlands (upstream-Thyolo) and Lower Shire Valley (downstream-Chikwawa). The up-stream area was Dwale EPA under Thyolo district and the down-stream area was Livunzu EPA under Chikwawa district. Thyolo shares a boundary with Chikwawa and normally receives an average rainfall of 1,125 mm per year with mean monthly maximum and minimum temperatures of 26.5 ^{o}C and 15.7 ^{o}C, respectively; while Chikwawa district receives an average total rainfall of 1,240 mm per year with mean monthly maximum and minimum temperatures of 30 °C and 27 °C, respectively (Anon, 2015).

2.2. Treatments

Four untreated white hybrid maize varieties (DKC 9089, DKC 8053, SC 719 and SC 627) were procured from the farm section at Chitedze Agricultural Research Station (CARS) in Lilongwe district, central Malawi during the two storage seasons. The selected varieties are also grown by farmers in the Shire Valley. The grain was procured from CARS because it was difficult to get the required volume of untreated maize grain in Shire Valley. Subsequently, the maize varieties were mixed in equal proportions and homogenized by mixing the grain thoroughly on a tarpaulin using shovels to minimise variations among the treatments. The mixing of different maize varieties mimicked smallholder farmers' practice at storage. Grains that were already infested at the time of set-up were not removed as insect infestation typically starts in the field before harvesting, and so this ensured the treatments were trialled under realistic infestation pressures. The grain moisture content was determined at CARS (13.7 %) using an electric moisture meter (Moisture tester Burrows DMC-500, Illinois) before the grain was transported to the study site, 377 km from Chitedze Station. All storage facilities used in the studies had a storage capacity of 50 kg each, which is the standard storage container size used in Malawi and were procured either from the local distributors or imported if not locally-available. The homogenized shelled maize grain was subjected separately to a total of seven treatments, which were applied as per manufacturer's or famers' recommendations (Table 1).

Untreated grain was weighed into 50 kg lots and each lot was loaded into one of the following storage facilities; MS (outlets were then sealed tightly using thick elastic strips of car-tyre rubber tube), SGB, PICS, ZFB and PP. After filling the hermetic bags (SGB and PICS) with grain, the bags were squeezed to remove the excess air in the plastic liner, twisted and tied tightly according to the manufacturer's instructions. A burning candle was placed on top of the grain inside the MS, and the lid then fitted and sealed tightly using the elastic rubber strips, to help "deplete the available oxygen" and accelerate the suffocation of the insects (Kimani et al., 2018). The grain protectants treatments (ASD and Neem) were separately admixed thoroughly with the maize grain on a tarpaulin using shovels before loading into PP bags.

Table 1 List of the treatments, their sources and application rates as used in the maize grain storage trials in Chikwawa and Thyolo districts, Malawi in 2014/15 and 2015/16

Treatments	**Source**	**Application rate**
Polypropylene bag (PP)	Blantyre Netting Company	Untreated grain
Metal silo (MS)	fabricated by local master artisans in the Farm Machinery Section at Chitedze Agricultural Research Station	Untreated grain
Actellic Super Dust (ASD) admixed with grain then stored in PP bag	Agricultural Trading Company	25 g per 50 kg of grain
Super Grain bag (SGB)	Chemicals and Marketing Company	Untreated grain
Purdue Improved Crop Storage (PICS)	PolyPack Manufacturing Company	Untreated grain
ZeroFly bag (ZFB)	imported from Vestergaard, Switzerland because they were not locally available	Untreated grain
Neem leaf powder (NM) admixed with grain then stored in PP bag	collected and processed by farmers following their normal practice	153.3 g per 50 kg of maize (application rate derived from farmers' practice)

Note: The ASD (Pirimiphos methyl 16g/kg+ Permethrin 3.0g/kg) treated grain stored in a polypropylene bag and the untreated grain stored in a PP bag were used as positive and negative controls, respectively. ZFB is a polypropylene bag with deltamethrin-incorporated into its fabric at 3 mg/kg

The trials were hosted by a total of eight smallholder farming households between the two EPAs. The host farmers were purposively-selected as responsible and approachable members of the community who would enhance the sharing of the grain protection knowledge generated with others in the community. Each of the eight farmers stored the seven treatments in one room, separately from their own grain, within their houses for the duration of the trial in each season. The treatments were placed on wooden pallets to avoid direct contact with the floor, to facilitate air circulation, and to prevent the grain absorbing moisture from the floor. The ZFB treatments were kept at least 1 m away from the other treatments to prevent pesticide contamination during the study period. Additionally, all the treatments were placed 1 m away from the walls of the store to simplify monitoring and inspection, and manage rodents. The treatments were kept under ambient conditions and relied on natural insect pest infestation as opposed to artificial introduction of insects by the research team. The experiments were laid out in a randomized complete block design (RCBD) and each farmer represented a block and replicate per EPA, making four replicates per EPA.

2.3. Temperature and relative humidity measurement

Data loggers for measuring humidity/temperature (Model RHT10, EXTECH Instruments Corporation) were obtained during the second season (2015/2016). It had unfortunately not been possible to acquire them during the first season (2014/2015). Two farmers from each EPA were purposively selected for the collection of temperature and relative humidity (RH) data using the data loggers which started from week 15 of the storage period, when the loggers became available. The temperature and RH data loggers were fixed on walls within the stores where the treatments were placed. Temperature and RH data were recorded every 30 minutes and downloaded to the computer every eight weeks during the sampling visits.

2.4. Grain sampling and sample analysis

At the start of each season's trial, baseline samples were collected. Subsequent samplings were done every eight weeks during the 32 week long trials in the 2014/2015 and 2015/2016 storage seasons. At every sampling session, a sample of ~ 1 kg of maize grain was taken from each treatment using a 166 cm long multi-compartmented sampling spear (Burrow Equipment Company, Dean gamet MFG CO, Evanston, Illinois). Each treatment bag or silo was opened in turn and the sampling spear was carefully inserted in at least five different positions from the top surface of the grain, in an identical manner for all treatments. The multi-compartmented sampling spear was used to ensure that grain from bottom, middle and top of the storage facilities was sampled from each treatment. Two sampling spears were used during each sampling session to prevent contamination among the grain protectant treatments and the storage facilities containing untreated grain. The spears were cleaned using a detergent and dried using tissue paper where necessary to prevent cross-contamination between grain protectants. The high ambient temperature in the area aided rapid drying of the cleaned spears. Special care was taken to prevent the puncturing of the hermetic liners of the SGB and PICS bags during sampling to maintain airtightness.

The collected samples were placed in clearly-labelled transparent plastic bags and tied tightly using elastic bands, and placed in polypropylene bags for safe transportation to the Crop Storage Laboratory at CARS for analysis. At the laboratory, each sample was weighed to obtain the total weight and later sieved using nested sieves of 3.35 mm and 1 mm aperture, respectively, (Endecotts Limited, London, England) to separate grains, insects and trash (flour dust). The sieved adult insects were separated into live and dead per species and were counted. Grain MC was determined three times per sample using an electric moisture meter (Moisture tester Burrows DMC-500, Illinois). Grain MC was determined during the 2015/16 storage season only as the electric moisture meter had developed a fault during the 2014/15 storage season. The grain samples were divided using a riffle divider (Burrows, Evanston, Illinois, 60204) to get two sub-samples (~500 g each), then one sub-sample was discarded while the other one was further divided into two sub-samples (~250 g each). Each of the two sub-samples of 250 g was further divided into two sub-samples (~125 g each), making a total of four sub-samples of ~125 g each. Three of such sub-samples were analysed by manually separating and recording the number and weight of visually insect damaged (grains with storage insect exit and feeding or boring holes) and undamaged grains. The fourth sub-sample was placed in a labelled jar closed using a screw lid fitted with wire mesh of 0.8 mm apertures and kept under ambient conditions for five weeks to monitor the emergence of adult moths such as *Sitotroga cerealella*, *Ephestia* spp. or *Plodia* spp. because these insect species were typically damaged during sieving and so their numbers could not be captured accurately during the normal sample analysis.

2.5. Maize germination tests

Germination tests were conducted at CARS Crop Storage Laboratory at the end of 40 weeks during the 2015/2016 storage season only. The tests were conducted on undamaged grain randomly selected from the maize samples collected at each field sampling interval. Grain from each of the seven treatments collected from each of the four farmers from each of the two EPAs (7 treatments x 4 replicates x 2 EPAs totalling 56 samples) were used for these germination tests. A total of 100 undamaged maize kernels were randomly picked from each sample treatment replicate collected. Cotton wool was placed inside waterproof petri dishes (Pyrex® United States of America, sizes 15 cm in circumference and 2.5 cm high) and the 100 grains were firmly embedded into the cotton wool (International Seed Testing Association, 2010). Water was added to moisten the cotton wool and over-watering was avoided to achieve normal germination. All petri dishes were incubated under ambient mean monthly temperature of 22 °C and 54 % RH for 7 to 10 days after which germinated and ungerminated kernels were separated and counted to calculate the percentage of germinated kernels for each sample treatment replicate.

2.6. Data analyses

Data on insect damaged grains, weight loss, number of insect pests by species, and grain moisture content were initially analysed using descriptive statistics. Statistical analysis was then carried out on percentage damaged grain, percentage grain weight loss, total insect pests (live and dead) per species per kg of grain, and total *P. truncatus, Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) per kg of grain using R version 3.5.1 (R Core Team, 2018) to test for significant differences among treatments at each EPA. As data were not normally distributed, data for each storage season were subjected to non-parametric Kruskal-Wallis chi-squared analyses followed by Mann-Whitney multiple comparison test at 5 % after significant differences were found. The data from both sites (Dwale and Livunzu EPAs) were combined after preliminary analysis showed no significant differences between the sites. The data were split into the early storage stages (week 8 and 16) and the late storage stages (week 24 and 32) as differences between treatments typically become more pronounced during the later stages of storage as grain damage increases. Box and whisker plots were created and the compact letter display generated during the Mann Whitney multiple comparison tests of the median values of each pair of treatments, was added to these plots to show which treatments were significantly different from each other at ($p < 0.05$). Percentage grain germination data were subjected to one-way ANOVA in Statistical Package for Social Scientists (SPSS) version 19.0 (Gamble 2001). Tukey's test at 95 % probability was used for post-hoc multiple comparisons where significant treatment differences were observed.

3. Results

3.1. Insect grain damage during the 2014/2015 storage season

In 2014/2015 storage season, the percentage of insect damaged grains at trial set-up ranged from 1.4 to 3.4 %. By 8 weeks storage, less than 12.6 % of grains were insect damaged in all treatments in both Dwale and Livunzu EPAs (Figs. 1a and b). Insect damage in the Neem and PP treatments had increased rapidly to above 30 % in both EPAs by 16 weeks storage (Figs. 1a and b). The increase in insect damaged grains continued and by 32 weeks storage was highest in the NM treatment which experienced mean levels of 92.1 % and 72.6 % at Dwale and Livunzu EPAs, respectively (Figs. 1a and b). The hermetic storage facilities (MS, PICS and SGB) kept grain damage low throughout the 32 weeks storage with mean grain damage levels of 19.3 %, 3.6 % and 5.3 % occurring in the treatments in Dwale EPA, respectively, and 29.8 %, 8.6 % and 19.2 % in Livunzu EPA (Figs. 1a and b). Some rodent and termite damage of the outer woven polypropylene bags for treatments ASD, PP, PICS and SGB was observed at three of the eight participating farmers; two in Dwale and one in Livunzu EPAs at week 16 during the 2014/2015 season.

When the 2014/2015 data were combined across sites (Dwale and Livunzu EPAs), during the early stages of storage (8 and 16 weeks storage), there was already a statistically significant difference in insect damage between treatments (Kruskal-Wallis Chi-squared = 58.397, 6df, $p < 0.001$) (Fig. 2). Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed insect damage was significantly ($p < 0.05$) higher in the NM and PP treatments than in all the other treatments. Insect damage was lowest (< 5 % damaged grain) in the hermetic (PICS, SGB) and the pesticide (ASD) treatments, but only the PICS hermetic bag treatment had kept insect damage statistically significantly lower ($p < 0.05$) than the MS and ZFB treatments as well as the NM and PP treatments at this early stage of storage (Fig 2a).

The difference in grain damage between treatments was still significantly different by the later stages of storage (24 and 32 weeks) (Kruskal-Wallis Chi-squared = 64.777, 6 df, $p < 0.001$). Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed damaged grain was significantly ($p < 0.05$) higher in the NM and PP treatments, 60.7 % and 47.8 %, respectively, than in the other treatments despite considerable variation between replicates of the MS, ZFB, ASD, PP, NM treatments (Fig. 2b). Grain damage was lowest (< 7 %) in the hermetic bag treatments (PICS and SGB), although only in the PICS bag treatment was grain damage statistically significantly lower ($p < 0.05$) than in the MS, ZFB, ASD, PP, NM treatments during these later stages of storage (24 and 32 weeks storage period).

