UTILIZATION OF LIGHTED CANDLE AND SEALING METHODS IN METAL SILOS FOR MANAGEMENT OF THE LARGER GRAIN BORER, *PROSTEPHANUS TRUNCATUS* (HORN) (COLEOPTERA; BOSTRICHIDAE) IN STORED MAIZE

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DECLARATION

I declare that this thesis is my original work and has not been submitted for any award of degree in any University. It is being submitted for the degree of Master of Science in Crop Protection in the University of Nairobi.

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DEDICATION

I dedicate this work to my husband, Dr. Haron Karaya and children; Boniface, Wilson and Purity for their love, encouragement and support during the study period.

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LIST OF ACRONYMS

CABI- Centre for Biosciences and Agriculture International

CFIA- Canadian Food Inspection Agency

CIMMYT –International Centre for Maize and Wheat Improvement

CPC- Crop Protection Compendium

DDT- Dichloro-Diphenyl-Trichloroethane

ELISA- Enzyme- Linked Immuno-sorbent Assay

FAO- Food and Agricultural Organization of the United Nations

GAIN- Global Agricultural Information Network

GoK- Government of Kenya

HDPE- High Density Polyethelene

ICPE- International Centre of Insect Physiology and Ecology

IITA-International Institute of Tropical Agriculture

IRRI- International Rice Research Institute

ISTA- International Seed Testing Association

LGB- Larger grain borer

MoA- Ministry of Agriculture

NGOs- Non- Governmental Organizations

PBS- Phosphate Buffer Saline

PICS- Purdue Improved Cowpeas Storage

SDC -Swiss Agency for Development and Cooperation

USDA – United States Department of Agriculture

Abstract

Postharvest losses in maize in sub-Saharan Africa are estimated at 20% annually. Effective storage technologies will ensure food and income security for small holder farmers in developing countries. Larger grain borer *(Prostephanus truncatus)* is the most destructive pest of farm-stored maize causing losses as high as 30% in 6 months. Chemical pesticides are also available for the management of *P. truncatus* but have potential negative effects to human health and the environment. Globally, metal silos have been promoted for safe storage of grains at small holder levels. The metal silos are cheap, safe and environmentally friendly. To determine the effect of sealing metal silos with different materials available locally for the control *P. truncatus* in stored maize, an on-station trial with four treatments was conducted. Metal silos with a holding capacity of 100 kg were loaded with 90 kg of grain and a lighted candle placed on top of the grain. One hundred 10-day old *P. truncatus* were artificially introduced into the grain and the silo lids sealed with rubber band, grease, rubber band combined with grease and without rubber band or grease (control). The treatments were replicated four times, arranged in a completely randomized design and stored in a room roofed with corrugated iron sheets at ambient temperatures of 27±2^{o}C and relative humidity of 58±5%.

A second on-station trial with five treatments was conducted. The experiment consisted of: metal silo loaded with 90 kg of grain and a lighted candle placed on top of the grain before sealing the metal silo with rubber band; metal silo loaded with 45 kg of grain and a lighted candle placed on top of the grain before sealing with rubber band; metal silo loaded with 90 kg of grain and sealed with rubber band without lighting the candle; metal silo loaded with

45kg of grain and sealed with rubber band without lighted candle and polypropylene woven bag loaded with 90 kg of grain and tied tightly with rubber band and sisal rope (control) .

After thirty five days of storage results from the first trial exhibited significant ($p<0.05$) differences in weight loss, grain damage and insect mortality. The metal silos sealed using rubber band combined with grease had significantly ($p<0.05$ the least weight loss (0.6%) and grain damage (4.5%) compared to the control which had the highest weight loss (1.9 %) and grain damage (6.6%). Metal silo sealed with rubber band combined with grease had significantly higher CO_2 level (2.1% v/v) compared to the control which had the least amount of CO_2 (0.5% v/v). Insect mortality (100%) was highest in metal silos sealed with rubber band, grease and rubber band combined with grease compared to the control which had the least (80%). A mean of 3 (F_1) insect progeny emerged in the control after incubation and none in the other treatments.

From the second trial significant differences ($p<0.05$) were observed where the metal silo loaded with 45 kg of grain and a lighted candle had higher insect mortality (100%), higher CO_2 level (3.3% v/v), lower O_2 (17.6% v/v), lower grain damage (3.7%) and weight loss (0.7%) compared to the control that suffered the highest weight loss (22.2%), grain damage (49.4%), higher O_2 level (20.94% v/v) and least CO_2 level (0.05% v/v). The number of live LGB increased tenfold after ninety days of storage. *Sitophilus zeamais* and *Tribolium castaneum* infested the grain in the control. Grain germination rate in the control reduced significantly ($p<0.05$) from 66% to 49% compared to the metal silos where the rate reduced minimally from 66% to 62%.

Therefore, proper sealing of metal silo with either rubber band or grease and use of lighted candle effectively controlled *P. truncatus* and preserved grain in storage. Use of lighted candles in metal silos interfered with air composition, quickly killing the LGB, resulting in reduced grain damage and weight loss of the stored maize.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Agriculture is an important economic activity which ensure small holder farmers in developing countries are food secure and have improved living standards (CIMMYT, 2011). In sub- Saharan Africa (SSA), it accounts for about 20% of the total gross domestic product and about 60% of the total labor force (Beintema and Stads, 2004). Maize (*Zea mays* L.) is the third most important cereal after rice and wheat in the world (FAOSTAT, 2012). Its annual yield in 2012 exceeded 870 million tons valued at about $53 billion dollars (FAO-STAT, 2012).

