Food Sec.
DOI 10.1007/s12571-016-0567-9

ORIGINAL PAPER

Low permeability triple-layer plastic bags prevent losses of maize caused by insects in rural on-farm stores

Jeremiah Ng'ang'a[1,2] · **Christopher Mutungi**[2,3] · **Samuel M. Imathiu**[1] ·
Hippolyte Affognon[2,4]

Received: 19 August 2015 / Accepted: 9 March 2016

Abstract Participatory on-farm trials were conducted to assess effectiveness of Purdue Improved Crop Storage (PICS™) bags for storage of maize in small-scale farmers' stores in rural villages in eastern Kenya. A PICS bag is a three-layered hermetic bag-system that forms a barrier against the influx of oxygen and the escape of carbon dioxide. Jute, woven polypropylene or PICS bags were filled with shelled maize grain, purchased from the participating farmers, and the three sets of bags kept in the farmers' own stores for 35 weeks. Oxygen and carbon dioxide levels in the PICS bags were monitored, as well as the temperature and relative humidity in all the bags. Grain moisture, live insect population, grain damage and weight loss were examined at intervals of seven weeks. Oxygen and carbon dioxide composition demonstrated that PICS bags are capable of sustaining good air-barrier properties under farmer storage conditions. Moreover, moisture content of maize stored in PICS bags did not change throughout the storage period whereas the moisture content of maize stored in polypropylene and jute bags decreased significantly in the final 14 weeks. Maize stored in PICS bags remained free from insect infestation and the weight loss due to insect damage was below 1 %. On the contrary, polypropylene and jute bags permitted profuse build-up of insect populations. At 35 weeks, grain damage reached 77.6 % and 82.3 % corresponding to 41.2 % and 48.5 % weight loss in the polypropylene and jute bags respectively. These findings demonstrate that PICS bags are effective in controlling losses caused by storage pests under farmer storage conditions.

Keywords Maize · On-farm · Storage losses · Hermetic bags

Introduction

Maize (*Zea mays* L.) is one of the most important grain staples in Sub-Saharan Africa (SSA). The crop accounts for nearly 20 % of plant-based food supply (Abebe et al. 2009), and is a major source of calories and income for many households (Zia-Ur-Rehman 2006). Each year, however, enormous amounts of the harvested and stored grain are lost to insects during storage because control of these pests is still a challenge for many small-scale farmers, particularly in poorly managed stores. The destructive effects are aggravated by the lack of knowledge and appropriate, affordable and effective grain care technologies (Moreno-Martinez et al. 2000; Baributsa et al. 2014). Consequently, food and income security of many rural farmers, become tremendously diminished when stored volumes, quality, food value, and marketability of the grain is lost to insect feeding, damage and contamination (Affognon et al. 2015).

The larger grain borer (LGB), *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and the maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) are the main insects that attack stored maize (De Groote et al. 2013). Others include *Sitotroga cerealella* (Olivier), *Plodia interpunctella* (Hübner, [1813]), and *Rhyzopertha dominica*

✉ Hippolyte Affognon
h.affognon@cgiar.org

[1] Department of Food Science and Technology, Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000-00200, Nairobi, Kenya

[2] International Centre of Insect Physiology and Ecology, P.O. Box 30772-00100, Nairobi, Kenya

[3] Department of Dairy, Food Science and Technology, Egerton University, P.O. Box 536-20115, Egerton, Kenya

[4] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), BP 320 Bamako, Mali

(Fabricius) (Ortega 1987). *P. truncatus* is the most damaging pest for farm-stored maize and, in endemic situations, extensive grain damage results in over 30 % loss of dry weight after storage for only 3–6 months (Lamboni and Hell 2009; Mutambuki and Ngatia 2012). Such weight loss may be accompanied by heavy grain damage, which could render the grain totally unfit for human consumption (Njoroge et al. 2014). The maize weevil (*S. zeamais*) can cause 10–20 % weight loss after storage for 3–6 months and up to 80 % loss may occur if untreated maize is stored in traditional structures (Mutiro et al. 1992; Boxall 2002). To avoid losses caused by these insects, farmers opt to sell their maize shortly after harvest, the effect of which is the loss of opportunity to earn revenue at peak market prices. Other farmers apply synthetic insecticides as storage protectants but adequate protection is often not achieved (Meikle et al. 2002; Obeng-Ofori 2011). Moreover, the indiscriminate use of insecticides by some farmers might cause the insects to develop resistance (Subramanyam and Hagstrum 1996) and, in addition, bring about environmental and human health risks (Clevo and Clem 2001).

Hermetic storage technologies could offer farmers cost-effective alternatives for protection of stored maize against storage insect pests. The technologies rely on creation of modified atmospheres around the produce via physical, chemical or biological means to retard activity and survival of the insects that might be packed together with the grain (Anankware et al. 2012). Among these, bio-generated hermetic storage systems which achieve sub-normal oxygen levels by simply enclosing the produce in air-tight containers have received more attention because they are cheaper and safer (Murdock et al. 2003; De Groote et al. 2013). The metal silo, for instance, was developed as a valid and effective option for protecting stored grains in Central America and promoted in Asia and Africa (Tadele et al. 2011). In Kenya, however, Kimenju and De Groote (2010) reported that metal silos were not economically interesting if the capacity were smaller than 500 kg. Thus even though they demonstrated large impact on the welfare and food security of users, high initial cost became a disincentive to adoption especially for individual small farmers who store fewer than five 90 kg bags and whose opportunity cost of capital is high (Gitonga et al. 2013). On the other hand, the larger more cost effective silos would require communal ownership which is unpopular because many small-scale farmers still prefer to store their own produce, so as to retain greater control and flexibility in its marketing and use in the household (*World Bank* 2010).

Hermetic storage containers that have a capacity of about 90 kg or less, give individual small-scale farmers the flexibility and control that they desire. The Purdue Improved Crop Storage (PICS®) triple-layer hermetic storage bag is one such technology. The technology applies a two-layer envelope made of two 80 μm-thick high density polyethylene (HDPE) liners, one surrounded by the second, enclosed by a third bag made of woven polypropylene. The polyethylene inner liners have finite oxygen permeability which is sufficiently low that it greatly hinders oxygen leakage into the bag from surrounding air (Murdock et al. 2003). PICS bags were originally developed for preservation of cowpeas against cowpea weevil, *Callosobruchus maculatus* (Coleoptera: Chrysomelidae) in West Africa (Murdock et al. 2003). The two-layer HDPE assembly creates low air permeability so that when the bag is filled with grain and sealed, oxygen level drops whereas the carbon dioxide concentration increases as a result of insect, fungal, and seed respiration, causing the insects to die (Moreno-Martinez et al. 2000; Murdock et al. 2012).

In Eastern Africa, hermetic PICS bags were shown to successfully control *S. zeamais* and *P. truncatus* in artificially infested maize stored under laboratory conditions (Njoroge et al. 2014). Similar results were also reported by Edoh-Ognakossan et al. (2013) in Western Africa, although *P. truncatus* was found to make perforations in the HDPE liners. More recently, Baoua et al. (2014) conducted storage trials with traders, marketing cooperatives, private seed companies and private food processors in Benin, Burkina Faso and Ghana under natural infestation, and concluded that PICS bags could be used by these value-chain actors to safeguard against insect damage of the stored maize. Environment, however, might influence effectiveness of the hermetically sealed bags in controlling stored grain insect pests. It is therefore important to understand how the technology might perform in farm storage conditions where most harvested grain is stored, and where the conditions are diverse in terms of the storage structures and store management practices. The present study compared performances of PICS, woven polypropylene (PP) and jute bags in the protection of shelled maize against insect damage in farm stores of individual rural small-scale farmers.