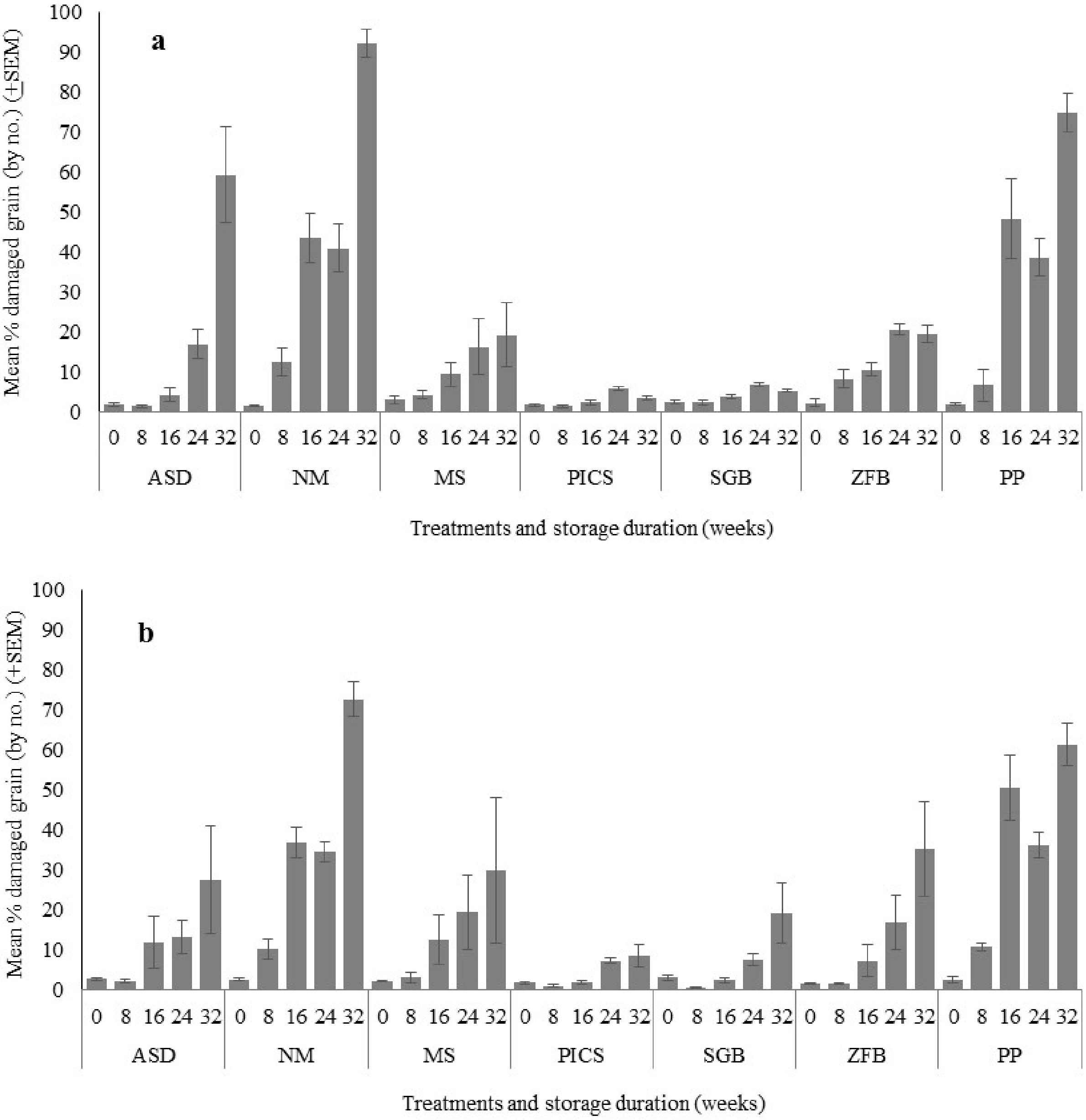


Fig 1. Mean percentage number of damaged grains (± SEM) recorded in different storage treatments during the 2014/2015 storage season in **a)** Dwale Extension Planning Area, Malawi (n = 4), and **b)** Livunzu Extension Planning Area, Malawi (n=4).

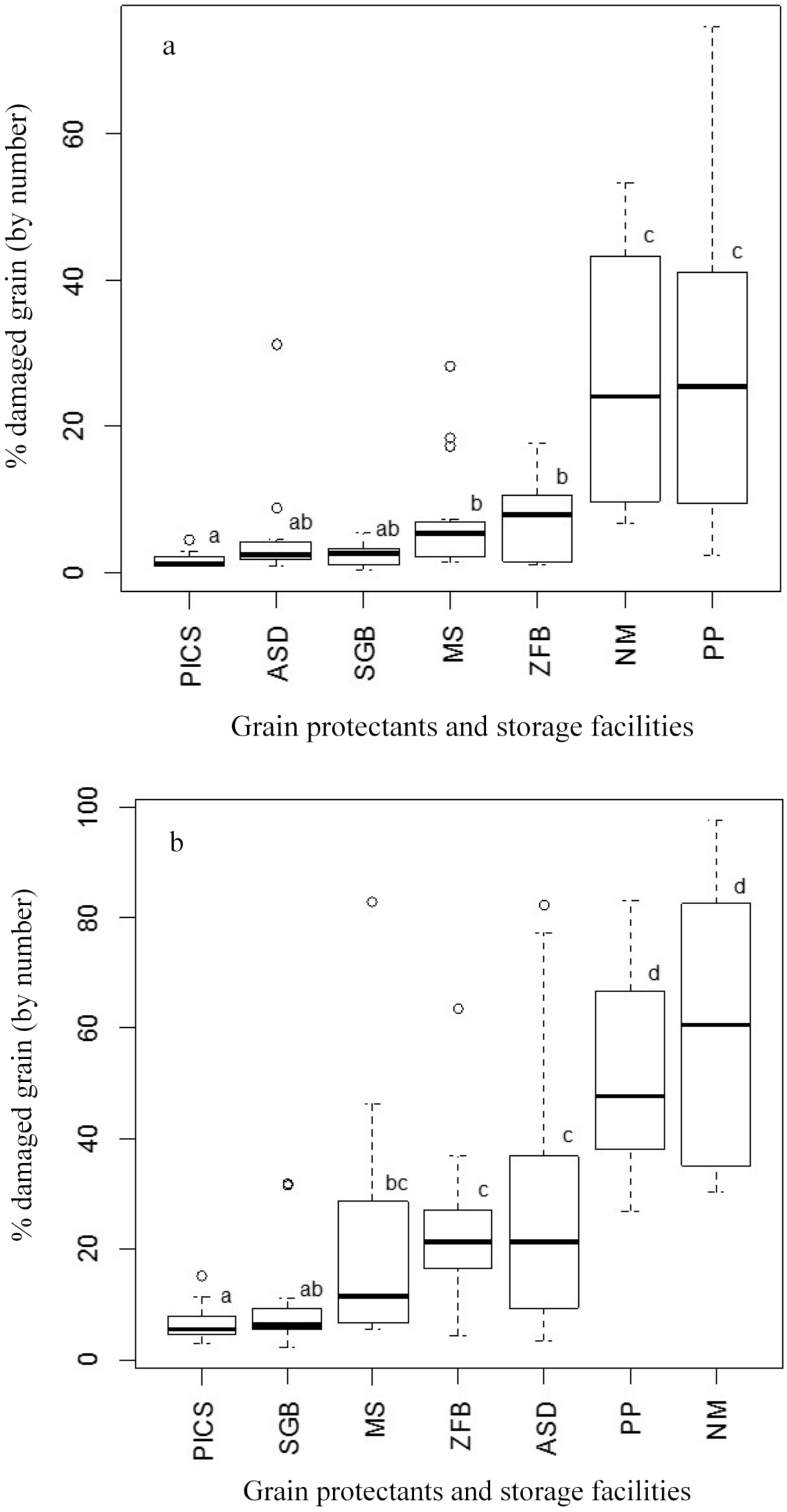


Fig. 2. Effect of different storage treatments on the mean percentage insect damage to stored maize grain, combining data from both Dwale and Livunzu Extension Planning Areas, Malawi in the 2014/15 season at **a)** the early stages of storage (8 and 16 weeks) (n = 16), and **b)** the later stages of storage (24 and 32 weeks) (n = 16).

3.2. Insect grain damage during the 2015/2016 storage season

At the start of the 2015/2016 storage season, mean grain damage was less than 1 % in all the treatments in both Dwale and Livunzu EPAs (Figs. 3a and b). Mean grain damage was lower in this second season (2015/16) than in the first season (2014/15), remaining below 22.3 % in all treatments throughout the 32 weeks storage period (Figs. 3a and b). Damage remained lowest in the hermetic bag treatments (PICS, SGB) and the ZFB in both EPAs, at less than 2.0 % during the 32 weeks storage. However, grain damage was higher in the NM, MS, PP and ASD treatments than the PICS, SGB or ZFB, and there was a high variation between replicates.

When the 2015/16 data were combined across sites (Dwale and Livunzu EPAs) for the early stages of storage (8 and 16 weeks storage), despite the low damage levels there was still a significant difference in the mean percentage number of damaged grains between treatments (Kruskal-Wallis Chi-squared = 55.520, 6 df, $p < 0.001$). Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed grain damage was significantly ($p < 0.05$) higher in the NM and MS treatments than in SGB, ASD, PICS, ZFB treatments (Fig. 4a).

The difference in damage levels between treatments when data were combined across the two EPAs remained significant as the 2015/16 storage season progressed (24 and 32 weeks storage) (Kruskal-Wallis Chi-squared = 73.965, 6 df, $p < 0.001$). Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed grain damage was significantly ($p < 0.05$) higher in the MS, PP and NM treatments during this later stage of storage (week 24 and 32) than in all the other treatments (Fig. 4b). Damaged grain levels in the two hermetic bag treatments (SGB and PICS) and the ASD grain protectant were not significantly different, and similarly MS, NM and PP were not significantly different. However, insect damaged grain in the ZFB treatment was significantly different to damaged grain in MS, SGB, PP and NM treatments ($p < 0.05$) (Fig. 4b).