In Kenya, maize is a major staple food constituting 65% of the total staple food calories consumed (Short *et al.,* 2012). It is a source of food, income and employment for ninety percent of the Kenyan population in Rift valley, Central, Western and Eastern regions (Wangai *et al.,* 2012). Maize production in Kenya has been increasing steadily since 2008 from 2,367,237 MT to 3,600,000 MT in 2012 (FAOSTAT, 2012) with an annual per capita consumption of 98kg of the maize products (Ariga and Jayne, 2011). However, the country imports maize to meet the demand which exceeds domestic production (Short *et al.,* 2012). Maize production in Kenya is constrained by rising human population, increased weather variability, high cost of production, increased post-harvest losses and increased pest and disease incidences such as the newly reported Maize Lethal Necrosis Disease (MLND) (USDA, 2013; Wangai *et al.,* 2012). There is need to increase food security and agricultural productivity through the improved cost effective storage facilities to reduce post-harvest losses incurred during storage (Babangida and Yong, 2011). Twenty five percent of the annual staple food grains produced are lost during post-harvest processes (Babangida and

Yong, 2011; Cao *et al.*, 2002). These losses occur during harvesting and handling, transport, marketing and from bio deterioration that occur along the post-harvest chain including storage (Tefera, 2012). Songa and Irungu (2010) estimated 30% losses due to poor and ineffective grain storage technologies accessible to small scale farmers.

Maize weevil, (*Sitophilus zeamais* Motschulsky), larger grain borer, (*Prostephanus truncatus,* Horn), granary weevil, (S*itophilus granarius* L.), lesser grain borer, (*Rhyzopertha dominica*, Fabricius) and Angoumois moth, (*Sitotroga cerealella,* Olivier) are the main pests of stored maize in Kenya (Abebe *et al.,* 2009; Bett and Nguyo, 2007; Kimenju and De Groote, 2010; Tefera *et al.*, 2011b). They attack the crop in the field as it reaches physiological maturity and proceed to storage where most damage takes place (Yuya *et al.,* 2009). Storage pests cause quantitative, qualitative and economic losses (Abebe *et al.,* 2009; Kimenju *et al.,* 2009). Quantitative loss is the loss in weight of damaged grains while qualitative loss is loss in grain quality through contamination or damage including nutritional loss (Tefera, 2012). Economic loss according to FAO (2010) is the loss of monetary value of the product. The magnitudes of these losses depend on the level of grain moisture content and temperature before and during storage, the container used and the duration of storage (Tefera, 2012). High grain moisture content, humidity and temperature encourage proliferation of mould and provide conducive environment for insect infestation (Semple *et al.,* 1992; Tefera, 2012). Most small scale farmers store their grain in polypropylene bags which has led to increased losses from rodents and insects by creating favourable conditions for their proliferation including micro-organisms (Babangida and Yong 2011; Ngamo *et al.,* 2007). Cases of mycotoxin contamination and poisoning have been reported in stored grain with high levels of pest infestation (Tefera, 2012).

Emergence of new storage pests like larger grain borer which cause devastating losses in stored maize has necessitated change from traditional storage facilities to other options. Over the years, farmers have used an admixture of organo-phosphates and pyrethroids to control storage pests (Golob, 2002a). However, this has negative impact on human health, non-targeted organisms and eco-toxicity due to accumulation of pesticide residues in food and environment (Sambarashe *et al.,* 2013). For the pesticides to be effective, they must be applied repeatedly which is expensive, forcing small holder farmers to dispose their produce at low prices and go hungry a few months after harvesting because of their inability to afford increased food prices (Kimenju *et al.*, 2009).

In the world today, concerns on the environment and food safety have increased and consumers are demanding high quality products that are free from chemical residues, aflatoxin and insect contamination (Weinberg *et al.*, 2008). Insects have also developed resistance to pesticides resulting in their resurgence (Sambarashe *et al.*, 2013). Therefore, there is need for safe and effective alternatives to preserve and protect stored grains. Technologies explored to minimize post-harvest losses are use of biological control, pest resistant varieties, low temperatures, diatomaceous earth and hermetic storage facilities (Golob, 2002a). Hermetic storage is advocated for as an affordable, safe and cost effective method for control of post-harvest insect pests in stored maize grain especially in Asia (Quezada *et al.*, 2006). The technique works by a synergistic effect of low oxygen and high carbon dioxide levels produced by aerobic metabolism of insects, micro-organisms and grain respiration. Aerobic metabolism uses up oxygen and produce carbon dioxide to levels that are lethal to insects and moulds in the grain mass (Navarro *et al.*, 2007; Yakubu *et al.*, 2011). According to Murdock *et al.* (2012), hypoxia stops larval feeding which in turn affects insect development thereby reducing insect population growth. It follows then, that damaging infestations do not develop because the insects do not mature and reproduce. Exposure of eggs, larvae and pupae of *Callosobruchus maculatus* to elevated levels of carbon dioxide (hypercarbia) causes them to die (Murdock *et al.,* 2012).

Metal silos are among hermetic structures that are being promoted worldwide to manage storage pests. They are cylindrical structures constructed from galvanized iron sheet and hermetically sealed to allow storage of grain for long periods without attacks from rodents, insects and birds (Tefera *et al*., 2011a). Metal silos can be of different holding capacities between 100kg to 3,000kg (CIMMYT, 2009; FAO, 2008; SDC, 2008a, b) and therefore can be used by farmers and other stakeholders at different levels of the maize value chain to reduce post-harvest losses. Metal silos have been successfully promoted in Central America by POSTCOSECHA program (Hellin and Kanampiu, 2008) and through Food and Agriculture Organization of the United Nations in 16 countries of the world (FAO, 2008). In El Salvador, Central America, farmers use approximately 65,000 silos (Bokusheva *et al.,* 2012, POST COSECHA, 2011) in combination with phostoxin (Yusuf and He, 2011). According to a survey carried out in Central America, the introduction of metal silos increased food security by 30-35 days per year (SDC, 2012). In Western Australia, metal silos are used in combination with carbon dioxide treatments to control storage pests in legumes and cereals (Andrews *et al.,* 1994). In Kenya, Catholic Relief Service and CIMMYT have promoted the use of metal silos to control storage pests in stored maize. Research done in Kenya, has shown the effectiveness of metal silos in controlling *S. zeamais* and *P. truncatus* in stored maize for six months without insecticides (CIMMYT, 2011; De Groote *et al.,* 2013).