Materials and methods

Trial site, timing, and selection of farmers

On-farm storage trials were conducted with individual farmers in 9 villages in Kibwezi (02° 23'S, 37° 57'E; 1036 m), Machinery (02° 54'S, 37° 28'E; 1004 m) and Makindu divisions (02° 18'S, 37° 50'E; 1019 m) in Makueni County, in Eastern Kenya. The trial site was selected for being a hot-spot for insect-induced storage losses. The region is generally semi-arid and experiences a bimodal rainfall pattern in which rains fall in March - April and November - December. Annual rainfall ranges between 200 and 700 mm, and day-time temperature ranges between 20 and 30 °C. Trials were conducted over a 35-week storage period beginning May 2014 to February 2015, and covered the typical maize storage cycle which spans 8–9 months starting shortly after the short rains harvest season. A total of 33 farmers (3–4 farmers in each village) who had a harvest of at least five 90 kg bags of maize, and who also expected to store part of it were recruited for the trial. A rapid appraisal using a semi-structured questionnaire was conducted to gather information on storage structures and storage challenges of the participating farmers.

Materials

Shelled maize grain harvested in the previous harvest season, and which had not been treated with insecticide was purchased in quantities of 100 kg from each participating farmer. Storage structures were voluntarily granted by the participating farmers in their own homesteads. Jute and woven polypropylene (PP) bags of 50 kg capacity were purchased from a dealer in Nyamakima market in Nairobi, Kenya. The PICS bags (50 kg) were supplied by Lela Agro Industries Limited, Kano, Nigeria.

Bagging, storage and sampling

Each 100 kg maize lot was sieved through a 2 mm aperture sieve to remove free insects, dirt and other debris, and then subdivided into three portions of 33 kg which were used to fill PICS, PP or jute bags. Before filling the PICS bags, air leakage was checked by inflating each of the two HDPE liners with air, and pressing between the hands while the open end was tightly twisted with one hand. Only PICS bags whose HDPE liners did not leak were used. An EL-USB-2 data logger (Lascar electronics Inc., Pennsylvania, USA), programmed to record data every hour, was placed in each of the treatments to record the temperature and relative humidity conditions during storage. Each bag was then shut firmly by twisting the open end, and fastening with sisal twine and placed on wooden planks in the farmers' stores. Another EL-USB-2 data logger was placed at a strategic open point outside the farm store of at least one farmer in each village to record the temperature, relative humidity and dew point of the locality.

Baseline sampling was done during experimental set ups (500 g) and subsequent sampling was done at seven-week intervals. Before opening the PICS bags, oxygen and carbon dioxide levels were measured using a portable Mocon Pac Check Model 325 oxygen/carbon dioxide analyzer (MOCON Inc., Minneapolis, USA). To take measurements, the inner HDPE liner was punctured with the analyzer needle at the top, middle and bottom. Holes were then sealed with self-adhesive tape. Subsequent measurements were performed from the same spot by lifting and replacing the tape. To obtain samples for examination of other parameters, the bags were briefly opened and a composite sample of about 500 g of maize from each treatment was drawn from five random points by pushing a two-inch diameter hollow tube sampler from the top of the bag. Each 500 g sample was mixed well and analyzed for moisture content. The sample was then subdivided into four 125 g sub-samples by quartering on a flat surface. One sub-sample was randomly selected for insect damage and weight loss determination, and another for live insect count.

Moisture content determination

A Dickey-John mini GAC® plus moisture tester (DICKEY-john Corporation, Illinois, USA) calibrated on the basis of U.S. federal standard grain calibration was used. About 400 g whole grain samples were placed in the tester cup, levelled off and the moisture content recorded.

Insect damage and weight loss

Sub-samples (125 g) were sieved through a 2 mm mesh kitchen sieve, and the dust-free grains were sorted into insect damaged and undamaged grains. Weight of undamaged grains (*Wu*), weight of insect damaged grains (*Wd*), number of undamaged grains (*Nu*), and number of insect damaged grains (*Nd*) were determined. Percent damage was calculated as $[Nd/(Nd + Nu)] \times 100$. Percentage weight loss was calculated by the count and weigh method using the expression: % weight loss = $ND(WU-WD)/(WU(NU + ND)) \times 100$ (Boxall 1986).

Live adult insect counts

Sub-samples (125 g) were first kept in a refrigerator maintained at 2 °C for 3 h to immobilize crawling insects. The damaged grains were further split open to remove any insects lodged within the grain. Insect counts were reported as the number of live adult *P. truncatus* or *S. zeamais* or *T. castaneum* per 125 g of grain.

Statistical analysis

Insect count data were $\log_e(x + 1)$-transformed while percentage data (grain damage, weight loss and moisture content) were arcsine square root (x/100)-transformed to normalize them, and then subjected to analysis of variance (ANOVA) using Stata SE version 12 (StataCorp LP, Texas, USA). Further, because of the inherent limitations of ANOVA in describing differences in progression of variables over time, the analysis of covariance (ANCOVA), which combines features of both ANOVA and regression, was also applied to test effects of treatment and storage duration, and the interaction effects. When the coefficient of the interaction term was significant ($P < 0.05$), it was concluded that there was a significant difference between treatments over the storage period. One-way ANOVA was performed where treatment outcomes at a specific point in storage time needed to be compared. Means were separated using Bonferroni adjustment at 95 % confidence level.

Results

Farmers maize production and customary storage structures and storage practices

The average maize production of participating farmers varied but was within the scale of smallholder producers. About half of the farmers (46.7 %) harvested 10–20 bags. Another 30 % harvested more than 20 bags while 23.3 % of the farmers harvested fewer than 10 bags. The quantity of grain reserved for storage for household consumption and other house uses varied as well. Two-thirds of the farmers (63.3 %) stored between 6 and 10 bags, 20 % stored fewer than 5 bags while 16.7 % stored more than 10 bags. Figure 1 summarizes key characteristics of the farmers involved in the storage experiment with respect to important maize storage practices. Slightly more than half of the farmers (53.3 %) harvested and stored traditional maize varieties (*kinyanya*) whereas 36.7 % of the farmers had pure improved varieties. A small proportion (10 %) harvested and stored both traditional and improved varieties. Most of the farmers (90 %) stored their maize as shelled grain while 10 % stored their maize as dehusked cobs as well as shelled grain. About three quarters of farmers (73.3 %) stored their maize grain mainly for household use for a period exceeding 7 months. Only a small proportion (26.7 %) of the farmers stored their maize for a period of less than 6 months. The majority of farmers (66.7 %), who stored shelled maize, packed the grain in woven polypropylene bags and placed the bags in granaries (*ikumbi*). A third of the farmers (33.3 %), however, preferred to store the bags in designated rooms in the living house. The granaries were mainly raised structures constructed using wooden slats or sisal stems with either grass thatch (traditional granaries, 42.1 %) or iron sheet roofing (improved cribs, 57.9 %). Some of the granaries, particularly the improved cribs, were fitted with rat guards (5.3 %) but many (94.7 %) were not, and the farmers used commercial baits or kept domestic cats for rodent control. The special rooms used for maize storage by the farmers were mainly brick wall rooms with concrete floor but farmers habitually installed raised wooden platforms on which the bags were laid. Most farmers (83.3 %) stored maize grain together with other commodities including cowpeas, pigeon peas and green gram in the same storage structure.