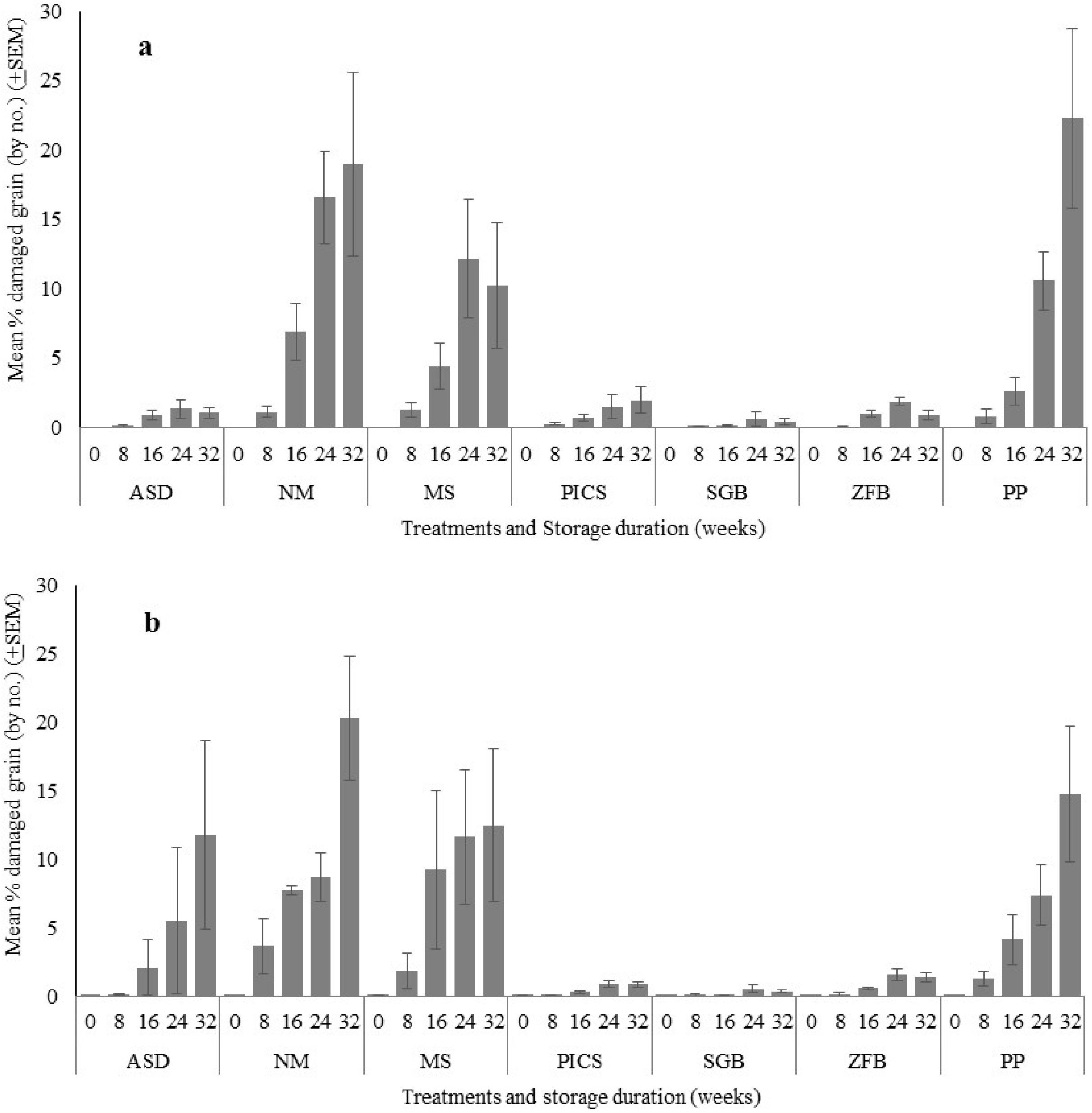
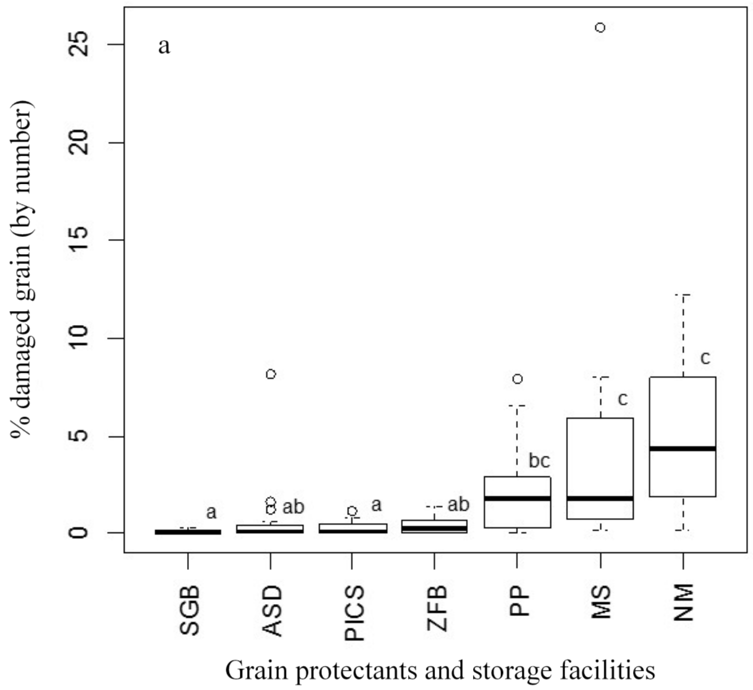


Fig. 3. Mean percentage number of damaged grains (+ SEM) recorded in different storage treatments during the 2015/2016 storage season in **a)** Dwale Extension Planning Area, Malawi (n=4), and **b)** Livunzu Extension Planning Area, Malawi (n=4).



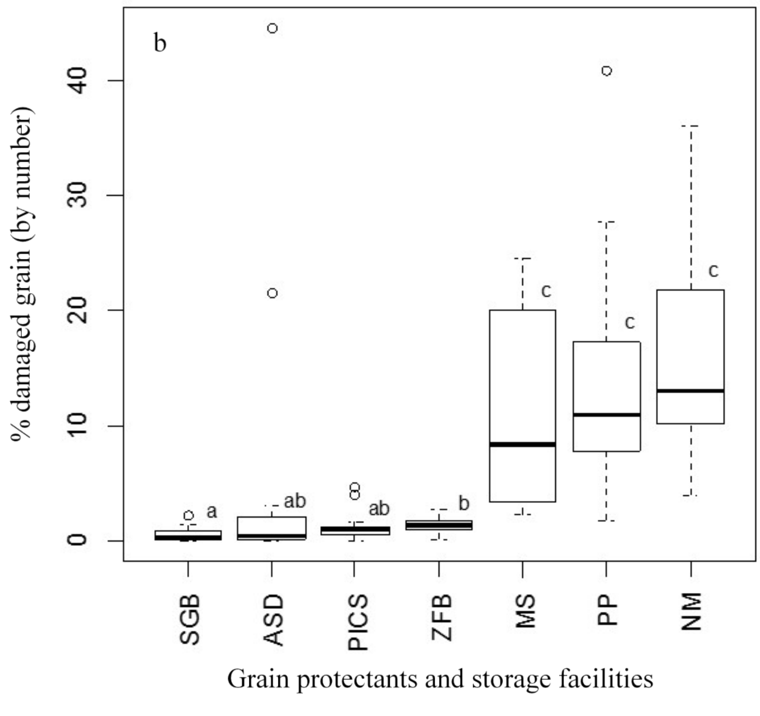


Fig. 4. Effect of different storage treatments on the mean percentage insect damage to stored maize grain, combining data from both Dwale and Livunzu Extension Planning Areas, Malawi in the 2015/16 season for **a)** the early stages of storage (8 and 16 weeks) (n = 16), and **b)** the later stages of storage (24 and 32 weeks) (n = 16).

3.3. Grain weight loss during the 2014/2015 storage season

During the first 24 weeks of storage in the 2014/15 season, the highest grain weight losses in Dwale and Livunzu EPAs were 4.6 % and 5.3 %, respectively, across all treatments (Fig. 5a and b). By week 32, mean grain weight losses had increased to 6.4 %, 17.4 % and 29.0 % in the ASD, PP and Neem treatments, respectively, in Dwale EPA, but remained between 0.1 and 2.1 % in the PICS, SGB, MS and ZFB treatments (Fig. 5a). In Livunzu EPA at 32 weeks storage, mean grain weight losses had increased to 7.2 %, 7.8 %, 11.5 % and 18.9 % in the ZFB, MS, PP and NM treatments, respectively, it remained below 3.5 % in the ASD treatments, and below 1.8 % in the PICS and SGB treatments (Fig. 5b).

Statistical analysis of percentage grain weight loss combining data from both EPAs for the early stages of storage (week 8 and 16) in the 2014/15 season confirmed the differences between treatments were statistically significant (Kruskal-Wallis Chi-squared = 42.719, 6 df, $p < 0.0001$). Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed that despite the low figures, grain weight loss was already significantly ($p < 0.05$) higher in PP, NM, ZFB, MS and ASD treatments than in the SGB, and that grain weight loss in the PICS bags was not significantly higher than in the SGB, but it was also not significantly lower than the ASD, MS and ZFB treatments at this stage (Fig. 6a). The difference in grain weight loss between treatments was still evident during the later stages of storage (week 24 and 32) in 2014/15 (Kruskal-Wallis Chi-squared = 52.876, 6 df, $p < 0.0001$). Mann-Whitney multiple comparison tests confirmed that grain weight loss in the hermetic bags (SGB, PICS) had remained significantly lower than in all the other treatments, grain weight loss was highest in the PP and NM treatments, but not statistically significantly higher than in the ASD and MS treatments ($p < 0.05$) (Fig. 6b).

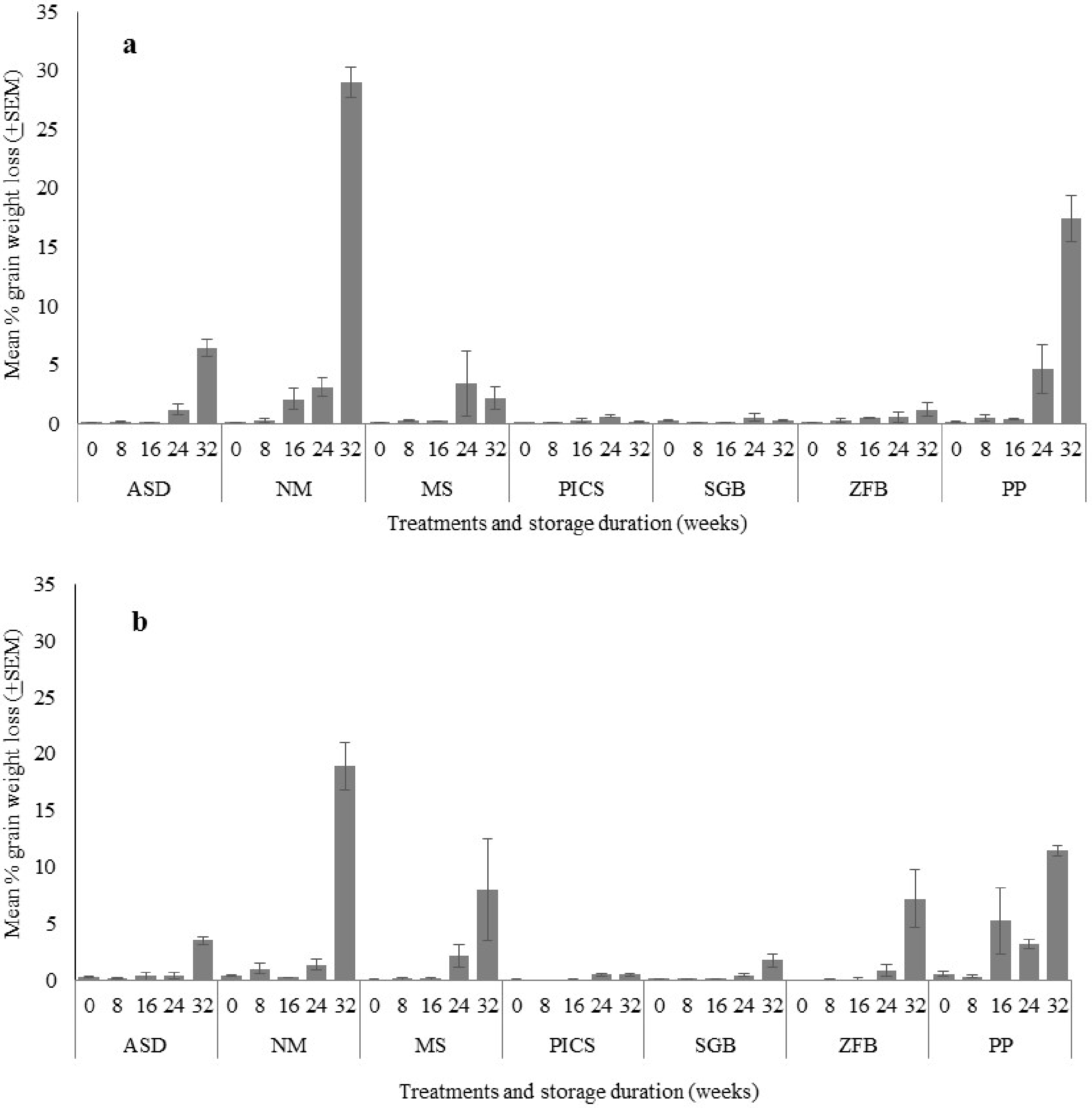


Fig. 5. Mean percent grain weight loss (± SEM) recorded in different grain storage treatments during the 2014/15 storage season in **a)** Dwale Extension Planning Area, Malawi (n = 4), and **b)** Livunzu Extension Planning Area, Malawi (n = 4).