1.2 Problem Statement

Post -harvest losses for maize range from 17% to 37% depending on the size of the farm (World Bank, 2009) but overall losses which are caused by post-harvest insect pests, poor grain storage practices and inadequate storage management technologies are estimated at 30% (Songa and Irungu, 2010). Studies have shown that larger grain borer is the most destructive pest of farm-stored maize and dried cassava in Africa (Boxall, 2002b).

Tefera *et al.* (2011b) reported that LGB causes 67% weight loss and 53% flour production, compared to 6.9% weight loss and 1.2% flour production caused by maize weevil in a period of 90 days in the laboratory. In Kenya, *P. truncatus* was introduced through Taita Taveta border from Tanzania and established in the dry parts of Eastern and Coast regions in early 1980s (Hodges *et al.*, 1983). It has since spread to Rift valley and Western regions (Anonymous, 2003). Omondi *et al.* (2011) reported the highest number of *P. truncatus* in pheromone traps in Kitale and Kakamega compared to Kitui, Thika and Mombasa. This poses food security threat if larger grain borer is not properly managed. Several management measures including; use of pesticides, biological control and cultural methods have been put in place to manage larger grain borer but are not efficient and cost effective (De Groote *et al*., 2013;Giles *et al.,* 1996). Over time, small scale farmers have continued to use pesticides to manage LGB but have not been cost effective because they require frequent application (Kimenju *et al.,* 2009). Recently, new management technologies such as use of hermetic containers have been developed and found to be cheap, effective and environmentally friendly in Central America, Asia and West Africa (Baoua *et al.,* 2012a, b; FAO, 2008; Quezada *et al.,* 2006 and Villers *et al.,* 2008). However, they have not been fully evaluated in Kenya.

1.3 Justification

Spread of LGB to Rift valley and Western regions which are the bread-basket of Kenya, is a threat to food security. This is because maize is a staple food in Kenya. Therefore, there is need to develop and deploy effective post-harvest management practices and storage facilities to control the larger grain borer and reduce food insecurity. Several methods including chemical, biological and cultural methods have been explored but none is efficient and cost effective in the control of larger grain borer (De Groote *et al.,* 2013). Hermetic containers which include super grain bags, Purdue Improved Cowpea Storage (PICS) and Cocoons have been reported as cheap, safe and effective storage alternatives in Asia (Quezada *et al.,* 2006) and recently in Africa (Baoua *et al.,* 2012a,b; Jones *et al.*, 2011; Murdock *et al.,* 2012; Phiri and Otieno, 2008 and Villers *et al.,* 2008). Hermetically sealed metal silos have also been promoted worldwide for effective control of storage pests (De Groote *et al.,* 2013; FAO, 2008; Hellin and Kanampiu, 2008; Tefera *et al.,* 2011a). Beside reduction in post-harvest losses, metal silo technology can contribute to improved livelihoods for small scale farmers in rural areas (De Groote *et al.,* 2013). Although metal silos are effective in the management of storage pests, a survey which was carried out in Central America reported losses of up to 20 % due to inadequate silo management (POST COSECHA, 2011). Therefore, it is important to ensure that farmers manage properly their metal silos.

This study was to evaluate various methods of managing metal silos for reduced pest infestations. So far no work has been done on the effect of air presence, grain volume and use of lighted candle on the level of damage and loss of grain in metal silos. The type of materials used to seal the in-let and out-let of the metal silo is important in determining the effectiveness of the metal silo in controlling stored product pests and maintenance of grain quality.

1.4 Objectives

1.4.1 Broad Objective

To contribute to the effective management of *P. truncatus* (LGB) in stored maize using improved hermetic storage for improved food and nutrition security.

1.4.2 Specific Objectives

1. To evaluate different sealing methods of metal silos for the control of larger grain borer in stored maize.
2. To determine the effect of lighted candle and grain volume on the rate of oxygen depletion and carbon dioxide build up in the metal silos.

1.5 Hypotheses

This study was carried out on the basis that:

1. The effectiveness of metal silos for the control of larger grain borer is influenced by the adopted sealing method.
2. Grain volume and use of lighted candle affects the rate of oxygen depletion and carbon dioxide build up in metal silos and hence the control of *P. truncatus*.

CHAPTER TWO

LITERATURE REVIEW

2.1 Maize Production and Constraints

2.1.1 Maize Production and its importance

World population is expected to reach 9.1 billion people by the year 2050. Most of this increase will be recorded in developing countries (Babangida and Yong, 2011). Tefera (2012) estimated a desired increase of 70% in food production to feed the population. Maize is ranked first among cereals in terms of quantity produced in the World (FAOSTAT, 2012). Global maize production decreased from over 888 million MT in 2011 to 872 million MT in 2012 due to severe drought throughout the major growing seasons in US and Europe (FAO, 2012). In Sub-Saharan Africa, maize is an important food security crop and an income earner to many small holder farmers (Tefera, 2012). The annual per capita consumption in the region exceeds the average globally with 98 kg per annum in Kenya, 122 kg/year in Zimbabwe and 148 kg/year in Malawi (Smale and Jayne, 2003). Despite its importance, the region experience maize shortages due to weather variability, declining soil fertility, pest damage and heavy post-harvest losses (FAO, 2011; Tefera, 2012).