All farmers experienced losses during storage. Close to 60 % of the interviewed farmers attributed this loss to insect infestation, while 30 % of the farmers attributed it to both insects and rodents, and only 10 % of farmers attributed the losses to both insects and mold infections. In farmers own estimation, the losses amounted to 100–200 kg (about 1–2 bags; average losses 16.4 %) for farmers who stored 6–10 bags for home use. Higher losses of more than 200 kg were

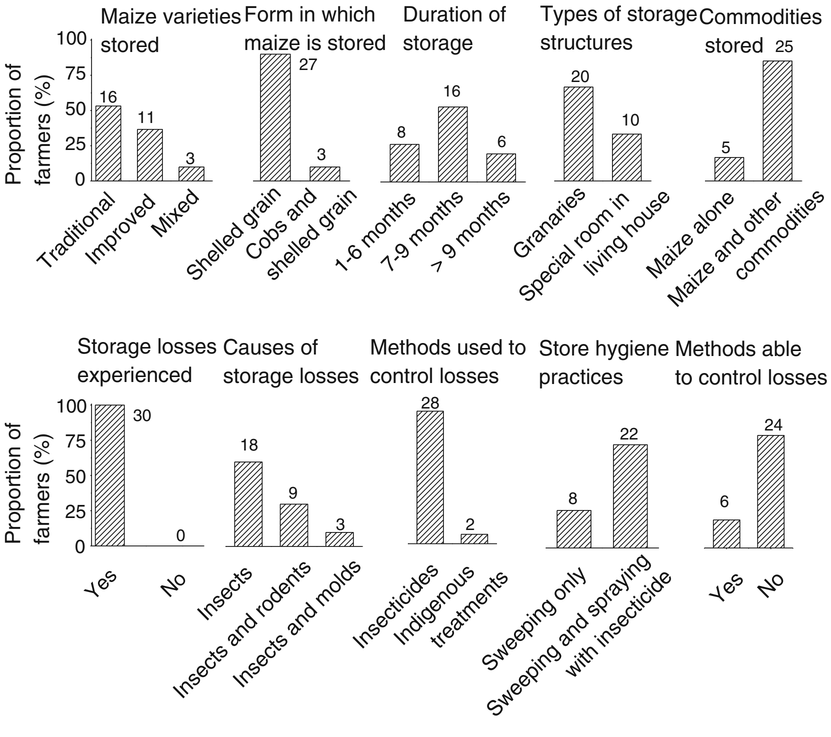


Fig. 1 Maize storage practices and experiences of farmers ($n = 30$) with on-farm storage losses in the trial site. The number of farmers associated with a practice or experience is indicated adjacent to the top of each bar

reported by farmers who stored more than 10 bags, particularly those selling at peak market prices (average losses 24.8 %), while for farmers who stored fewer than 5 bags, the losses were less than 100 kg (average loss 6.7 %). Almost all farmers (93.3 %) applied insecticides mainly Actellic Super® dust ((Pirimiphos methyl (1.6 g/100 g) + permethrin (0.3 g /100 g)) to control storage pests and losses whereas a few (6.7 %) used indigenous methods such as admixing with wood ashes. Farmers were also aware of good storage hygiene. All the farmers removed the old stock and cleaned their stores, and, in addition, three quarters of the farmers (73.3 %) sprayed the store and storage bags with insecticide before introducing newly harvested produce. With these efforts, however, many farmers (80 %) did not achieve effective control of storage losses.

Gas composition, temperature and relative humidity conditions

Figure 2 shows the mean oxygen and carbon dioxide concentrations in the PICS bags over the 35-week storage period. Initial oxygen and carbon dioxide concentrations determined immediately after closure of the bags were 20.5 ± 0.5 % (range: 20.5–20.7 %) and 0.2 ± 0.1 % (range: 0.2–0.3 %) respectively. Within the first 7 weeks of storage, oxygen levels dropped rapidly to 4.9 ± 0.3 % (range: 1.2–7.6 %). On the other hand carbon dioxide increased to 10.5 ± 0.5 % (range: 6.7–18.5 %) within the same storage period. During the rest of storage period, oxygen concentration increased gradually to 10.3 ± 0.3 % (range: 8.0–12.6 %). Carbon dioxide on the other hand had minimal changes throughout the storage period and almost stabilized at 10.6 ± 0.6 % (range: 4.9–15.9 %) at 35 weeks.

The atmospheric temperature, relative humidity and dew point conditions taken every hour in the study sites are given in Fig. 3. Profiles of these parameters in the three types of storage bags during the course of storage are also shown. The mean atmospheric temperature, relative humidity and dew point at the study site were 23.9 ± 3.2 °C, 59.9 ± 11.1 %, and 15.9 ± 2.2 °C, respectively. These patterns, however, are characterized by wide ranges between 17.2–35.2 °C (temperature), 24.4–91.5 % (relative humidity) and 7.9–20.7 °C (dew point).

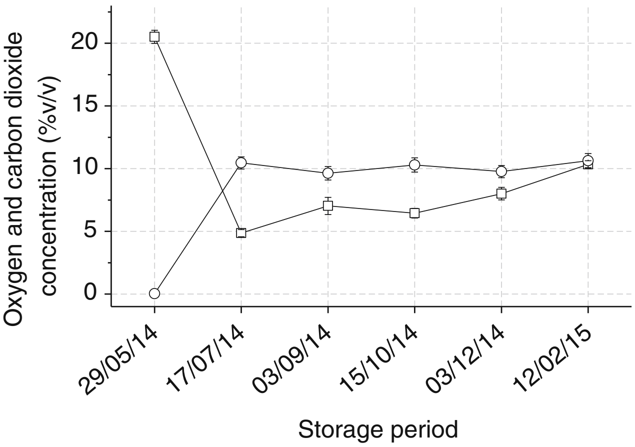


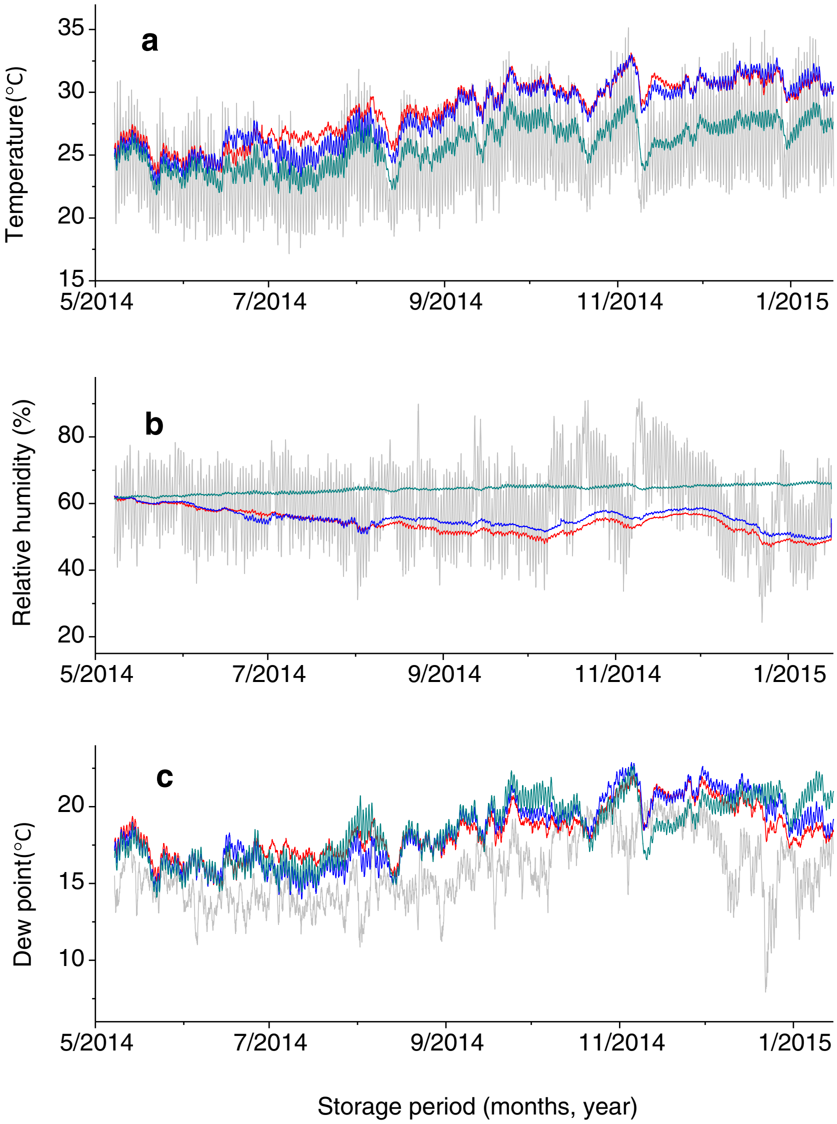
Fig. 2 Oxygen (□) and carbon dioxide (○) levels in PICS bags filled with maize grain and stored for 35 weeks. Plotted data are means ± standard errors of 26 replications, represented by 26 farmers participating in the storage trial