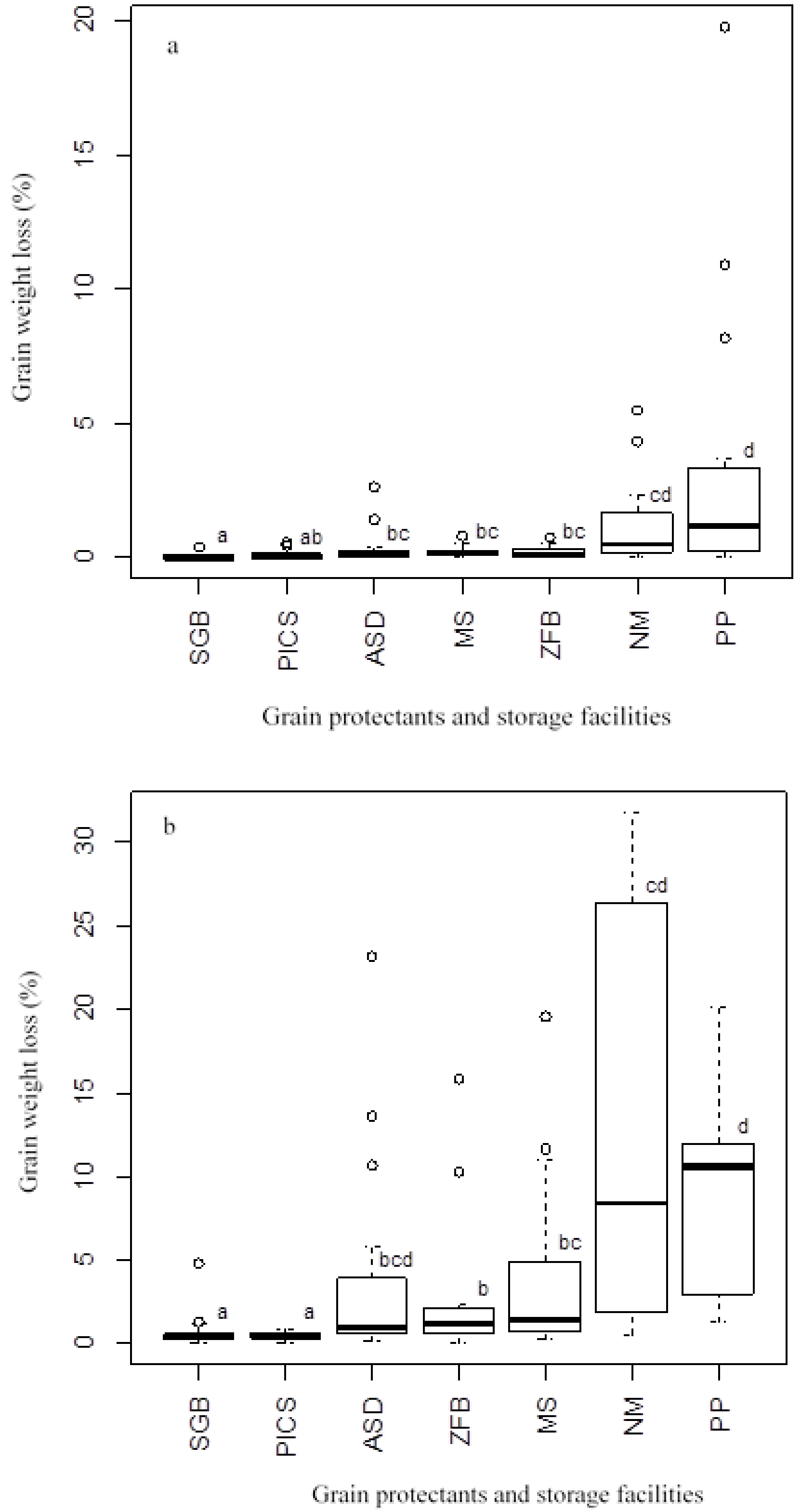
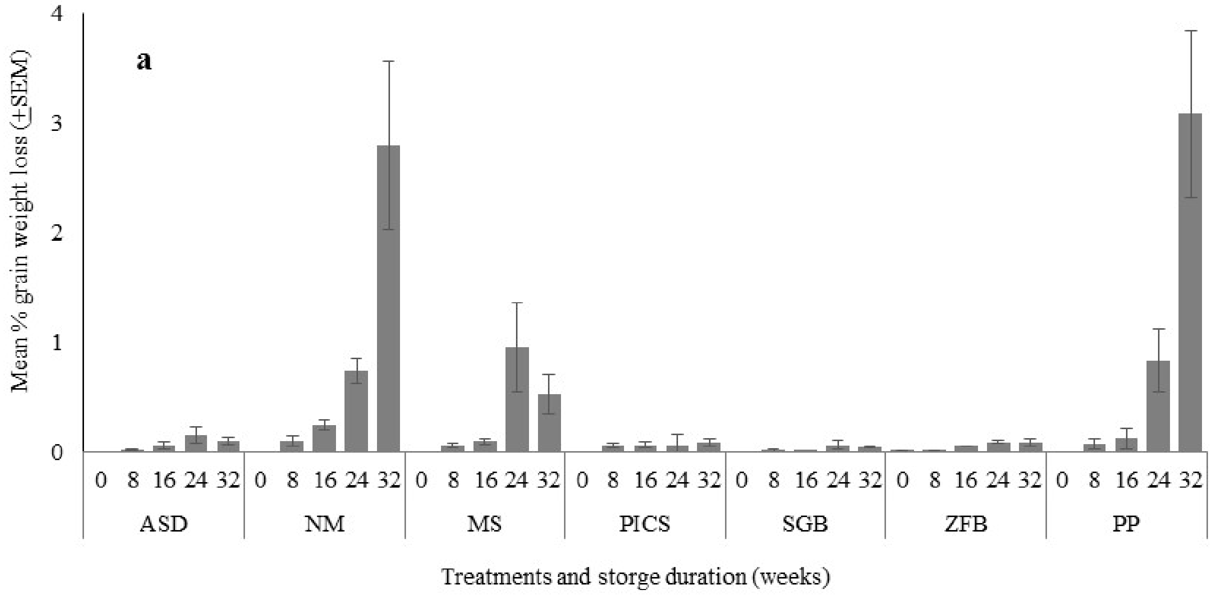


Fig. 6. Effect of different storage treatments on the mean grain weight loss to stored maize grain, season for **a)** the early stages of storage (8 and 16 weeks) (n = 16), and **b)** the later stages of storage (24 and 32 weeks) (n = 16).

3.4. Grain weight loss during the 2015/2016 storage season

In Dwale EPA in the 2015/16 season, grain weight loss remained low between 0 and 4 % from week 0 to 32 in all treatments, with the highest grain weight loss of 3.1 % being recorded in the PP treatment at week 32 (Fig. 7a). While in Livunzu EPA in the 2015/16, grain weight losses were also low at between 0 and 1.0 % in all the treatments up to 24 weeks storage, it then increased notably to 2.4 % and 2.8 % in NM and ASD treatments, respectively, by 32 weeks storage (Fig. 7b). All the hermetic storage facilities (MS, PICS, SGB) and the ZFB treatment kept grain weight losses below 0.9 % in Dwale EPA, and below 0.8 % in Livunzu EPA throughout the 32 weeks of the 2015/2016 storage season (Figs. 7a and b).

Combined percentage grain weight loss data from both EPAs for the early stages of storage (week 8 and 16) in the 2015/16 season showed significant differences between the treatments (Kruskal-Wallis Chi-squared = 36.465, 6 df, $p < 0.0001$). Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed that grain weight loss at 8 and 16 weeks was significantly ($p < 0.05$) higher in NM treatments than in all the other treatments except PP and MS, and that grain weight loss in the SGB and ZFB treatments was significantly lower than in the PP, MS and NM treatment but not significantly lower than in the ASD and PICS treatments (Fig. 8a). The difference in grain weight loss between treatments was still evident during the later stages of storage (week 24 and 32) in 2015/16 (Kruskal-Wallis Chi-squared = 60.936, 6 df, $p < 0.0001$). Mann-Whitney multiple comparison tests confirmed that the trends in treatment performance seen in the early stages of storage (week 8 and 16), remained at the later stages (week 24 and 32). Grain weight loss was significantly ($p < 0.05$) higher in the MS, NP and PP treatments than in the SGB, PICS, ASD and ZFB treatments (Fig. 8b).



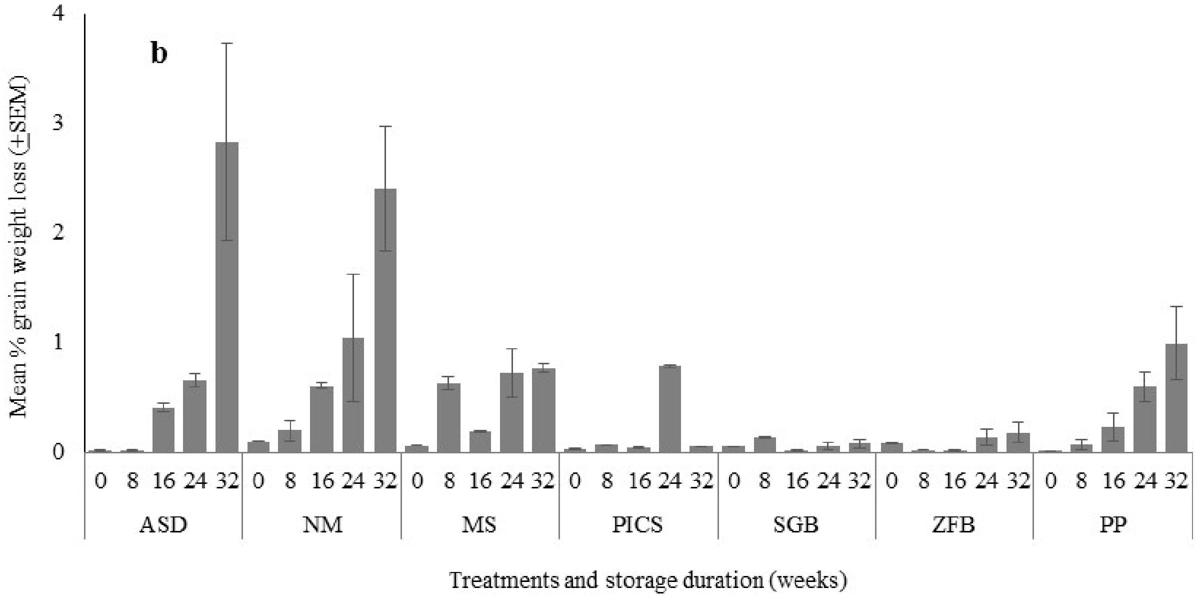


Fig. 7. Mean percent grain weight loss (± SEM) recorded in different grain storage treatments during the 2015/16 storage season in **a)** Dwale Extension Planning Area, Malawi (n = 4), and **b)** Livunzu Extension Planning Area, Malawi (n = 4).

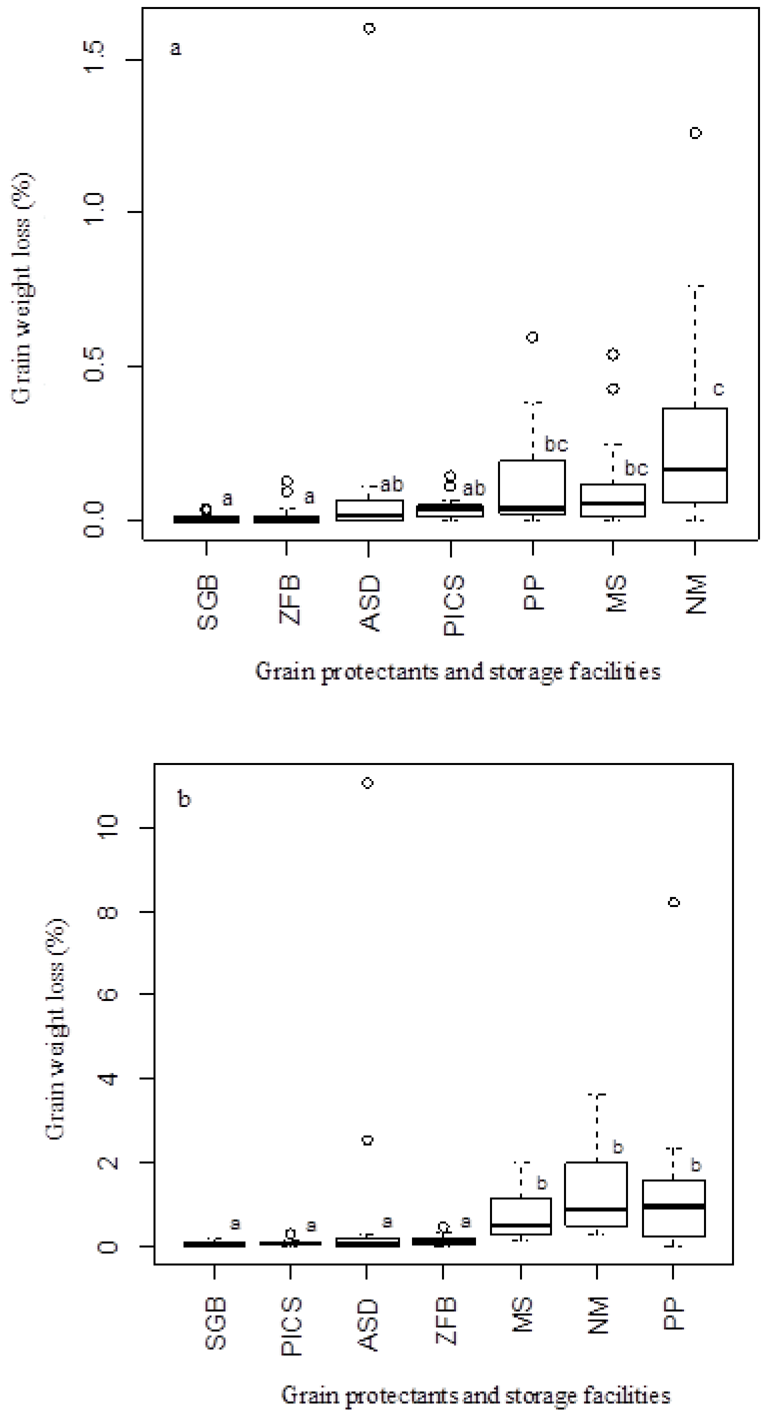


Fig. 8. Effect of different storage treatments on the mean grain weight loss to stored maize grain, combining data from both Dwale and Livunzu Extension Planning Areas, Malawi in the 2015/16 season for **a)** the early stages of storage (8 and 16 weeks) (n = 16), and **b)** the later stages of storage (24 and 32 weeks) (n = 16).