Kenya produces on average 3 million metric tons of maize annually (USDA, 2013). This has not been enough for the Kenyan population that is currently at 40 million and expected to reach 60 million by 2030 (FAO, 2013). Since 2007-2008 post-election violence, maize production in the country decreased but resumed in 2010 to an average of over 3 million MT (Table 2.1). In 2010, Kenya produced 3.5 million metric tons of maize but decreased in 2011 to 3.3 million metric tons due to post-harvest losses that were accelerated by heavy rains at harvest and the effect of Maize Lethal Necrosis Disease (MLND) in parts of southern Rift Valley and Nyanza regions that affected about 60, 000 hectares (USDA, 2013; Wangai *et al.*, 2012). Despite efforts by Government of Kenya to encourage crop diversification, maize consumption has continued to increase (USDA, 2013). Kenya's maize imports increased to 1.5 million tons in 2009 from an average of 186 000 tons during the period 2000–2008 (FAOSTAT, 2012).

Table 2. 1 Maize productions ('000 MT) in Kenya 2006 – 2012

Year	2006	2007	2008	2009	2010	2011	2012
Production ('000 MT)	3247	2929	2367	2439	3465	3377	3600
Import ('000 MT)	147	114	244	1508	230	411	500

Source: FAOSTAT, 2012; USDA, 2013.

2.1.2 Constraints in Maize Production

Farmers in less developed countries encounter both biotic and abiotic constraints which result in total or partial crop failures (Tefera *et al.,* 2011a). The abiotic factors include; unfavorable climatic conditions aggrevated by the climate change, unaffordable farm inputs like fertilizers, declining soil fertility, soil acidification due to use of Di Ammonium Phosphate (DAP) every year, inadequate storage facilities and low rate of adoption of new technologies and appropriate agronomic practices (FAO, 2003; Kanyanjua *et al.,* 2002; Nyoro *et al.,* 2007). The major biotic factors affecting maize production are common infestation by weeds in the field and insect pests both in the field and in storage (CFIA, 2006; IITA, 2007 b). Maize stalk borers are the major insect pests whose incidence levels range from 60- 95%. They attack maize in the field causing an estimated 13.5% loss valued at 7.2 billion shillings (De Groote *et al.,* 2002). Other insect pests includes: armyworms, grain moths, beetles, weevils, grain borers and rootworms. *Striga* is the most important weed, causing 65-100% yield losses in maize (Anthony, 2006) and affecting about 210,000 hectares in Nyanza, Western and Coast regions at an estimated loss of US$ 53 million per year (Hassan *et al.,* 1995). Other important constraints are diseases such as; downy mildew, grey leaf spot, northern leaf blight, rusts, rots (root, stalk and ear), smuts, *Maize streak virus* and the most recent and devastating maize lethal necrosis disease (Infonet-biovision, 2012; Wangai *et al.,* 2012). Maize lethal necrosis is a viral disease of corn. It is caused by a double infection of two viruses, a new virus, *Maize Chlorotic Mottle Virus* (MCMV) (Jiang *et al.,* 1990; Scheets, 1998) and a potyvirus, *Sugarcane mosaic virus* (SCMV) (Niblett and Claflin, 1978). In Kenya, the disease was first reported in 2011, in the low altitudes of Bomet District (Longisa Division, altitude 1900m above sea level) affecting 200 Ha of the second season maize crop (Wangai *et al.,* 2012) and later spread to high altitude areas of Bomet District. The disease has since spread to different parts of the country. Other biotic factors include infestation by soil pests such as termites, nematodes, cutworms, chaffer grubs, wildlife damage on crops that neighbor forested areas, bird's damage on isolated early maturing crop, post-harvest losses and aflatoxin contamination (Josphert *et al.,* 2012; MOA, 2012).

2.2 Post-harvest losses

In the world considerable amount of post-harvest losses occur in all crops from cereals, pulses and root crops (FAO, 1999). Post-harvest losses aggravate food insecurity (Tefera, 2012). They accelerate poverty levels in less developed countries where the poor devote most of their disposable income to food (FAO, 2011). They lead to loss of valuable resources such as food, energy, agricultural inputs, water, labour and land (FAO, 2011). Post-harvest losses in maize are defined as measurable decrease in food grain occurring during post-harvest system which can be quantitative, qualitative or economic (FAO, 2003). Quantitative losses refer to loss in weight as a result of grain damage by pests, loss during transportation or spillage. Qualitative loss is loss in quality of the grain including nutritional value through damage or contamination and economic loss which is the loss in monetary value of the product after selling at low market prices (FAO, 2003; FAO, 2011; Tefera, 2012).

In less developed countries, post-harvest losses are 3% higher than in developed countries although the losses vary with the crop, the pests and the region (Cao *et al*., 2002). FAO (2011) estimated that 1 out of 5 kilos (20%) of grains produced in Sub- Saharan Africa is lost to pests and microorganisms. In Africa, 25% of maize grain harvested valued at 4 billion dollars annually is lost due to poor post-harvest management (FAO, 2010; Tefera, 2012). This value according to FAO (2011) is equivalent to total annual value of cereal imports in sub- Saharan Africa that ranged between US $ 3-7 billion in 2000-2007 and exceeds the value of cereal food aid received in the region in the last ten years. At 2500 Kcal per day per person, these losses are enough to feed 48 million people in a year (FAO, 2011).

Post-harvest losses occur at all stages from harvesting to consumption (Tefera, 2012). The level of post-harvest losses is also influenced by production conditions during the pre-harvest stages. Drought stress and mechanical damage as a result of insect damage can contribute to aflatoxin contamination and subsequently mould growth during post-harvest stages (FAO, 2011). Drought stress and mechanical damage as a result of insect damage can contribute to aflatoxin contamination and subsequently mould growth during post-harvest stages (FAO, 2011).During harvesting, weather condition, harvesting method (manual or mechanical) and genetic characteristic of the variety will influence the level of losses incurred. According to Tefera (2012), harvesting and drying process in the maize value chain contribute to most losses averaging 11% of the total 25%. Although hand harvesting, which is common among many small scale farmers in Africa, may be less wasteful compared to mechanical harvesting, labour constraints lead to delays or failure to harvest resulting in high post-harvest losses at farm level (FAO, 2011).