In the storage bags, temperature changed with the varying environmental temperature. Average temperature in the PICS bags ($n = 12$) was 25.7 ± 0.4 °C (range: 21.9–29.8 °C). On the other hand, temperature prevailing in PP ($n = 12$) and jute bags ($n = 12$) averaged 28.2 ± 0.5 °C (range: 22.7–33.0 °C) and 28.6 ± 0.6 °C (range: 23.5–33.2 °C), respectively. Whereas temperature in PICS bags remained significantly lower than in PP and jute bags ($F = 13.01$; $df = 2, 33$; $P = 0.001$), the temperature conditions prevailing in PP and jute bags did not differ significantly ($P = 1.0$). Overall, there was a general rising trend in temperature of the environment, and this, likewise, occurred in the three types of storage bags. Lowest temperatures were recorded in June - July, whereas highest temperatures were recorded in October - February. Atmospheric relative humidity also varied but did not change much except for a notable increase in October – December coinciding with the short rainy season experienced during this time of the year in the trial site. Fairly constant relative humidities were maintained in the PICS bags ($F = 0.58$; $df = 7, 88$; $P = 0.768$), and the levels varied from 57.9–76.4 % (mean 64.3 ± 1.8 %; $n = 12$) depending on the moisture content of the grains. Relative humidity in PICS bags remained significantly higher than in the PP and jute bags ($F = 27.03$; $df = 2, 33$; $P < 0.001$). The lower humidity levels prevailing in the PP and jute bags, however, did not differ significantly throughout the storage period and averaged 55.6 ± 1.1 % (range: 50.4–59.6 %; $n = 12$) and 54.2 ± 1.0 % (range: 49.7–59.4; $n = 12$), respectively.

Effect of type of storage bag on grain moisture content

The initial moisture content of maize grain varied from farmer to farmer and averaged 13.3 ± 0.2 % (range: 12.4–15.0 %) at the start of experiment. From analysis of covariance, moisture content depended significantly on the interaction effect between type of bag and storage period ($F = 6.03$; $df = 10, 522$; $P < 0.001$). Maize stored in PICS bags retained its moisture content throughout the storage period ($F = 0.25$; $df = 5, 174$; $P = 0.940$) at about 13.3 ± 0.1 % as shown in (Fig. 4). By contrast, moisture contents of maize stored in PP and jute bags started to decline from the 14th week, and reached levels that were significantly lower than in PICS bags from the 21st weeks of storage onwards ($F = 13.59$; $df = 2, 87$; $P < 0.001$). There was, however, no significant difference in the moisture contents of maize stored in PP and jute bags

Fig. 3 Temporal variations in temperature (**a**), relative humidity (**b**) and dew point (**c**) in the trial sites (grey), and in the storage bags: polypropylene bags (blue), jute bags (red) and PICS bag (green)



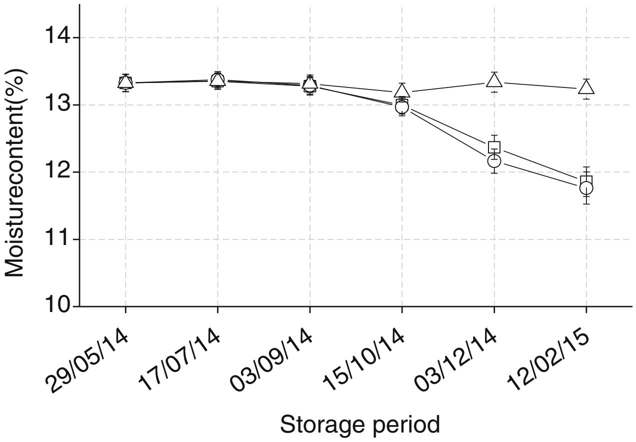


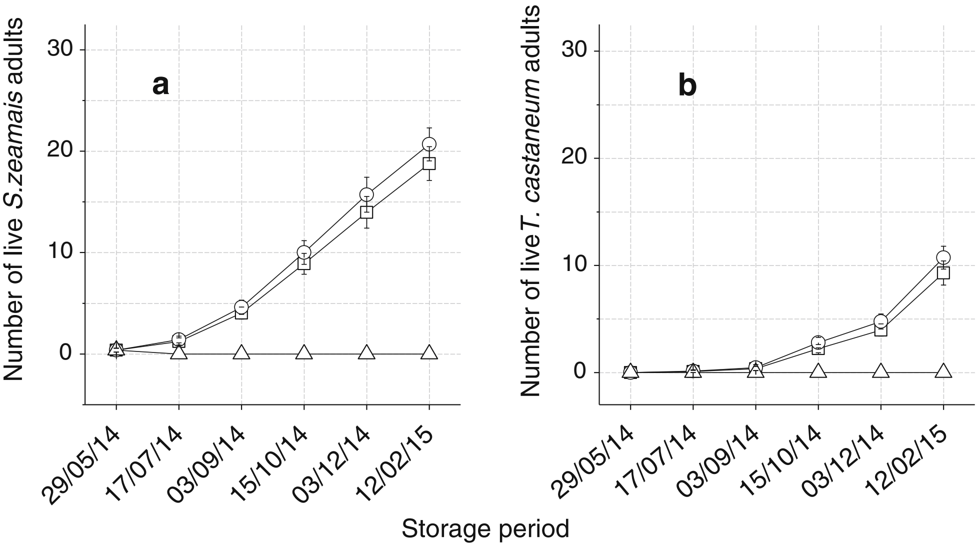
Fig. 4 Moisture contents of maize grain stored in polypropylene bags (□), jute bags (○) and PICS bags (Δ) over 35-weeks. Plotted data are means ± standard errors of 30 replications, represented by 30 farmers participating in the storage trial

throughout the entire storage period $P = 1.000$ (Fig. 4) and the lowest moisture contents attained were 11.8 ± 0.2 % and 11.7 ± 0.3 %, respectively.

Effect of type of storage bag on live insects count

In this study only *S. zeamais* and *T. castaneum* were detected. Figure 5 shows the populations of surviving adults of the two pests in the three types of bags. At the start of the experiment, some of the maize acquired from farmers had already been infested to different levels, but the visible emergent infestations were relatively low. The average number of live *S. zeamais* adults was 4–5 insects per kg whereas no live adults of *T. castaneum* were present. Interaction effect between type of storage bag and storage duration was significant for both *S. zeamais* ($F = 25.98$; $df = 10, 522$; $P < 0.001$) and *T. castaneum* ($F = 25.72$; $df = 10, 522$; $P < 0.001$). On all sampling occasions except the baseline

Fig. 5 Populations (number per 125 g) of live adult *S. zeamais* (**a**) and live adult *T.castaneum* in polypropylene bag (□), jute bags (○) and PICS bags (Δ) over 35-weeks storage period. Plotted data are means ± standard errors of 30 replications, represented by 30 farmers participating in the storage trial



sampling, no live insects were detected in the PICS bags. On the contrary, proliferation of insects in PP and Jute bags continued, and the populations of live adult *S. zeamais* remained higher than those of *T. castaneum*. Significant numbers of *T. castaneum* became evident starting from the 14th week of storage, and a drastic increase occurred in the 28th - 35th week interval, when the ratio of live adult *S. zeamais* to *T. castaneum* approximated 2:1. The populations of these pests in PP and jute bags, however, did not differ significantly (Fig. 5).

Effect of type of storage bag on grain damage and weight loss

Grain damage and grain weight loss in the three types of storage bags are presented in Table 1. At the start of experiment, the maize had a low level of grain damage of 3.6 ± 1.3 %. No further damage was observed in PICS bags during the 35 weeks of storage (Table 1). In contrast, grain damage in PP and jute bags increased steadily, and reached 77.5 ± 5.6 % and 82.3 ± 5.1 %, respectively at the end of the storage trial. The interaction effect of type of storage bag and storage period on grain damage was highly significant ($F = 21.21$; $df = 10, 522$; $P < 0.001$). Notably, beginning from the 7th week of storage, significantly higher damage was found in the PP and jute bags as compared to the PICS bags, and the trend continued throughout the storage period ($F = 26.05$; $df = 2, 87$; $P < 0.001$). Moreover, although grain damage measured in jute bags was consistently higher than that measured in the PP bags throughout the entire storage period, the two bags did not differ significantly (Table 1).