3.5. Storage insect pest population development during the 2014/2015 storage season

Four different insect pest species; *P. truncatus, S. zeamais, Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae) were recorded in the ASD, NM, PICS and PP treatments in Dwale and Livunzu EPAs by 32 weeks of storage in the 2014/15 storage season (Figs. 9a and b). *Sitophilus zeamais* was the only insect pest species recorded throughout the 32 weeks of the trial in all the treatments in both Dwale and Livunzu EPAs in 2014/15. *Sitotroga cerealella* was only recorded at 32 weeks of storage and only in the ASD, NM, PICS and PP, treatments in Dwale, and in the ASD, NM, PICS and SGB treatments in Livunzu EPA. Only low populations (< 4 insects per kg) of *P. truncatus* were recorded in the samples throughout the 2014/15 trial at both sites. At both sites at 32 weeks storage, insect numbers were lowest in the hermetic bag treatments (PICS and SGB). At 32 weeks storage during the 2014/2015 season, the inner liner bags of three out of the sixteen SGB and PICS bags had perforation holes which were likely made by *P. truncatus*.

Further analysis of the numbers per kg of the main primary pests *P. truncatus* and *S. zeamais* during the early stages of the trial in 2014/15 (combining data for week 8 and 16) showed that despite the low numbers of these pests, there was a statistically significant difference between treatments (Kruskal-Wallis Chi-squared = 15.047, 6 df, $p < 0.020$). However, when Mann-Whitney multiple comparison tests of the median values of each pair of treatments was used the differences between treatments were not found to be significant ($p < 0.05$).

By the later stages of storage (24 to 32 weeks storage) although mean numbers of these two pests per kg were still relatively low, there was a significant difference in number of *P. truncatus* and *S. zeamais* insects per kg of maize between treatments (Kruskal-Wallis Chi-squared = 25.734, 6 df, $p < 0.001$). Although Mann-Whitney multiple comparison tests of the median values of each pair of treatments confirmed that the number of *P. truncatus* and *S. zeamais* insects per kg of maize was significantly higher in the ZFB treatment than in MS and the PICS treatments ($p < 0.05$), neither group differed significantly to SGB, NM, PP, and ASD treatments (Fig 10).

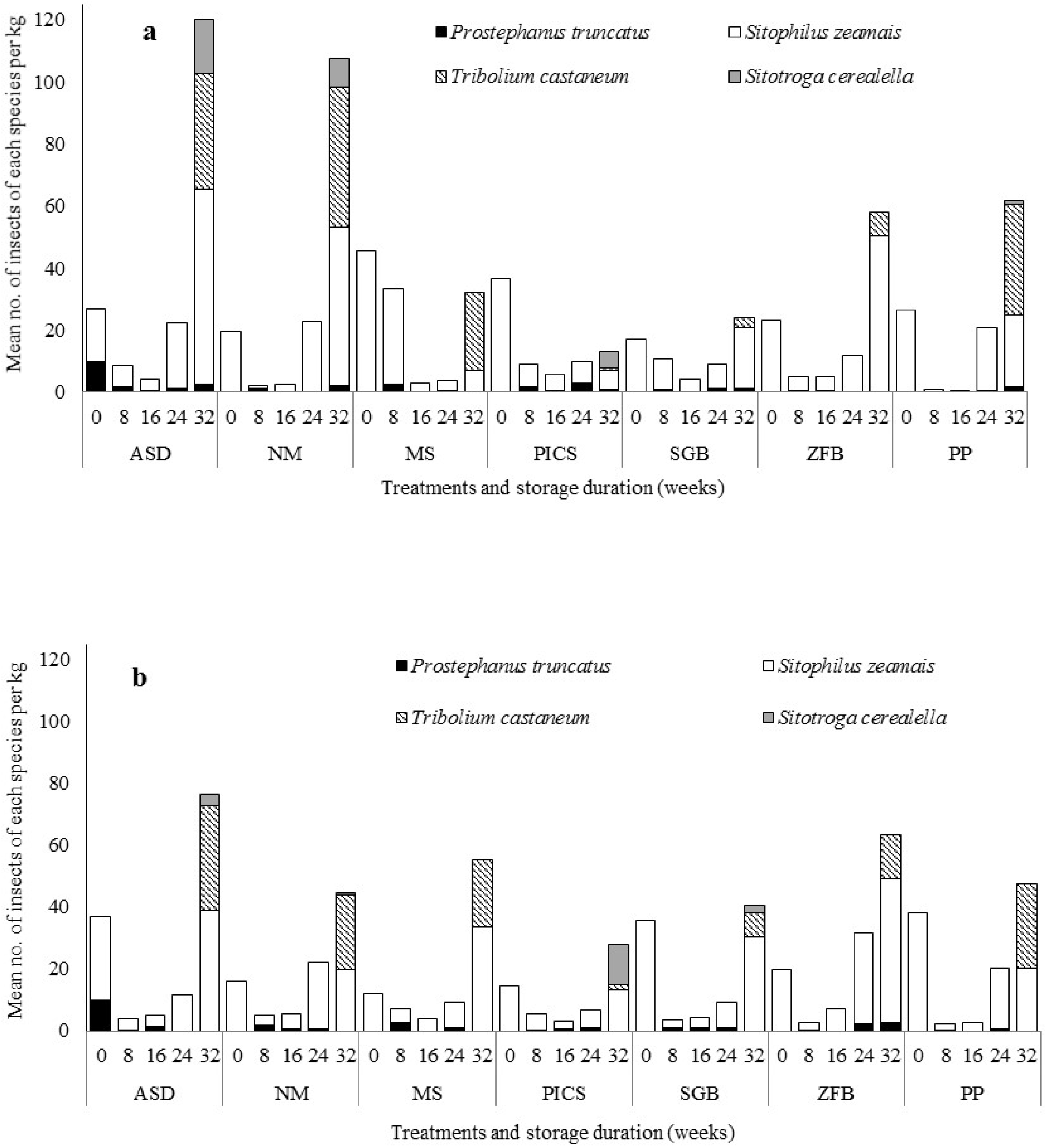


Fig. 9. Mean total insect pests per species per kg of maize grain in different storage treatments during the 2014/15 storage season in **a)** Dwale Extension Planning Area, Malawi (n=4), and **b)** Livunzu Extension Planning Area, Malawi (n = 4).

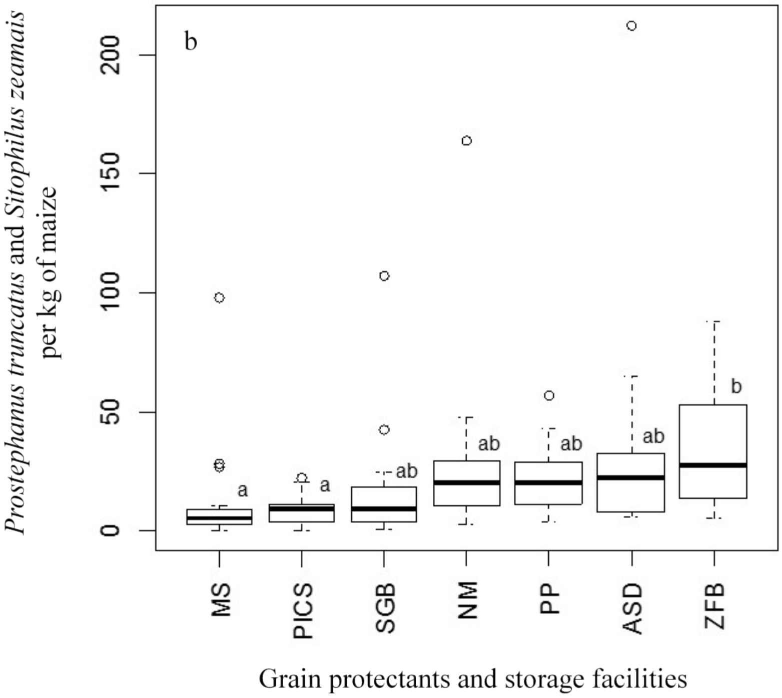


Fig. 10 Total number of *Prostephanus truncatus* and *Sitophilus zeamais* insects per kg of maize grain stored using different treatments in the late storage stages (week 24 and 32) of the 2014/15 storage season in Dwale and Livunzu Extension Planning Areas, Malawi (n = 16).

3.6. Storage insect pest population development during the 2015/2016 storage season

In the 2015/2016 storage season, five insect pest species were recorded (*P. truncatus, S. zeamais, T. castaneum, S. cerealella and Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae) in Dwale and Livunzu EPAs (Figs. 11a and b). *Cryptolestes ferrugineus* was not recorded in the 2014/15 trial, but was present in the ASD, NM, MS, SGB and PP treatments in Livunzu EPA in the 2015/16 trial, and in the MS and ZFB treatments in Dwale EPA.

During the 2015/16 trial in Dwale EPA, insect numbers remained low (< 19 insects per kg) in all treatments throughout the 32 weeks. *Tribolium castaneum* was the most common insect pest and recorded in the highest numbers in all the treatments from week 16 to 32 followed by *S. zeamais* (Fig. 11a). The lowest number of insect pests per kg of maize grain was recorded in the hermetic bag treatments, PICS and SGB. In Livunzu EPA in 2015/16, insect numbers remained below 20 insect per kg in all treatments except ASD in the later stages of the trial (Fig. 11b). The ASD treatment had a mean of 28 *P. truncatus,* 12 *T. castaneum* and 3 *S. zeamais* per kg by 32 weeks storage (Fig. 11b).

Further analysis of the combined data for the number per kg of the main primary pests *S. zeamais* and *P. truncatus* from both sites for the early storage stages (8 and 16 weeks storage) in 2015/16 found there was a statistically significant difference between treatments (Kruskal-Wallis Chi-squared = 13.654, 6 df, $p < 0.034$). However, the Mann-Whitney multiple comparison tests of the median values of each pair of treatments showed no significant difference between treatments at this early stage of storage.

Analysis of the combined data for the number per kg of the main primary pests *S. zeamais* and *P. truncatus* from both sites for the later storage stages (24 and 32 weeks storage) found no significant difference between treatments (Kruskal-Wallis Chi-squared = 5.685, 6 df, $p < 0.459$). This absence of significant difference was confirmed by Mann-Whitney multiple comparison tests of the median values of each pair of treatments. There was high variability between replicates in the ASD treatment.

3.7. Grain germination

Grain germination was high (>75 %) in the undamaged grains stored in the ASD, ZFB and PP treatments in both EPAs, but lower in the NM treatment at (53.5 - 57.8 %), and even lower (< 20 %) for the hermetic treatments (MS, PICS, SGB) in both Dwale and Livunzu EPAs after 40 weeks of storage in the 2015/16 season (Fig. 12). In both Dwale and Livunzu EPA, percentage germination (< 10 %) of undamaged grains from the hermetic bags (PICS, SGB) was statistically significantly ($p < 0.05$) lower than in all the other non-hermetic treatments tested (ASD, NM, ZFB, PP). None of the grain collected from the MS in Dwale EPA germinated, while in Livunzu 14.3 % germinated from the MS and although lower, this was not significantly lower than in the NM treatment.