Climate change cause weather variability which sometimes lead to heavy rains during harvesting resulting in increased post-harvest losses due to increased pest incidences and mould growth (FAO, 2011). Most farmers in Africa rely on sunshine to dry their produce, this may expose the produce to attack by rodents, insects, birds, baboons and monkeys. Lack of adequate sunshine will lead to incomplete drying, resulting in wet pockets and temperature variations during storage which favour mould growth and pest attack (FAO, 2003; FAO 2011). The amount of damage incurred during threshing and shelling is proportional to the moisture content of the grain and the method used (FAO, 2003). Small scale farmers shell their maize manually hence less spillage compared to large scale farmers who use machines resulting in higher losses through grain spillage and breakage (FAO, 2003). Tefera (2012) estimated an average of 3 % loss due to grain cracking, grain breakage, attack by rodents and birds during shelling and threshing. Post-harvest losses during on-farm storage average 4-10%, mainly due to insects, rodents, moulds, birds and mites (Tefera, 2012). This depends highly on temperature and humidity, type of storage structure, duration of storage, level of damage prior to storage during harvesting, transportation and shelling and management implemented before and during storage (FAO, 2003; FAO, 2011). Adoption of safe and effective storage technologies will reduce post-harvest losses; ensure income and food security at household levels (CIMMYT, 2011). Metal silos will prevent damage by storage pests including birds and rodents and will enable farmers to store their produce and sell later at better prices.

2.3 Storage Pests

Coleoptera (beetles) and Lepidoptera (moths and butterflies) are economically the most important insect pests of stored foods (FAO, 1999). They occur in the tropics, sub tropics and temperate regions in the world although their level of damage varies greatly. Higher levels of damage are reported in the tropics and sub tropics because climatic conditions favour their proliferation (FAO, 1999). Other pests that are important in storage are rodents and birds (Tefera, 2012). Pest problems in the world are aggravated by introduction of alien pests into new habitats either intentionally or accidentally through global trade or other pathways (CABI, 2014). These exotic pests often cause serious damages because indigenous natural enemies are not able to control their populations (FAO, 1999). Coleopteran larvae and adults as well as lepidopteran larvae are responsible for most damage caused on stored products (FAO, 1999). Some of these pests have strong flight ability that enables them to infest the crop in the field and continue damaging while in stores (Demissie *et al*., 2008; FAO, 2003). Storage pests are classified as either primary or secondary pests. Primary pests attack intact grains unlike secondary pests that attack already damaged grains or grain products (FAO, 2003).

In sub-Saharan Africa, insect pests cause an estimated 20-30 % loss annually during storage (FAO, 1999). Maize weevils and larger grain borers are the most important storage pests of maize in Kenya among other pests (Tefera *et al.*, 2011a, Table 2.2, Plate 2.1). Maize weevils were reported as the most destructive pest of untreated on-farm stored maize with high moisture content in Africa before introduction of larger grain borer in 1980s (Boxall, 2002b; Tefera *et al.*, 2011a). Boxall (2002b) reported grain weight loss of 12-20% and up to 80% grain damage by maize weevils in untreated maize stored in traditional structures.

Some storage pests apart from causing grain weight loss reduce grain quality by feeding on the endosperm while others cause poor germination and loss of viability by feeding on the germ (Malek and Parveen, 1989; Santos *et al.*, 1990). Together with these damages, insect pests contaminate the grain with frass, dead bodies, their presence in the grain and others lead to bad smell and taste causing loss of value in marketability and palatability of the grain (FAO, 2003). In addition, storage insect pests are associated with mycotoxin contamination and poisoning (Tefera, 2012). Insect feeding raise the temperature of the grain resulting in `hot spots' that encourage fungal activity and grain deterioration (FAO, 1999). Insect pests can also facilitate spread of fungal and bacterial spores in stored grain increasing chances of aflatoxin contamination (FAO, 2003). *Sitophilus oryzae* were found to have *Aspergillus flavus* in their alimentary canal and facilitated spread of the fungus from infested to healthy grains (Pande and Mehrotra, 1988).

Vertebrate pests such as rodents and birds can cause loss and damage to stored grain when drying in the sun and threshing. Rodents (rats and mice) cause more loss and damage to food grain than insects in several tropical countries (FAO, 2003). In the world, *Rattus rattus* (roof rat) and *Mus musculus* (house mouse) are the most common species in storage facilities. *Rattus norvegivus* (brown rat) is common in the temperate regions (FAO, 1999). These species cause crop loss in field and in storage through consumption, contamination of stored grain with their feaces, urine and hairs and spillage when they destroy storage containers (FAO, 1999; FAO, 2003). Birds can cause loss when drying and threshing grain in the sun or when stored in open cribs. They cause less loss compared to rodents (FAO, 1999)