Initial weight loss of maize grain at the start of experiment was 0.7 ± 0.3 %. No further losses were observed in the PICS bag during storage. However, weight losses of maize stored in PP and jute bags exceeded 5 % in 14 weeks, and increased steadily to 41.2 ± 3.3 % and 48.5 ± 3.4 %, respectively in the 35th week. The interaction effect between type of bag and storage duration was significant ($F = 33.70$; $df = 10, 522$; $P < 0.001$). Notably, beginning at the 14th week, significantly higher weight loss was determined in the PP and jute bags as compared to the PICS bags, and the trend continued throughout the storage period ($F = 18.41$; $df = 2, 87$; $P < 0.001$). Similar to insect damage, there was no significant difference between the weight loss of maize stored in PP bags and that stored in jute bags (Table 1) although weight losses measured in the jute bags were consistently higher during the entire period of storage.

Discussion

Subsistence maize farming in rural areas requires that farmers store their produce to assure supply between harvests. Findings of this study show that farmers stored varying quantities for different reasons under varying storage conditions for different periods. Traditional storage methods that these rural farmers adopt at farm level are usually adapted to their environments and the types of crops they traditionally expect to store. However, the advent of factors such as new crop varieties which are usually more susceptible to infestation by insects than traditional ones (Amoson et al. 1997), and the spread of exotic storage pests such as *Prostephanus truncatus* could disrupt erstwhile effective storage practices. All the participant farmers in the present study experienced storage losses due to insect attacks. Although farmers applied insecticides and other traditional treatments to control pests, fewer than 25 % succeeded in mitigating losses. They thus perceived these control methods as ineffective. Indigenous treatments such as admixing with wood ash, have low efficacy because no standard application guidelines exist (Stathers et al. 2008),

Table 1 Percentage grain damage and weight loss of maize grain stored in polypropylene, jute and PICS bags for 35 weeks ($n = 30$)

	Storage duration (weeks)*					
	0	7	14	21	28	35
Grain damage (%)						
PICS	3.6 ± 1.3a	3.5 ± 1.3a	3.5 ± 1.2a	3.7 ± 1.2a	3.7 ± 1.2a	4.0 ± 1.2a
PPB	3.6 ± 1.3a	9.2 ± 2.4b	25.8 ± 3.9b	50.1 ± 5.5b	56.9 ± 5.6b	77.6 ± 5.6b
Jute	3.6 ± 1.3a	10.0 ± 2.5b	30.1 ± 4.3b	53.7 ± 5.7b	61.4 ± 5.8b	82.3 ± 5.1b
Weight loss (%)						
PICS	0.7 ± 0.2a	0.7 ± 0.2a	0.8 ± 0.3a	1.2 ± 0.4a	0.8 ± 0.3a	0.8 ± 0.2a
PPB	0.7 ± 0.2a	1.8 ± 0.5b	6.3 ± 0.9b	17.7 ± 1.9b	24.8 ± 2.8b	41.2 ± 3.3b
Jute	0.7 ± 0.2a	2.1 ± 0.5b	7.5 ± 1.1b	20.1 ± 2.4b	27.6 ± 3.0b	48.5 ± 3.4b

*Storage was conducted between May 2014 and February 2015. Data are means ± standard errors. Entries in the same column followed by same letters are not significantly different ($P > 0.05$). Means were separated using Bonferroni adjustment

and their use is only practical when preserving small quantities of grain in the short-term. The limited effectiveness of synthetic insecticides used by the farmers could be explained by a number of reasons, among them possible adulteration of the insecticides by vendors, improper application practices such as delayed treatment (Golob and Hanks 1990), incorrect dosage and patchy use by the farmers (Mutambuki and Ngatia 2012), or the progressive loss of insecticidal potency of the active ingredients (Denloye et al. 2008). This limited efficacy of common insecticides on stored maize has also been reported by other authors. For instance, Meikle et al. (2002) reported a weight loss of 7 % and a depreciation of the market value of 27 % in maize stored for six-months with Sofagrain™ (Pirimiphos-methyl (1.5 %) + Deltamethrin (0.5 %)) in Ghana. Similar observations were also reported for maize stored with Actellic Super® dust in West- (Biliwa and Richter 1990) and East-Africa (Stathers et al. 2008; Mutambuki and Ngatia 2012). In addition, rodents are reported to be the greatest vertebrate pest in East Africa. They are usually responsible for substantial damage to food and cash crops (Fiedler 1994). As shown in this study, some participants attributed losses to both insects and rodents but it was actually difficult to quantify the losses due to rodents only. Previously, Makundi et al. (1991) stated that in unprotected storage structures and where a food source is abundant certain species of rodents can increase to very high numbers within a short period, leading to severe losses. Thus, in rural communities in Africa, crop damage in the field and grain losses in storage, although not fully quantified, could undoubtedly be high.

Results of gas composition in PICS bags obtained in the present study show that the bags are capable of retaining good air barrier properties in on farm stores, and therefore could offer a maize storage alternative for rural farmers. A fairly stable modified environment was achieved in PICS bags as the HDPE liners were able to trap products of aerobic respiration emanating from within the bag. Although oxygen and carbon dioxide levels of 4.9 % and 10.5 %, respectively, were measured within the first 7 weeks of storage, it is possible that lower levels of oxygen and higher levels of carbon dioxide may have been reached in the bags, but were undetected because these first measurements were taken after a long interval. In addition, the tendency of oxygen to continue rising after attaining a minimum could be explained as being a consequence of this initial steady change in concentration of the two gases. First, because oxygen depletion and carbon dioxide build-up would retard insect activity and other survival processes in the bags (Murdock et al. 2012), it is probable that oxygen around individual grains would tend to increase as air proceeds to leak slowly through the partially impermeable HDPE liners following concentration gradient. Second, after sampling and closing the bags, depletion of oxygen in enclosed air may be less rapid. At this stage, we speculate that because oxidative metabolism is severely attenuated, oxygen consumption drops to very low levels while the oxygen level in the surrounding airspaces gradually rises toward normal (Baoua et al. 2012a).

Previous work has reported disparate oxygen and carbon dioxide progression and retention patterns in hermetic systems. Baoua et al. (2014) reported oxygen and carbon dioxide concentrations varying between 6.1 and 12.4 % and 3.1 and 7.7 % in PICS bags packed with naturally infested maize grain and stored for 6.5 month. In a separate study with naturally infested cowpeas stored where gas compositions were recorded daily for 12 days, Baoua et al. (2012a) observed a trend where oxygen levels dropped in the range of 2–3 % before gradually rising again to 12 and 15 %, while carbon dioxide was observed to rise to 5 % before gradually decreasing again: this was attributed to low aerobic metabolism processes in the PICS bags. Generally, oxygen depletion and carbon dioxide build-up in hermetic conditions is a function of elements of the storage system, including insect populations, moisture content of grain, fungal inocula, quality of the grain, and gas-tightness (Moreno-Martinez et al. 2000). For instance, Moreno-Martinez et al. (2000) observed gradual decrease in oxygen to 13.7 % by 24 days of storage that eventually stabilized at about 8.4 % within 30 days in clean maize stored without insect infestation and fungal infection under hermetic conditions. Similarly, Williams et al. (2014), using clean maize grain conditioned at 12 % moisture content, showed that oxygen and carbon dioxide levels did not change drastically, and stabilized at only 18.3 % and 1.2 %, respectively, during storage for one month in PICS bags because the respiration rate of the grains was low. This failure of stored grains to produce marked changes in gas composition in PICS bags was also reported in storage trials with other commodities including dry non-infested pigeon peas (Vales et al. 2014) and dry non-infested cowpeas (Murdock et al. 2012). For the present trial it is highly probable that oxygen and carbon dioxide content measured in the bags did not reach extreme levels because the respiration rate of surviving forms was low and the occasional opening for sampling (Murdock et al. 2012). Furthermore, grains are capable of absorbing some carbon dioxide, the extent of which depends on factors such as storage temperature, moisture content and grain type (Cofie-Agblor et al. 1995; Yamamoto and Mitsuda 1980). It is, however, also worth noting that the PICS bags seemed to maintain a fairly stable modified environment level because measurements were taken before opening the bags following a long interval of closure, and with extreme care to prevent changes in gas composition. Occasional opening of the bags for sampling would be expected to be marked by obvious spikes in gas composition levels. Although subsequent gas measurements immediately after sampling and closure of the bags was not carried out to know the extent of these changes, such information is of interest because many small-scale users would need to open the bag frequently to draw out grain for household use.