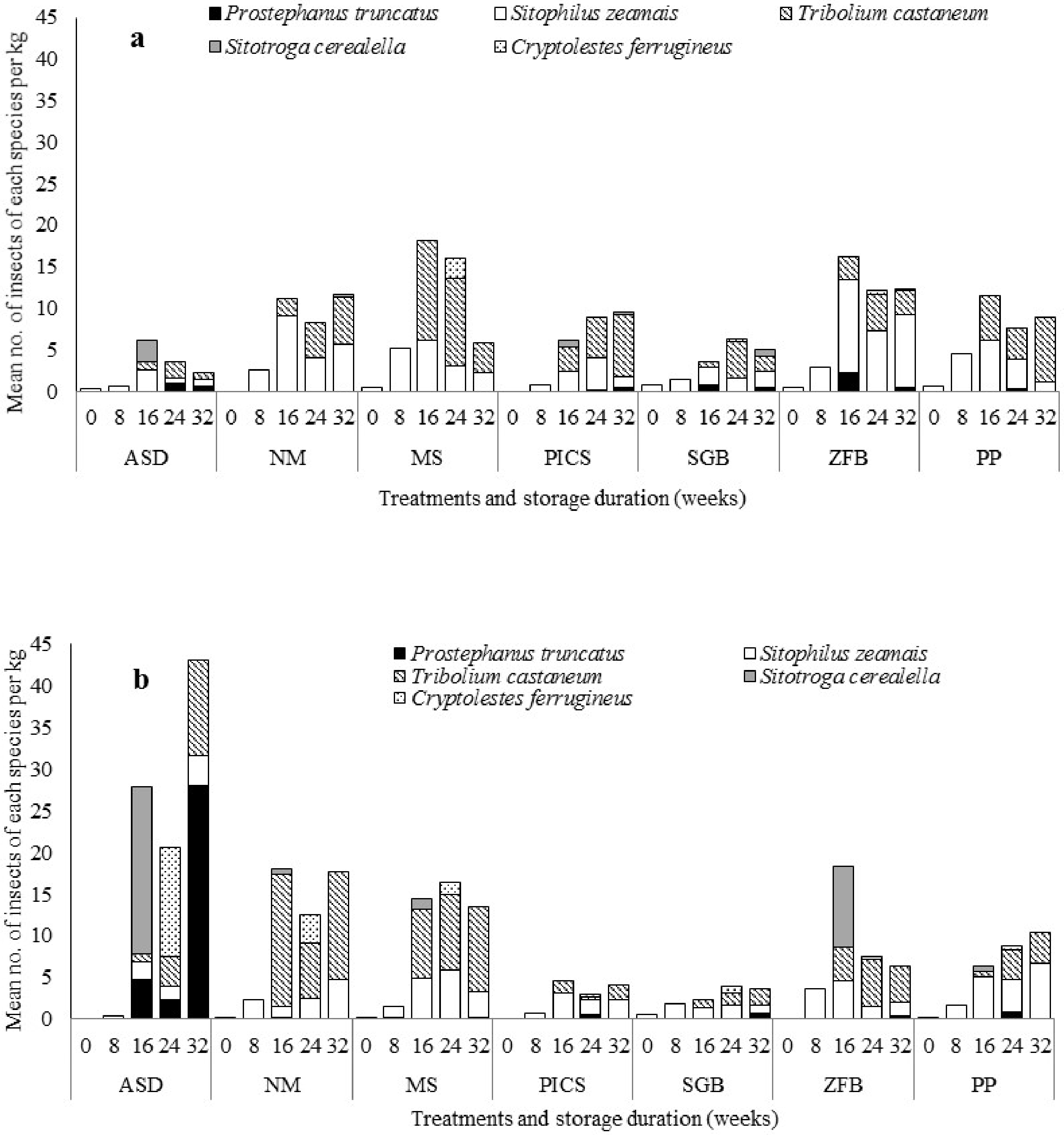


Fig. 11. Mean total insects of each species per kg of maize grain in different grain storage treatments during the 2015/16 storage season in **a)** Dwale Extension Planning Area, Malawi (n = 4), and **b)** Livunzu Extension Planning Area, Malawi (n = 4).

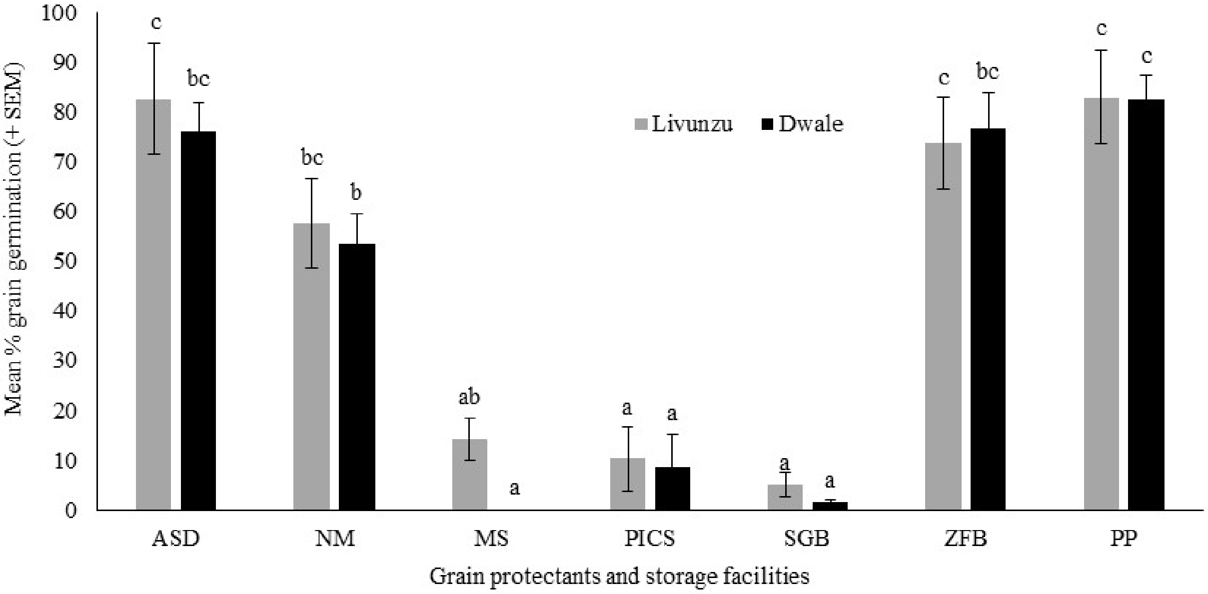


Fig. 12. Mean percent germination (± SEM) of undamaged grains stored using different treatments for 40 weeks during the 2015/16 storage season in Dwale and Livunzu Extension Planning Areas (n = 4).

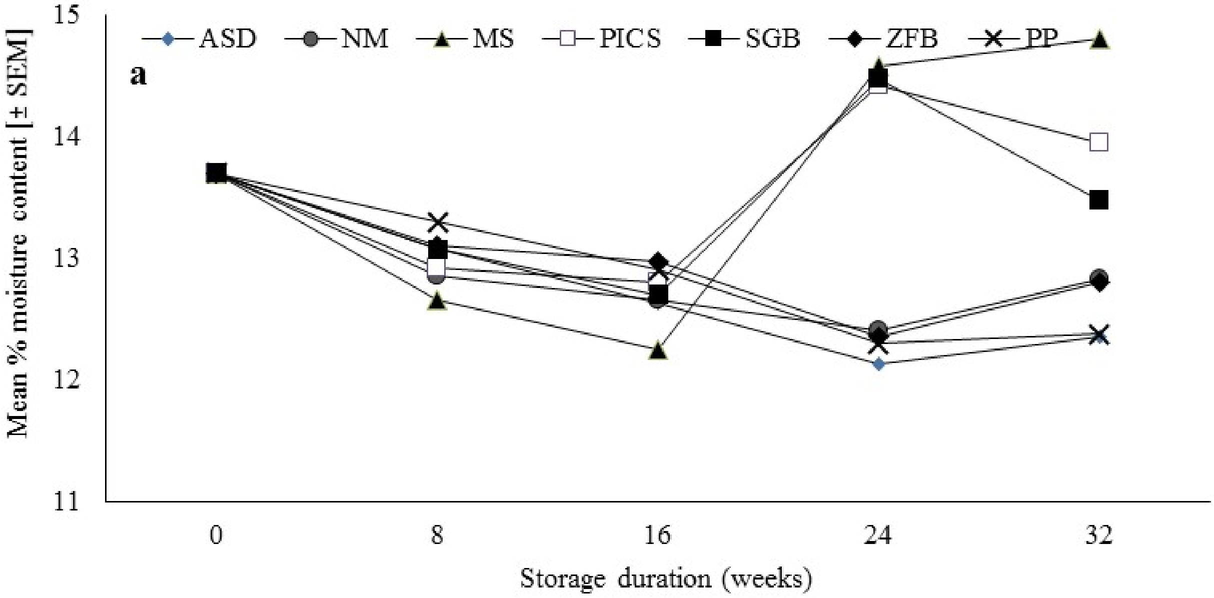
3.8. Grain moisture content, temperature and relative humidity conditions inside the grain store

In Dwale EPA, the mean MC of grain stored in the PP treatment decreased from 13.7 % at week 0 to 12.3 % by week 24 during the 2015/16 storage season (Fig. 13a). Although prior to transportation of the grain to the trial site the mean grain MC was 13.4 %, this had increased to 13.7 % by the day when the trial was set up. The lowest grain MC recorded during the trial in 2015/16 was 12.1 % and was from the ASD treatment at 24 weeks storage. Among the hermetic storage facilities (PICS, SGB, MS) the lowest mean grain MC of 12.3 % was recorded from the MS at week 16, but by week 32 mean grain MC in the MS treatment was 14.8 % (Fig. 13a). While in the non-hermetic storage facilities (ASD, NM, ZFB and PP) the lowest grain MC recorded was 12.1 % in NM at week 24 during the 2015/2016 storage season (Fig. 13a).

In Livunzu EPA during the 2015/16 storage season, the highest mean grain MC of 15.2 % was recorded at week 24 from the MS treatments (Fig. 13b). While the overall lowest mean grain MC of 12.3 % occurred in the ASD treatments at week 24. After 16 weeks storage, the mean grain MC of the hermetic treatments (MS, PICS, SGB) increased to above 14.7 % for the remainder of the trial, while the mean grain MC amongst the non-hermetic treatments (ASD, NM, PP and ZFB) dropped to <12.5 % at week 24 and then increased slightly, but remained below 13.5 % (Fig. 13b).

In Dwale EPA, the mean weekly temperature recorded inside the grain stores of the participating farmers ranged from 25.3 ^{o}C to 38.1 ^{o}C in 2015/16 while in Livunzu EPA, the mean weekly temperature ranged between 26.3 ^{o}C and 37 ^{o}C (Fig. 14a). The data highlight the fluctuation in mean weekly temperatures within the store rooms during the storage season. The ambient mean weekly temperatures in both EPAs were lower than the temperatures recorded inside the farmers stores from week 15 to 32.

The lowest mean weekly RHs recorded in the stores of the participating farmers were 36.9 % (at week 15) and 40.3 % (at week 17) in Dwale and Livunzu EPAs, respectively, during the 2015/2016 storage season. The highest mean weekly RHs recorded were 69.3 % and 70.6 % which both occurred during week 25 in Dwale and Livunzu EPAs, respectively, during the 2015/2016 storage season (Fig. 14b). The periods of low RH coincided with the periods of high temperatures at both sites.



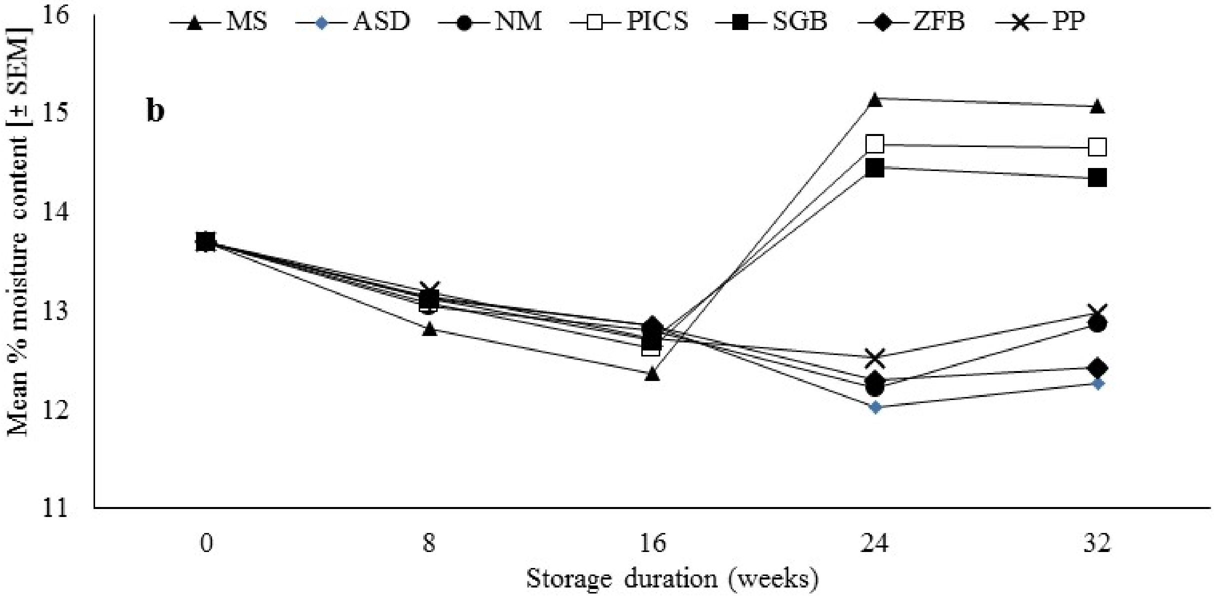


Fig. 13. Mean % grain moisture content (± SEM) recorded from different storage treatments during the 2015/2016 storage season in **a)** Dwale Extension Planning Area, Malawi (n = 4), and **b)** Livunzu Extension Planning Area, Malawi (n = 4).