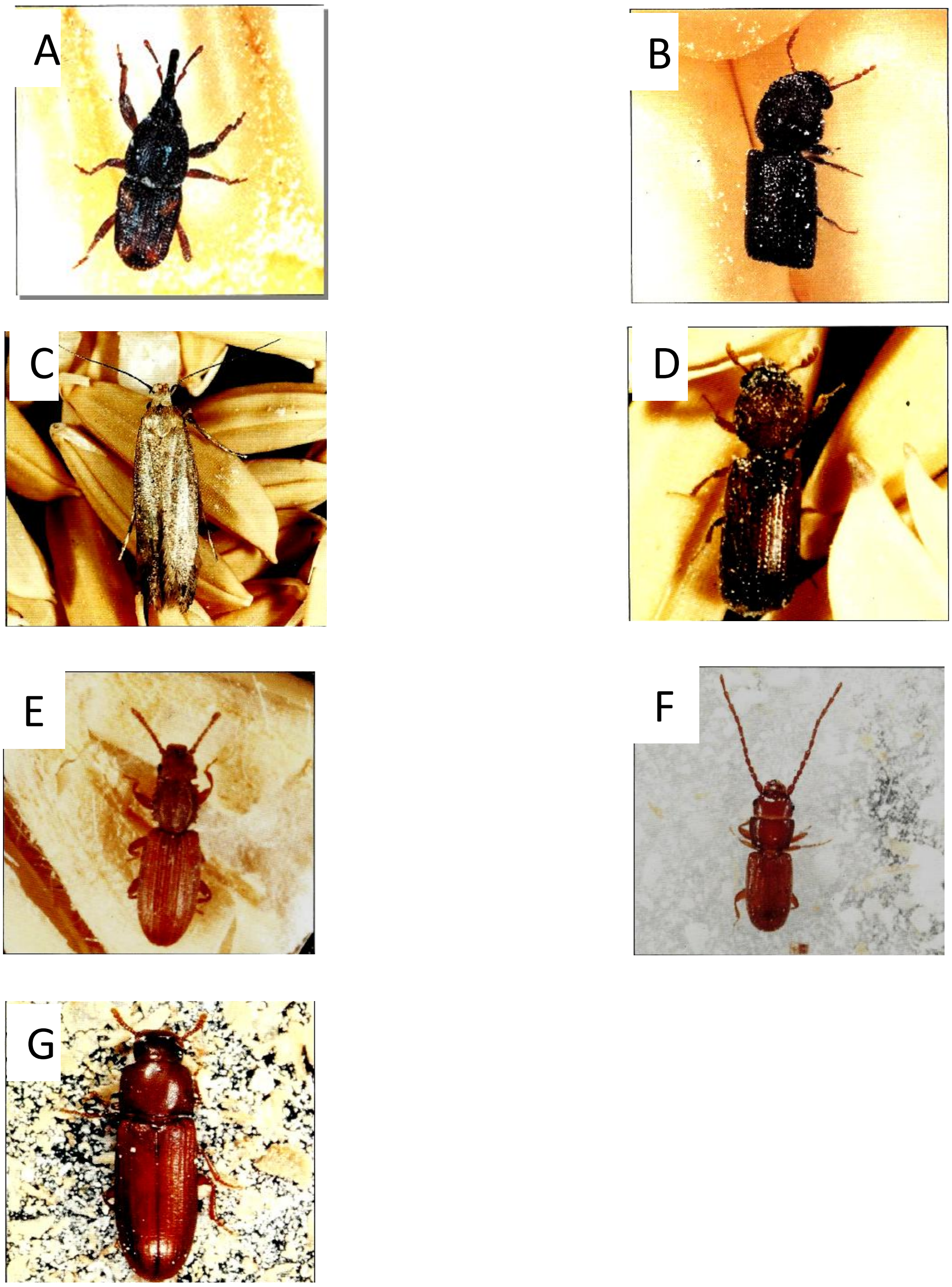

Plate 2. 1 Pictorial view of common storage pests of cereals

A) *Sitophilus* spp *(*Maize and Rice weevils*)*
B) *Prostephanus truncatus (*Larger Grain Borer*)*
C) *Sitotroga cerealella (*Angoumois Grain Moth)
D) *Rhyzopertha dominica* (Lesser Grain Borer)
E) *Oryzaephilus* spp, (Saw -Toothed Beetle)
F) *Cryptolestes spp* (Flat Grain Beetle)
G) Tribolium castaneum (Rust-Red Flour Beetle)

Source: Natural Resource Institute (NRI):Insects in Tropical Stores.

Table 2. 2 Common insect pests infesting stored grain

Order/ family	**Name: Common, Scientific**	**Product damaged/ infested**	**Type of damage**	**Temp at which population growth is reduced ^{o}C**	**Optimum temperature for reproduction ^{o}C**
Coleoptera/ Curculionidae	Granary weevil, *Sitophilus granarius* (L)	Sorghum, rice, maize, wheat, paddy	Larvae develop inside kernel and feed on starch.	17	28-30
	Rice weevil, *Sitophilus zeamais* (Motschulsk)		Adults hatch and feed voraciously on the grain	18	29-31
	Maize weevil, *Sitophilus oryzae* (L)			18	29-31
Coleoptera/ Bostrichidae	Lesser grain borer, *Rhizopertha dominica* (F)	Paddy, rice, wheat, maize, dried cassava/ potato	Larvae enter and feed on starchy part of the grain.	21	30-35
	Larger grain borer, *Prostephanus truncatus* (Horn)	Maize and dry cassava tubers/ chips	Adults bore grain freely and eat destroying the whole grain kernel.	18	32
Coleoptera/ Silvanidae	Saw- toothed grain beetle, *Oryzaephilus surinamensis* (L)	Maize, wheat, sorghum, rice, pulses, oil seeds	Larvae feed on broken and damaged grain. Only larvae cause serious	19	34
Dermestidae	Khapra beetle, *Trogoderma granarium* (Everts)		damage on stored products	22	33-37

Order/ family	Name: Common, Scientific	Product damaged/ infested	Type of damage	Temp for population control ^{o}C	Optimum temp for reproduction ^{o}C
Coleoptera/ Tenebrionidae	Confused flour beetle, *Tribolium confusum*	Maize wheat, sorghum, flour, ground nuts, milled cereal products, dried fruits, legumes	Larvae and adults feed on broken and damaged grain.	21	30-33
	Rust- red flour beetle, *Tribolium castaneum* (Herbst)		Larvae free-living on broken and damaged grain.	22	36
Cucujidae	Flat grain beetle, *Cryptolestes pusillus* (Schonherr)		Adults will attack the germ of sound grain	20	33-35
Lepidoptera/ Gelechiidae	Angoumois grain moth, *Sitotroga cerealella* (Olivier)	Maize, wheat, rice, paddy, sorghum.	Attack grains in the field. Most damage caused by larvae in storage.	16	28-30
Pyralidae	Tropical warehouse moth, *Ephestia cautella* (Walker)	Groundnut, rice, maize, wheat, sorghum.	Heavy webbing and frass on the produce. Adult moths are short lived and do not feed.	16	28-30
	Rice moth *Corcyra cephalonica* (Stainton)	Maize, wheat, rice, millet, sorghum, groundnut, cocoa.		18	30-32

Source: FAO, 1999; FAO, 2003.