The results from this study indicate that PICS bags are good barriers against the fluctuation of grain moisture content or loss by grain stored in them, whereas moisture of grain stored in PP and jute bags could gradually change. Such changes have implications on the quality and safety of the stored maize as well as the saleable weight. Moisture content of maize stored in PP and jute bags gradually decreased during storage owing to the fairly warm and dry conditions that prevailed at the trial site. Similar observations were also made elsewhere (Williams et al. 2014; Baoua et al. 2014). From laboratory trials, however, Njoroge et al. (2014) reported an increase in moisture content of maize stored in PP bags for six months, and attributed this to heavy insect infestation. Heavy fungal growth especially on insect damaged grains might also result in moisture gain (Compton et al. 1998). Moreover, different maize varieties could also have different tendencies to give up or absorb moisture in storage environments. Thus, in addition to environmental conditions, nature of the grain and biological activity could influence the final moisture content of maize packed in storage bags.

The modified environment created by enclosing PICS bags with maize effectively suppressed insect survival thereby stopping grain damage and losses. Oxygen depletion and carbon dioxide enrichment of intergranular atmosphere form the basis for suppression of insect infestations in hermetic storage via a number of mechanisms. The lowest oxygen level for multiplication of insect pests is 2–3 % (Moreno-Martinez et al. 2000; Vachanth et al. 2010), although some studies also indicate that insects may adapt to low oxygen tensions and evolve into forms that resist sub-normal oxygen levels of about 1 % (Annis 1986; Donahaye 1990). A low oxygen level of about 2–3 % has been found to interfere with feeding of larval forms of insects which could become extremely slow or even cease, causing death (Moreno-Martinez et al. 2000; Murdock et al. 2012). In addition, Bailey and Banks (1980) indicated that oxygen depletion retarded development, impaired metamorphosis and altered fecundity of insects without necessarily killing them. Extremely low oxygen levels were not attained in this study. However, according to Banks and Annis (1990), the simultaneous exposure of insects to low oxygen and high carbon dioxide could contribute to insect inactivity or mortality in a synergistic way. Nicolas and Sillans (1989) reported that at lower humidity, more water loss from permanently open spiracles caused by stimulation with high carbon dioxide would lead to desiccation then to death. Carbon dioxide also dissolves in body fluids to form carbonic acid which could decrease haemolymph pH (Lea and Ashley 1978) and NADPH (Friedlander et al. 1984), influencing activities at cell membranes or inhibiting various enzyme systems. On the other hand, accumulated carbon dioxide induces diapause in some insects without necessarily causing mortality. Recently, Murdock et al. (2012) concluded that insects enclosed in limiting oxygen conditions died of desiccation because they were unable to generate the water they needed to maintain vital life processes, which they do by oxidizing energy-rich substrates in their diets.

This study has demonstrated significant grain damage and weight loss in maize stored in PP and jute bags compared to that which was stored in PICS bags. The high levels of grain damage and weight loss in PP and jute bags may be attributed to high rates of grain respiration and insect pest multiplication as a result of a conducive environment, particularly high oxygen concentrations within the bags. On the other hand, multiplication of insect pests was discouraged in PICS bags by the fact that the environment within the bags was modified (high carbon dioxide and low oxygen concentrations) reducing the extent of the damage and losses. In the present study the damage and losses were primarily a consequence of infestation by *S. zeamais*. Although losses by *S. zeamais* are generally regarded as low, other researchers have reported devastating losses caused by *S. zeamais* in farm stores. For instance, Sori and Ayana (2012) reported grain damage and weight losses averaging 54–80 % and 41–74 % respectively, on maize stored for 6 months in farmers stores in the Jimma zone of Ethiopia. In a separate study, Nukenine et al. (2002) reported that *S. zeamais* caused up to 80 % loss in Cameroon after storage for 6–8 months in traditional storage systems. Recently, Baoua et al. (2014) in storage trials with maize grain using PICS and woven polypropylene bags in Benin, Burkina Faso and Ghana under natural infestation conditions reported grain damage of 6.7–53.9 % corresponding to weight loss of 1.1–21.5 % in maize stored in PP bags where densities of *S. zeamais* were the dominant species after 6.5 months. During the storage trials, Baoua et al. (2014) used local storage spaces provided by the participants. However, despite the diversity of species and variability of pest density from one site to another the quality of grain stored in PICS bags was protected. In addition, Jay (1983) clarified that environmental factors such as temperature and relative humidity play important roles in proliferation of insect pests in stored products. The optimal conditions for reproduction and growth of *S. zeamais* and *T. castaneum* are 60–70 % relative humidity and temperatures of 25–30 °C (Madrid and Loschiavo 1990; Schwartz and Burkholder 1991). As these conditions prevailed in our trial sites this might explain the extensive damage and losses caused by *S. zeamais* on the maize stored in PP and jute bags. As expected, *T. castaneum* appeared in the PP and jute bags later after *S. zeamais* had caused damage to the whole grains. Further to weight loss, which represents direct loss of edible and saleable mass, grain damage causes loss of quality which is often associated with low food value and palatability. Such grain is also of low market value. Thus storage of maize in PICS bags would also prevent losses of quality and market value. In an exploratory study in Ghana, Compton et al. (1998) demonstrated strong quasi-linear negative relationship between grain damage and price. Whereas grain damage of 5–6 % or below did not attract discounted prices, maize with damage in excess of 5–6 %, was discounted at 0.6–1 % for every 1 % increase in grain damage. Furthermore, extensive damage renders grain unfit for human consumption and is occasionally unsafe as it is highly susceptible to mold infection and mycotoxin contamination.

In this study, *P. truncatus* was not observed during baseline and subsequent samplings probably due to the erratic nature of outbreaks of the pest (Hodges 2002). Previous on-farm storage trials conducted in western Kenya (Ngatia and Kimondo 2011) also reported absence of *P. truncatus* but the presence of *S. zeamais*, *S. cerealella* and *Tribolium castaneum*. Birkinshaw et al. (2002) and Hodges (2002) have reported that *Sitophilus* species are widespread and in most seasons and years, a high risk of their attack exists whereas *P. truncatus* outbreaks are sporadic for various biological reasons. However, a limitation of PICS bags with regard to retaining the modified micro-environment is the possibility of perforation of the HDPE liners by storage insects, thereby minimising their usefulness. In storage trials with maize and cassava Baoua et al. (2014), and Ognakossan et al. (2013) have reported the ability of *P. truncatus* to perforate the HDPE liners of PICS bag. Nevertheless, such perforations did not seem to affect performance of the bags when timely storage and closure of the bags was done. Although perforations were not observed in the present study where *S. zeamais* predominated, these cannot be ruled out, especially in cases where development of hermetic conditions is not rapid or where the bag has undergone mechanical weakening or developed surface imperfections due to repeated use.

Conclusion

Storage losses due to insect pest infestations are a serious problem that threatens the food security, nutrition and livelihood of rural farmers who rely on traditional storage systems. Because many infestations in endemic areas begin on the farm, prophylactic treatment using insecticides is almost never achieved. Moreover, in settings where adherence to best practices in the use of insecticides is poor, farmers who choose to protect their grain with insecticide may have to apply the insecticide more than once in order to achieve longer-term storage, which has cost, environmental and consumer health implications. Findings of this study show that storage in PICS bags is capable of halting destructive losses even for produce that may enter storage with some level of pre-storage infestation arising from field infestation or improperly cleaned storage structures. Since the PICS technology does not require use of chemicals, it is cheap, and would allow the high level of control and flexibility that subsistence farmer's desire in the use and handling of their grain. Future work should look at whether imperfections in HDPE liners such as those caused by repeated use and twisting could provide additional opoportunities for common maize weevils to bore through and hence affect the performance of the bags.