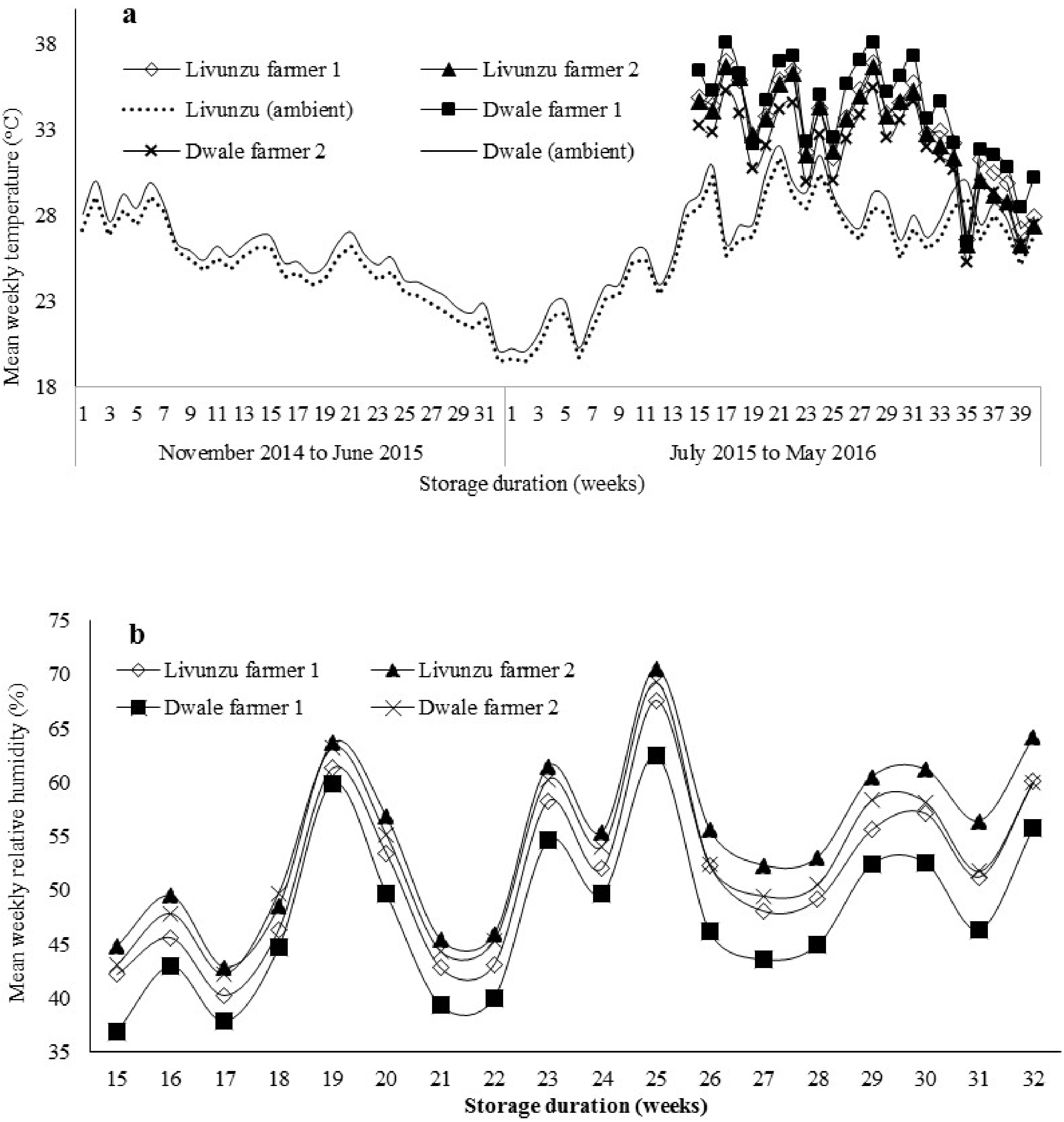


Fig. 14. Mean weekly data **(a)** Ambient temperature during the 2014/15 and 2015/16 storage seasons, and temperature inside four participating farmers' stores in Dwale and Livunzu Extension Planning Areas, Malawi during the 2015/2016 storage season from storage week 15 to 32 (*Ambient temperature data collected from Malawi Meteorological Office, Blantyre*); and **(b)** Relative humidity inside four participating farmers' stores in Dwale and Livunzu Extension Planning Areas, Malawi during the 2015/2016 storage season from storage week 15 to 32 (*Ambient relative humidity data were not available)*.

Discussion

The hermetic PICS and SGB bags were the most effective of the seven storage facilities that were tested in terms of suppressing insect grain damage and subsequent grain weight losses throughout the two storage seasons. These results confirm those of recent studies in other African countries in which hermetic storage bags successfully protected smallholders maize grain during storage (Bauoa et al., 2014; Mlambo et al., 2017; Abass et al., 2018). In Zimbabwe, hermetic storage facilities (PICS bags, SGBs and metal silos) outperformed a range of different botanical and synthetic chemical grain protection pesticides and the ZFB bags during storage periods of at least 8 months (Mlambo et al., 2017). In thirteen sites across Benin, Burkina Faso and Ghana, trials comparing the storage of untreated maize grain in hermetic PICS bags versus the commonly-used woven polypropylene bags found that percentage insect grain damage did not increase in the PICS bags during the 6.5 months but suffered a 6-fold increase on average in the polypropylene bags (Bauoa et al., 2014).

Laboratory studies in Kenya in which maize grain was artificially infested with *P. truncatus* and stored separately in PICS and woven polypropylene bags recorded 2.3 % and 47.7 % grain weight losses, respectively, within a 6 months storage period (Njoroge et al., 2014). However, in the current study, despite the efficacy of the hermetic bags, three out of the sixteen SGB and PICS bags used were perforated by *P. truncatus* by 24 or 32 weeks storage. Similar observations were made by Mlambo et al. (2017) in the Zimbabwean maize storage trials. These perforations caused loss of hermeticity of the SGB and PICS bags, and enabled insect pests to access and damage the stored grain. In another study, PICS bags containing artificially infested cassava chips recorded very high numbers of perforations on the inner plastic liner bags (1913 ± 114 holes per bag) by *P. truncatus* within eight months storage period (Hell et al., 2014). The large air spaces between the cassava chips are thought to have provided oxygen for the insects to survive inside the bags and subsequently perforate them (Hell et al., 2014). The laboratory studies in Kenya indicated that the use of PICS bags slowed the growth rate of *P. truncatus* populations and prevented grain infestation by stored insect pests from the surrounding storage environment (Njoroge et al., 2014). Low *P. truncatus* populations observed in PICS treatments up to 32 weeks of storage in the current study concurs with the findings of studies in West Africa where PICS bag prevented cross-infestation by insect pests and slowed down insect population growth in comparison to maize grain stored in polypropylene bags (Baoua et al., 2014). The hermetic SGB bag was also reported to be effective against rice storage insect pests but not effective against *P. truncatus,* one of the major insect pests of stored maize (Ben et al., 2006).

Looseningof the rubber bands used for sealing the inlet and outlets of the MS was reported by three farmers on three occasions during the current study in both Dwale and Livunzu EPAs. This would reduce the gas-tightness and allow gaseous exchange to occur between the MS and the environment, thereby providing conditions suitable for insect development, grain damage and weight loss. The loosening could be ascribed to the excessive heat experienced in the Shire Valley. While other studies have shown that metal silos can effectively protect stored maize grains against storage insect pests (Tefera et al., 2011; Chigoverah et al., 2016; Mlambo et al., 2017), in the current study they were not as effective. In the current study, and in both storage seasons, the maize grain stored in the MS was more heavily damaged than that stored in the PICS and SGB hermetic bags and became discoloured, an observation attributed to the high temperatures experienced within the stores. While the efficacy of the MS varied between households, its overall low and variable efficacy for longer-term protection of stored maize grain suggests it would not be an appropriate technology to recommend for smallholder farmers in the Shire Valley circumstances.

The current study found the efficacy of ZFBs varied between years, and during the first storage season (2014/15) they were not effective in protecting grain from insect damage during storage. The grain in the current study was not fumigated prior to trial set-up and contained low numbers of insects even at the start of the study, which is a typical situation for smallholder farmers as grains are often infested while still in the field or during drying. Another study reported that ZFB effectively controlled storage insect pests of cereal grains, pulses and oilseeds (Baban and Bingham Zivanovic, 2014), but only when the grain was fumigated prior to being loaded into the bags as per the manufacturers recommendations. Based on the current study's findings of high grain damage in ZFB stored grain and insect perforation of the ZFB in 2014/2015, and similar findings in other field trials (Mlambo et al., 2017; Abbas et al., 2018) coupled with the manufacturer's recommendation that grain should be fumigated prior to storage in ZFBs, makes it an inappropriate technology to recommend for smallholder farmer use in Malawi in its current form. Use of storage fumigants by smallholder farmers in Malawi and other SSA countries is prohibited due to the associated high risks to human life emanating from the high toxicity of the pesticide. In the Tanzanian study, 40 % of maize grains were damaged in the ZFB treatment by 30 weeks storage despite the grain having been fumigated prior to loading

(Abass et al., 2018). High temperatures cause degradation of pesticide (Katagi, 2004; Rumbos et al., 2016), including deltamethrin which can be applied to grain or incorporated into woven polypropylene fabric such as in ZFBs. Other studies confirmed that extended periods of high temperatures during grain storage affect the performance of grain protectants, as the active ingredients degrade more rapidly (Afridi et al., 2001; Mubayiwa et al., 2018), and global warming projections would be expected to result in reduced performance of existing grain protectants.

The untreated control grain stored in the woven polypropylene bags (PP) suffered high levels of grain damage (up to 75.0 %) due to attack by *P. truncatus* and *S. zeamais*. The Neem (NM) treatment was not effective in controlling storage insect pest damage even up to 16 weeks of storage in either season at either site. The grain treated with neem leaves experienced high insect infestation levels of up to 92.1 % damaged grain during the two storage seasons mainly due to *P. truncatus* and *S. zeamais*, and often higher than the damage experienced in untreated (PP) grain. Similar results were reported by Kamanula et al. (2011) where neem leaves were not effective in controlling insect pests in stored maize, but neem seed oil was more effective. The neem tree is commonly found in Shire Valley. While the current practice of admixing dried neem leaves with maize grain was not effective and would be risky to recommend, farmers could benefit if practical strategies to improve the grain protection efficacy of this locally-available plant material were found.

The main insect pests of the stored grain were *P. truncatus*, *S. zeamais* and *T. castaneum.* The grain was not fumigated prior to the start of the trial, in order to mimic the normal situation experienced by smallholder farmers whereby infestation starts in the field before harvesting. Due to this, the grain had some initial infestation and damage even at the start of the study. However, by 32 weeks storage, insect pest-related grain weight loss reached a maximum of 29.0 %, this occurred in the NM treated grain. In the current study, there was high survival rate of *T. castaneum* in the MS and similar results were obtained in Zimbabwe where *T. castaneum* was a major pest in most of their grain protectant treatments between 24 and 40 weeks of storage (Mlambo et al., 2017). The survival of this insect species warrants further investigation.