2.4 Larger Grain Borer, *Prostephanus truncatus* (Horn)

2.4.1 Origin and Distribution

Prostephanus truncatus is indigenous to Central America, tropical South America and the extreme south of the USA where it is a major but localized pest of farm-stored maize (Hodges *et al.*, 1983). It is not economically important in the region because it is biologically controlled by its natural parasites and predators (Hodges *et al.,* 1983). In Africa, larger grain borer was unintentionally introduced through maize aid to refugee camps at Urambo, Tabora in western Tanzania in late 1970s (Dunstan and Magazini, 1981). It spread to Kenya through Taveta border in 1983 (Kega and Warui, 1983) and has since spread to other areas in Eastern, Coast, Nyanza and most recently in Rift valley and Western regions (Omondi *et al.*, 2011).

In Africa, *P. truncatus* has been reported in 17 countries; Kenya (1983), Tanzania (1981), Togo (1984),Uganda (1997), Burundi (1984), Rwanda (1993), Malawi (1992), Zambia (1993), Mozambique (1999), Namibia (1998), South Africa (1999), Benin (1984), Nigeria (1992), Ghana (1989), Niger (1994), Guinea (1987) and Burkina Faso (1991) Fig. 2.1) (Boxall, 2002 b; CABI, 2014; Dick, 1989; Krall, 1984). In Europe, it has been reported in Italy and Sicily (Suma and Russo, 2005).

Figure 2. 1. Distribution of *P. truncatus* in Africa. Red colour indicate presence of *P. truncatus*

Source: Infonet-biovision, 2012.

2.4.2 Biology of *P. truncatus*

Prostephanus truncatus (Horn) is in the order: Coleoptera and family: Bostrichidae. In South America, Bostrichidae are known as pests of timber (Tooke and Scott, 1994). Of the three species in the genus *Prostephanus*, only *P. truncatus* is associated with stored products (CABI, 2014). It is reported as the most destructive pest of maize and dried cassava roots in Africa (Boxall, 2002b; Wright *et al*., 1993). *Prostephanus truncatus* is similar to lesser grain borer, *Rhizopertha dominica* which is in the same family. The adults of larger grain borer have a body 3-4.5 mm long and 1-1.5 mm wide with a sex ratio of 1:1 compared to lesser grain borer's body which is 2-3 mm long (Plate 2.2) (BioNET-EAFRINET, 2011; Nansen and Meikle, 2002). It is flattened and steep with many small tubercles over its surface and the end of its body terminates in a straight edge. It has a deflexed head, strong mandibles and a three segmented antennae (Infonet-biovision, 2012).

The eggs are white to yellow in colour with broad ovoid shape. The larva has a scarabaeiform body, white in colour and sparsely covered with hair, a small head and short legs (CABI, 2014). Both the larvae and the adults feed on the grain. They make neat round holes and tunnels generating a lot of dust as they feed (Plate 2.2). The adult females lay eggs in batches of 20 in chambers bored at right angle to the main tunnels and covered with finely chewed maize dust. Female adults lay more eggs on maize cobs which are stable than on loose shelled maize (Hodges and Meik, 1984). In shelled maize the rate of reproduction is lower and oviposition period is 7 days longer (CABI, 2014). An adult female lays 30-50 eggs in the produce (Infonet-biovision, 2012). Food availability (maize starch), temperature and relative humidity determine the length of the life cycle and survival rate of the larger grain borer. The larvae hatch from eggs in 3-7 days at 27^{o} C and takes 27 days to develop to adult at 32^{o} C and 80% relative humidity on maize diet (CABI, 2014). However, at 18° C and 60% relative humidity, eggs develop into adults within 166 days (Sekyembe *et al*., 1993).

Females live longer, for 61 days than males which live for 45 days (FAO, 1999). According to Scholz *et al*. (1997), males produce pheromones at the highest rate when they are on a suitable substrate and are not in the presence of females. Therefore, females can be captured in flight traps baited with the insects' male-produced aggregation pheromone (Dendy *et al*., 1989). Although *P. truncatus* develops best at high temperatures and relatively high humidity, it is able to develop and damage grains with low moisture content and dominate other storage pests under dry conditions (Haines, 1991). Field studies in Tanzania and Nicaragua showed maize with 9% and 10.6% moisture content respectively were heavily infested (CABI, 2014; Giles and Leon, 1975).