Acknowledgments C. Mutungi is thankful to Grand Challenges Canada for a grant (GCC-0423-01) to conduct this study. The authors thank the International Centre of Insect Physiology and Ecology (*icipe*) for institutional support.

References

Abebe, F., Tefera, T., Mugo, S., Beyene, Y., & Vidal, S. (2009). Resistance of maize varieties to the maize weevil (*Sitophilus zeamais*) (motsch.) (coleoptera: curculionidae). *African Journal of Biotechnology*, *8*, 5937–5943.

Affognon, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa. *A Meta - Analysis. World Development.*, *66*, 49–68.

Amoson, J. T., Conh de Beysac, B., Phlogene, B. J. R., Bergvision, D., Serratos, J. A., & Mihm, J. A. (1997). Mechanisms of resistance in maize grain to maize weevil and larger grain borer. *Crop Science*, *43*, 2043–2049.

Anankware, P. J., Fatunbi, A. O., Afreh-Nuamah, K., Obeng-Ofori, D., & Ansah, A. F. (2012). Efficacy of the multiple-layer hermetic storage bag for biorational management of primary beetle pests of stored maize. *Academic Journal of Entomology.*, *5*, 47–53.

Annis, P. C. (1986). Towards rational controlled atmosphere dosage schedules: a review of current knowledge. In E. Donahaye & S. Navarro (Eds.), *Stored Products Protection. Proceedings of the 4th International Working Conference on Stored-Product Protection* (pp. 128–148). Jerusalem, Israel: Tel Aviv, Israel. Maor-Wallach Press.

Bailey, S. W., & Banks, H. J. (1980). A review of recent studies of the effects of controlled atmospheres on stored product pests. In J. Shejbal (Ed.), *Controlled atmosphere storage of grains* (pp. 101–118). Amsterdam, The Netherlands: Elsevier Scientific Publishing Company.

Banks, H. J., & Annis, P. C. (1990). Comparative advantage of high CO_2 and low O_2 types of controlled atmospheres for grain storage. In M. Calderon & R. Barkai-Golan (Eds.), *Food preservation by modified atmospheres* (pp. 93–119). Boca Raton, Florida: CRC Press Inc.

Baoua, I. B., Margam,V., Amadou, L., & Murdock, L. L. (2012a). Performance of triple bagging hermetic technology for postharvest storage of cowpea grain in Niger. *Journal of Stored Products Research* 51: 81–85.

Baoua, I. B., Amadou, L., Ousmane, B., Baributsa, D., & Murdock, L. L. (2014). PICS bags for post-harvest storage of maize grain in West Africa. *Journal of Stored Products Research*, *58*, 20–28.

Baributsa, D., Djibo, K., Lowenberg-DeBoer, J., Moussa, B., & Baoua, I. (2014). The fate of triple-layer plastic bags used for cowpea storage. *Journal of Stored Products Research*, *58*, 97–102.

Biliwa, A., & Richter, J. (1990). Efficacité des insecticides binaries en poudre sur du maïs stocké en sacs. In F. Fleurat-Lessard & P. Ducom (Eds.), *Stored Products Protection. Proceedings of the 5th International Working Conference on Stored-Product Protection* (pp. 1577–1536). Bordeaux, France: Imprimerie du Médoc.

Birkinshaw, L. A., Hodges, R. J., Addo, S., & Riwa, W. (2002). Can 'bad' years for damage *by Prostephanus truncatus* be predicted? *Crop Protection*, *21*, 783–791.

Boxall, R. (1986). *A critical review of the methodology for assessing farm-level grain losses after harvest. tropical Development and Research Institute*. London: Great Britain.

Boxall, R. A. (2002). Damage and loss caused by the larger grain borer *Prostephanus truncatus*. *Integrated Pest Management Reviews*, *7*, 105–121.

Clevo, W., & Clem, T. (2001). Why farmers continue to use pesticides despite environmental, health and sustainability costs. *Ecological Economics*, *39*, 449–462.

Cofie-Agblor, R., Muir, W. E., Sinicio, R., Cenkowski, S., & Jayas, D. S. (1995). Characteristics of carbon dioxide sorption by stored wheat. *Journal of Stored Products Research*, *31*, 317–324.

Compton, J. A. F., Floyd, S., Magrath, P. A., Addo, S., Gbedevi, S. R., Agbo, B., Bokor, G., Amekupe, S., Motey, Z., Penni, H., & Kumi, S. (1998). Involving grain traders in determining the effect of post-harvest insect damage on the price of maize in African markets. *Crop Protection*, *17*, 483–489.

De Groote, H., Kimenju, C. S., Likhayo, P., Kanampiu, F., Tefera, T., & Hellin, J. (2013). Effectiveness of hermetic systems in controlling maize storage pests in Kenya. *Journal of Stored Products Research*, *53*, 27–36.

Denloye, A. A., Tesilim, K. O., Negbenebor, H., & Makanjuola, W. A. (2008). Assessment of the efficacy of actellic and sumithion in protecting grains from insect infestation during storage. *Journal of Entomology*, *5*, 24–30.

Donahaye, E. (1990). Laboratory selection of resistance by the red flour beetle *Tribolium castaneum* (herbst) to an atmosphere of low oxygen concentration. *Phytoparasitica*, *18*, 189–202.

Fiedler, L. A. (1994). *Rodent Pest Management in East Africa*. In *Plant Production and Protection Paper No. 123*. Rome: Food and Agriculture Organization (FAO).

Friedlander, A., Navarro, S., & Silhacek, D. L. (1984). The effect of carbon dioxide on NADPH production in *Ephestia cautella* (wlk.) pupae. *Comparative Biochemistry Physiology. B: Biochemistry and Molecular Biology.*, *77B*, 839–842.

Gitonga, Z. M., De Groote, H., Kassie, M., & Tadele, T. (2013). Impact of metal silos on households' maize storage, storage losses and food security: An application of a propensity score matching. *Food Policy*, *43*, 44–55.

Golob, P., & Hanks, C. (1990). Protection of farm stored maize against infestation by *Prostephanus trancatus* (horn) and *Sitophilus* species in Tanzania. *Journal of Stored Products Research*, *26*, 187–198.

Hodges, R. J. (2002). Detection and monitoring of the larger grain borer, *Prostephanus truncatus* (horn) (coleoptera: bostrichidae). *Integrated Pest Management Reviews*, *7*, 223–243.

Jay, E. G. (1983). Imperfections in our current knowledge of insect biology as related to their response to controlled atmospheres. In B. E. Ripp, H. J. Banks, E. J. Bond, D. J. Calverley, E. G. Jay, & S. Navarro (Eds.), *Controlled atmosphere and fumigation in Grain storage, 11–22 April 1983, Perth* (pp. 493–508). Amsterdam, The Netherlands: Western Australia. Elsevier Scientific Publishing Company.

Kimenju, S.C., and De Groote, H. (2010). Economic Analysis of Alternative Maize Storage Technologies in Kenya Cape Town, South Africa. African Association of Agricultural Economists (AAAE) and 48th Agricultural Economists Association of South Africa (AEASA)

Lamboni, Y., & Hell, K. (2009). Propagation of mycotoxigenic fungi in maize stores by postharvest insects. *International Journal of Tropical Insect Science*, *29*(1), 31–39.

Lea, T. J., & Ashley, C. C. (1978). Increase in free Ca^{2+} in muscle after exposure to CO_2. *Nature*, *275*, 236–238.

Madrid, F. J., White, N. D. G & Loschiavo, S. R. (1990). Insects in stored cereals, and their association with farming practices in Southern Manitoba. Canadian Entomologist 122, 515–523.

Makundi, R. H., Mbise, T. J., & Kilonzo, B. S. (1991). Observations on the role of rodents in crop losses in Tanzania and control strategies. *Beiträge Zur Tropischen Landwirtschaft Und Vertirinärmedizin.*, *29*, 465–474.