An early study by Schulten and Westwood (1972) reported just 3 % maize grain weight loss in farmers' traditional granaries (woven basket from bamboos) in southern Malawi within a nine month storage period, which was much lower than in the current study. In the 1970s the majority of Malawian farmers stored their maize untreated and on the cob in traditional granaries, and the major storage insect pest was *S. zeamais* (Schulten and Westwood, 1972). During a further postharvest loss assessment study of farmers' stores in the 1978/79 storage season in Shire Valley, mean maize grain weight losses of 2–5 % occurred during a 10 month storage period (Golob 1981b). The much higher weight losses in the current study are likely due to a combination of factors. These include: (1) the presence of *P. truncatus,* the most destructive storage insect pest of maize, that was accidentally introduced into SSA including Malawi in the early 1990s and led to farmers starting to store shelled maize as opposed to cob maize following recommendations to shell and treat maize grain with pesticide in order to combat *P. truncatus* damage (Markham et al., 1991; Hodges, 1994; Paliani et al., 2001); (2) the introduction of hybrid maize varieties which tend to be more susceptible to storage insect pests (Giga and Mazarura, 1991); and (3) changes in climatic conditions and smallholder storage systems.

During the current study some of the woven polypropylene bags in the ASD, PP, ZFB, Neem, PICS and SGB treatments were partially damaged by rodents and termites at three of the participating farmers (two in Dwale and one in Livunzu) during 2014/2015. Only the MS treatment was unaffected by rodent or termite attack as it provides a physical protection barrier between the grain and the pests.

In the 2015/2016 storage season, germination rates of undamaged grains that had been stored in the hermetic storage facilities (MS, PICS and SGB) for 40 weeks were extremely low (<15 %) compared to that of the undamaged grains from the PP, ZFB, ASD (>75 %) and NM (53-58 %) treatments at both sites. Given the importance of seed viability to smallholder farmers in Malawi, who often retain part of their harvested local maize varieties as seed for the next planting, the potential impacts of these germination findings for smallholder long-term food security are concerning. They suggest that distinct recommendations for storage of grain for food versus storage for seed are required as hermetic storage bags are more widely promoted. However, our findings contrast starkly with those from storage trials in which the germination rates of maize grains (Baoua et al., 2014), and shelled and unshelled groundnuts (Baributsa et al., 2017) stored in PICS bags for over 6 months did not decrease significantly, while those of maize and groundnuts stored in woven PP bags for the same period of time reduced significantly. Although the reduced germination of the grains stored in the woven PP bags in the two afore-mentioned studies was also due to the seed-embryos of many of the grains having been damaged by storage insect pests, in the current study only non-insect damaged grains from all treatments were used in the germination tests. The low percentage germination of grain stored in the hermetic technologies in the current study, may have been caused by a combination of the high temperatures and hermetic conditions, and the 13.7 % grain MC at the start of the study which is slightly higher than the Malawian recommended 13.5 % safe storage grain MC for maize. A previous study of maize grain stored at high MC (14 % or 16 %) in hermetic storage facilities for 75 days, led to the germination rate of the 14 % MC grain decreasing from 84.3 % (day 0) to 58.3 % (day 75) while the germination rate of grain at 16 % MC decreased from 82.8 % (day 0) to 21 % (day 75) (Weinberg et al., 2008). A study in the USA using maize grain of 14 % MC found germination dropped from the initial 43 % to ~ 30 % during three months storage in PICS bags, but dropped even lower in the maize stored in PP bags (Lane and Woloshuk, 2017). In a recent study in central Tanzania using 12.5 % MC maize grain, the germination rate dropped from an initial 92 % to 70-81 % during 30 weeks of on-farm storage in hermetic facilities, but dropped significantly lower to 37 % in the untreated grain stored in PP bags (Abass et al., 2018). These findings highlight the importance of sufficient drying of grain prior to storage; a situation which may become more challenging for some farmers as unexpected rains become a more frequent occurrence in the changing climate (Stathers et al., 2013).

During the current trial, temperatures of over 56 ^{o}C were reached in one farmer's store room which could have contributed to the grain discolouration in one MS, death of the grain embryos and lower grain germination rates after 40 weeks storage during the 2015/2016, although the effect was not as severe in the non-hermetic storage technologies. The houses of the farmers in the two EPAs of the current study had low roofs, and few and very small windows which provided only minimal ventilation, while houses roofed with corrugated iron sheets had particularly high temperature recordings within the store rooms. Given the current trend for storing grain inside houses in PP bags as opposed to outside in stand-alone granaries (Singano et al., in prep.), greater awareness raising is warranted of the need to store grain in well-ventilated conditions and that the bags should not be in direct contact with the walls or floors of the house from which they might absorb moisture (Hodges and Stathers, 2012). Germination reductions of 70 % have been reported in mung bean seed stored at 68.1 ^{o}C (Purohit et al., 2013). Further research should investigate the temperature and RH patterns inside hermetic storage facilities (MS, PICS and SGB) when stored in smallholder farmers store rooms and germination rates should be assessed regularly throughout storage period.

The high temperatures in store rooms also influenced grain MC in the PICS, SGB and MS causing increased grain respiration rate and condensation of air due to airtightness and the decrease in temperature in the evenings. Furthermore, the condensation due to high temperatures within the MS, may also cause corrosion of the metal inside the MS and over-time render it unsuitable for grain storage. Grain MC increased in these treatments as the grain absorbed the moisture from the condensed air within the hermetic storage facilities. These results confirm those of several other recent studies where the grain moisture content of maize grain stored in hermetic bags and silos increased during long-term storage (Williams et al., 2014; Ng'ang'a et al., 2016; Abass et al., 2018). Another study reported that in grain stored at high MC (14 % and 16 %) in hermetic storage facilities, the grain MC increased by 0.8–1.7 % due to respiration of the grain before the depletion of the oxygen after 75 days of storage (Weinberg et al., 2008). In a study in the USA, the moisture content of maize grain stored in PICS bags increased from 14 % at set-up to 14.2–14.3 % after 3 months storage, while that stored in PP bags increased to 14.9–15.9 % (Lane and Woloshuk, 2017). However, in the current study the increase in temperature within the store room allowed the grain stored in ASD, Neem, PP and ZFB treatments to continue drying because of the air movement occurring through the open-weave of the polypropylene bags.

The expectation is that climate change, particularly the increase in temperature will affect the development of some storage insect pests such as *P. truncatus* (Subramanyam and Hagstrum, 1991). Laboratory modelling studies showed that increased temperature affects the biology of insects including storage insect pests, therefore global warming is likely to affect the insects (Cammell and Knight, 1992; Fleming and Volney, 1995). Expected effects of global warming on insect pests include changes in: the number of generations per year, population growth rate, dispersal and migration (Porter et al., 1991). According to Demissie and Rajamani (2014), temperature and RH ranges of 30–32 °C and 70–85 %, respectively, are the optimal conditions for larval development and survival of *S. cereallella.* The low populations of *S. cereallella* in the current study may be due to the high temperatures between 34.7 to 38.1 °C during an 8 week storage period experienced during the trial, although the high mobility of the adult moth and the fragility of its body during sampling of stored grain (Mvumi, 2001) and during sample sieving in the laboratory (personal experience) can result in the pest commonly being underscored in grain samples. Other researchers suggest the effect of increased temperature could be either positive or negative as the effect on insecticides will depend on the mode of action, target insect species, method of application and quantity of insecticide ingested or contacted (Johnson, 1990). Others suggest increased temperature or decreased relative humidity may lead to lower effectiveness of natural plant products and biopesticides (Sharma and Prabhakar, 2014). A study by Neven (2000) demonstrated that changes in temperature effected insects' metabolism but that insects showed some adaptability to thermally challenging environments.

In addition to the storage technology such as hermetic storage facilities, the multiplication of storage insect pests such as *P. truncatus* and *Sitophilus* spp. and their natural enemies are greatly affected by storage conditions (temperature and RH) where an increase or decrease in each of the two affects the multiplication and development rates of the pests (Lachenicht et al., 2010). It was observed that during the later stages of the study (24 and 32 weeks storage), the number per kg of the main primary pests *S. zeamais* and *P. truncatus* were similar between the treatments.

Various reports suggest that global warming is likely to affect populations of stored product insect pests such as *P. truncatus* (Stathers et al., 2013; Delcour *et al.,* 2014). The mean weekly temperature ranges recorded within the stores in the 2015/2016 season of the current study, were higher at 25.3 to 38.1 °C than the ambient temperatures of 25.1 to 32.1 °C. However, further studies are needed to determine how temperatures within the stored grain as opposed to the store room compare to ambient temperatures. During the current study, the mean ambient temperatures (Dwale 26.3 °C and Livunzu 25.5 °C) were very similar to the annual mean temperatures recorded in the last 10 to 20 years (Dwale 26.5 °C and Livunzu 25.7 °C) (Anon, 2015).

The presence of humid conditions during transportation and temporary storage prior to the setting up of the trials caused the increase in grain MC from the initial 13.4 % to 13.7 %. The current study has shown that storage of grain at above 13.5 % MC in hermetic storage facilities (PICS, MS and SGB) in Shire Valley area is possible for smallholder farmers under the current prevailing climatic conditions (temperature and RH) in the area. Woven polypropylene bags have sufficient openings to enable further drying of grain of 13.7 % MC to occur during storage if the ambient conditions are warm and dry, but this is not the case in hermetic storage facilities. Further research should investigate the temperature and RH patterns inside hermetic storage facilities (MS, PICS and SGB) throughout storage period when stored in smallholder farmers stores. The ZFB cannot be recommended for use by smallholder farmers in Malawi due to its poor efficacy unless used with fumigated grain, which is impractical as smallholder farmers are prohibited by law from fumigating their grain in Malawi and many other SSA countries.

In conclusion, the study showed that the hermetic storage bags (PICS and SGB) effectively kept insect damage low during up to 32 weeks of smallholder farmer-managed maize grain storage in the Shire Valley of Malawi, where mean weekly ambient temperatures were between 19.5 °C to 32.1 °C. The hermetic storage bags (PICS and SGB) were more effective than the other treatments in the trial which included metal silos, traditionally used neem leaf powder materials, Actellic Super dust pesticide, and the ZeroFly® storage bag under grain stores temperatures of between 25.3 °C to 38.1 °C.

However, the viability of the grain stored in the hermetic storage facilities (PICS, SGB and MS) was greatly reduced with grain germination rates dropping to below 15 % after 40 weeks storage, while germination remained above 75 % in the undamaged grains in the PP, ASD and ZFB treatments. The high temperatures during the trial and the slightly high grain MC of 13.7 % instead of 13.5 % at trial set-up may have negatively affected grain viability in the hermetic facilities, and the efficacy of the NM and ASD grain protectants. Given the prevailing storage conditions in Shire Valley and projected increasing temperatures, Neem leaf powder as currently used cannot be recommended to farmers in Shire Valley in protecting grain intended to be stored for more than 8 weeks, and ASD and ZFB should not be recommended for protecting grain to be stored for more than 16 weeks. The high ambient temperatures may have resulted in faster degradation of the active ingredients of the ASD, and the deltamethrin incorporated into the fabric of the ZFB polypropylene bags and possibly the neem powder. Additionally, the ZFB was developed to be used for storing fumigated grain. However, smallholder farmers rarely fumigate their grain and are not supposed to use fumigation unless they have undergone formally certified training. Therefore, in Shire Valley and elsewhere across SSA, farmers' grain often has some level of insect infestation even at the start of the storage season and these insects can feed and breed on grain inside the ZFB bags resulting in heavy damage.

Based on the current study, it is recommended that the two hermetic storage bags (PICS and SGB) are promoted to smallholder farmers for long-term maize storage for up to 32 weeks in Shire Valley and other climate change prone areas of SSA. These hermetic bags are also known to be effective for storage of maize grain in areas where mean store temperatures are below the 25-38 °C experienced in these trials. However, given that climate change projections suggest southern Africa will experience warmer mean temperatures and more variable rainfall amounts and timings, it is important that the efficacy of hermetic bags for smallholder farmer grain storage continues to be assessed over time, as higher storage temperatures combined with more risky grain drying situations may result in challenging conditions including the storage of higher MC grain, more rapid development of pest populations, and lower germination rates of stored grain, all of which would have serious negative impacts on short and long-term food security outcomes. Though use of retained seed for planting in the next season is common in Malawi, no data are currently available to support this as Government of Malawi is discouraging the practice in favour of hybrids.

Further investigation regarding the survival of *T. castaneum* in a MS, and their potential tolerance to low O_2 conditions are also warranted. If practical techniques for improving the grain protection efficacy of Neem are discovered, further work on this loally available plant material might be warranted but in the current trials admixed neem leaves were not effective in protecting stored grain. The promotion of effective grain storage technologies should be integrated into practical training on good postharvest management to help ensure postharvest grain losses are minimised and the quality of the grain is maintained.

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