Meikle, W. G., Markham, R. H., Nansen, C., Holst, N., Degbey, P., Azoma, K., & Korie, S. (2002). Pest management in traditional maize stores in West Africa: a farmer's perspective. *Journal of Economic Entomology*, *95*, 1079–1088.

Moreno-Martinez, E., Jimenez, A. S., & Vazquez, M. E. (2000). Effect of *Sitophilus zeamais* and *Aspergillus chevalieri* on the oxygen level in maize stored hermetically. *Journal of Stored Products Research*, *36*, 25–36.

Murdock, L. L., Dogo, S. D., Ntoukam, G., Kitch, L., & Shade, R. E. (2003). Preservation of cowpea grain in sub-Saharan Africa-Bean/Cowpea CRSP contributions. *Field Crops Research*, *82*, 169–178.

Murdock, L. L., Margam, V. M., Baoua, I., Balfe, S., & Shade, R. E. (2012). Death by desiccation: effects of hermetic storage on cowpea bruchids. *Journal of Stored Products Research*, *49*, 166–170.

Mutambuki, K., & Ngatia, C. M. (2012). Assessment of grain damage and weight loss on farm stored maize in highlands areas of Bungoma district, Kenya. *Journal of Agricultural Science and Technology*, *B 2*, 349–361.

Mutiro, C. F., Giga, D. P., & Chetsanga, P. (1992). Postharvest damage in small farmers' stores. Zimbabwe. *Journal of Agricultural Research*, *30*, 49–59.

Ngatia, C. M., & Kimondo, M. (2011). Comparison of three methods of weight loss determination on maize stored in two farmer environments under natural infestation. *Journal of Stored Products and Postharvest Research*, 254–260.

Nicolas, G., & Sillans, D. (1989). Immediate and latent effects of carbon dioxide on insects. *Annual Review of Entomology*, *34*, 97–116.

Njoroge, A. W., Affognon, H. D., Mutungi, C. M., Manono, J., Lamuka, P. O., & Murdock, L. L. (2014). Triple bag hermetic storage delivers a lethal punch to *Prostephanus truncatus* (horn) (coleoptera: bostrichidae) in stored maize. *Journal of Stored Products Research*, *58*, 12–19.

Nukenine, E. N., Monglo, B., Awasom, I., Tchuenguen, F. F. N., & Ngassoum, M. B. (2002). Farmers' perception on some aspects of maize production and infestation level of stored maize by *Sitophilus zeamais* in the ngaoundere region of Cameroon. *CJBBS*, *12*, 18–30.

Obeng-Ofori, D. (2011). Protecting grain from insect pest infestations in Africa: producer perceptions and practices. *Stewart Postharvest Reviews.*, *3*, 1–8.

Ognakossan, K. E., Tounou, A. K., Lamboni, Y., & Hell, K. (2013). Postharvest insect infestation in maize grain stored in woven polypropylene and in hermetic bags. *International Journal of Tropical Insect Science*, *33*, 71–81.

Ortega, C.A. (1987). Insect Pests of Maize: a Guide for Field Identification. CIMMYT, Mexico, D.F. Retrieved on 23/01/2015 from: http://pdf.usaid.gov/pdf_docs/PNAAX152.pdf

Schwartz, B. E., & Burkholder, W. E. (1991). Development of the granary weevil (coleoptera: curculionidae) on barley, corn, oats, rice, and wheat. *Journal of Economic Entomology*, *84*, 1047–1052.

Sori, W., & Ayana, A. (2012). Storage pests of maize and their status in jimma zone, Ethiopia. *African Journal of Agricultural Research*, *28*, 4056–4060.

Stathers, T. E., Riwa, W., Mvumi, B. M., Mosha, R., Kitandu, L., Mngara, K., Kaoneka, B., & Morris, M. (2008). Do diatomaceous earths have potential as grain protectants for small-holder farmers in sub-Saharan Africa? The case of Tanzania. *Crop Protection*, *27*, 44–70.

Subramanyam, B., & Hagstrum, D. W. (1996). Resistance measurement and management. In B. Subramanyam & D. W. Hagstrum (Eds.), *Integrated Management of Insects in Stored Products* (pp. 331–397). New York, USA: Marcel Dekker, Inc.

Tadele, T., Kanampiu, F., De Groote, H., Hellin, J., Mugo, S., Kimenju, S., Beyene, Y., Boddupalli, P. M., Shiferaw, B., & Banziger, M. (2011). The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. *Crop Protection*, *30*, 240–245.

Vachanth, M. C., Subbu Rathinam, K. M., Preethi, R., & Loganathan, M. (2010). Controlled atmosphere storage technique for safe storage of processed little millet. *Academic Journal of Entomology.*, *3*, 12–14.

Vales, M. I., Rao, G. V. R., Sudini, S. B., Patil, S. B., & Murdock, L. L. (2014). Effective and economic storage of pigeonpea seed in triple layer plastic bags. *Journal of Stored Products Research*, *58*, 29–38.

Williams, S. B., Baributsa, D., & Woloshuk, C. (2014). Assessing Purdue Improved Crop Storage (PICS) bags to mitigate fungal growth and aflatoxin contamination. *Journal of Stored Products Research*, *59*, 190–196.

World Bank, (2010). Missing food: the case of postharvest grain losses in sub-Saharan Africa. Washington, DC: World Bank, 116 pp

Yamamoto, A., & Mitsuda, H. (1980). Characteristics of carbon dioxide gas adsorption by grain and its components. In J. Shejbal (Ed.), *Controlled atmosphere storage of grains international symposium, 12–15 may 1980* (pp. 247–258). Rome, Italy: Castelgandolfo.

Zia-Ur-Rehman (2006). Storage effects on nutritional quality of commonly consumed cereals. *Food Chemistry*, *95*, 53–57.

Jeremiah Ng'ang'a is a Master of Science candidate at Jomo Kenyatta University of Agriculture and Technology (Kenya) in the faculty of Agriculture. Jeremiah is currently a fellow on a Dissertation Research Internship Programme (DRIP) at the International Centre of Insect Physiology and Ecology, Nairobi, Kenya. His research interest is technologies for value addition and minimizing postharvest food losses among smallholder farmers in Kenya.

Christopher Mutungi is a food technologist with a PhD in food engineering from Technische Universität Dresden, Germany. He is currently a University lecturer and researcher at the Department of Dairy and Food Science and Technology at Egerton University. Christopher has over 15 years' experience of research, training and technology transfer in postharvest value chains of cereals, legumes and root and tuber crops. He worked previously as Senior Research Scientist involved in food products development and value addition at Kenya Industrial Research and Development Institute, before joining the International Centre of Insect Physiology and Ecology as a consultant in postharvest technologies. His research interests revolve around participatory development, testing and transfer of innovations that focus on adding value, cutting costs and reducing wastage or losses along value chains of common food staples for improved nutrition and health in sub-Saharan Africa. His recent work has included a Canadian Government funded project examining the potential of hermetic storage systems for control of postharvest losses and aflatoxin poisoning in Kenya. He is also involved in several other multidisciplinary projects having postharvest components being implemented in collaboration with international research teams.

Samuel M. Imathiu is a lecturer and researcher in the Department of Food Science and Technology at Jomo Kenyatta University of agriculture and Technology, Kenya. He holds a PhD in plant pathology from Harper Adams University, UK. His research interests are in the areas of the production and mitigation of mycotoxins in cereals pre- and postharvest, and microbiological food safety.

Dr. Hippolyte Affognon holds a PhD in Agricultural Economics and a Master of Science (M.Sc.) degree in Horticultural Economics from Leibniz University, Hanover, Germany. He is an agronomist and has more than 18 years of work experience in both interdisciplinary and multicultural teams, parts of which include experience as a project coordinator at the International Institute of Tropical Agriculture (IITA) and as a Post-doctoral Scientist at the International Livestock Research Institute (ILRI). Presently Dr. Affognon is a Senior Scientist at the International Centre of Insect Physiology and Ecology (ICIPE) where he is leading the Social Science and Postharvest Units. Hippolyte's recent work is concerned with postharvest phenomena, including the meta-analysis of postharvest losses in Sub-Saharan Africa and testing hermetic storage for various grains.