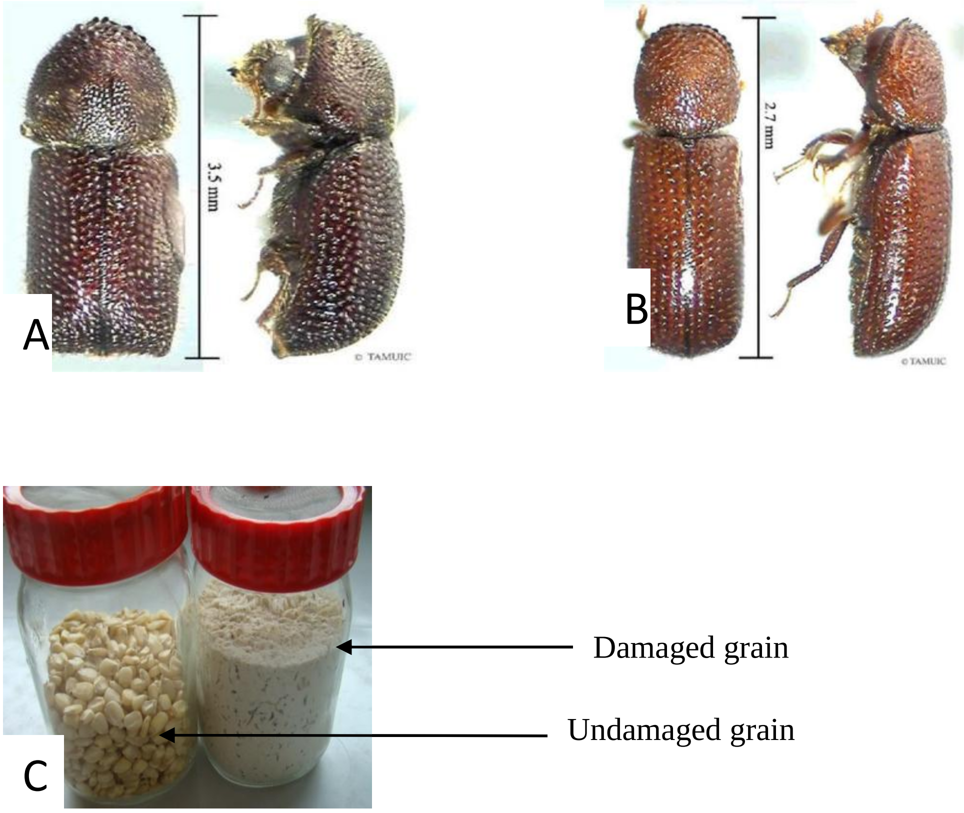

Plate 2. 2 Physical differentiation between *Prostephanus truncatus* and *Rhizopertha dominica*

A) Dorsal and lateral view of *P. truncatus.*

B) Dorsal and side view of adult *Rhyzopertha dominica*.

C) Damaged and undamaged maize grain in glass jars by *P. truncatus*.

Source: PaDIL Pests and Diseases Image Library. http://www.Padil.gov.au

2.4.3 Economic Importance of *Prostephanus truncatus*

Since the introduction of *P. truncatus* in Africa, farmers have incurred huge losses on dried cassava and on-farm stored maize (Boxall, 2002b; Wright *et al*., 1993). In Tanzania, farmers reported losses of up to 34% (dry weight) and in extreme cases, the maize was totally unfit for consumption with 70–80% of the maize grains damaged (Boxall, 2002 b). Mallya (1992) reported maize losses of up to 35% in 5-6 months in Tanzania and up to 60% after nine months of storage (Keil, 1988). In Togo, 30% weight loss was reported on farm-stored maize after six months (Pantenius, 1988) while Muhihu and Kibata (1985) reported 35% weight losses after 3-6 months of storing maize in East Africa. Tefera *et al*. (2011b) reported weight loss of 67.1% and 52.8% flour production was caused by *P. truncatus* compared to 6.9% weight loss and 1.2% flour production by maize weevil in a period of 90 days in the laboratory. In Togo, the larger grain borer was equally destructive in dried cassava roots and chips causing 70 % loss after four months of farm storage (Hodges *et al*., 1985). Wright *et al*. (1993) reported an average cumulative loss of 9.7% of cassava roots by a group of farmers which rose to 19.5% after seven months of storage. According to Demianyk and Sinha (1988), a single *P. truncatus* adult can destroy an energy equivalent of five corn kernels. These clearly indicate the importance of *P. truncatus* in grain storage, which is a potential threat to food security and affect negatively the livelihood of poor farmers.

For countries that depend on export of maize, *P. truncatus* has negative impact on their economy due to loss of trade. According to Boeye *et al.* (1992), many countries do not import maize from areas infested with *P. truncatus*. Most small scale farmers sell their produce immediately after harvest at low prices to avoid losses and buy when market prices are high (Kimenju *et al*., 2009). Infestations by *P.truncatus* leads to reduced nutritional value of the grain because it feeds on the endosperm (Sekyembe *et al*., 1993). *P. truncatus* has also led to increased levels of poverty and food insecurity in less developed countries.

2.4.4 Description of Damage Caused by *P. truncatus*

The larger grain borer is a serious pest of stored maize, and will attack maize on the cob, both before and after harvest (Tefera *et al*., 2010). Both the adults and larvae damage the grain but only the adults produce tunnels. They make neat round holes and produce huge amounts of grain dust as they tunnel (Hodges and Meik, 1984). The adults also attack a variety of foodstuffs as minor hosts (dried sweet potatoes, yam, sorghum and wheat) and other materials including wood, bamboo and plastic (Infonet-biovision, 2012). In Central America and Africa, large populations of *P. truncatus* were found in a number of tree species (Nang'ayo *et al*., 2002; Rees *et al*., 1990).

2.4.5 Spread of *P. truncatus*

The ability of the beetle to establish itself as a serious pest in both the hot, dry conditions of western Tanzania, the hot, humid conditions of Togo and up to an altitude of 2200 m in Mexico suggests that it has the potential to spread to all areas where maize is grown, and to other tropical and subtropical regions (Hodges, 1994). This is confirmed by the spread of *P. truncatus* from the lowlands to the highlands of Kenya (Omondi *et al*., 2011). Local dispersal of the pest is through movement of infested grain and through flight by adult beetles. Nansen and Meikle (2002) reported that an adult *P. truncatus* is capable of flying an equivalent of 25 km in 45 hours in the laboratory in search of food. However, trade in maize and other cereals among continents and regions have led to the spread of the pest over long distances (CABI, 2014).

2.5 Management of Larger Grain Borer

Storage is key in ensuring food security in all countries, particularly in developing countries where cereals, including maize, are produced seasonally and sometimes only one harvest a year (Proctor, 1994). Seasonal production leads to fluctuating supply at the international, regional, national and at household levels (Proctor, 1994). Effective storage will therefore reduce fluctuations and ensure steady market supply at low prices both at household and national levels throughout the year (FAO, 2011; Proctor, 1994). Traditionally farmers stored their unshelled maize in cribs, however with increased cases of theft and reduced maize production; many farmers shell their maize and store them in bags in their houses (Hellin *et al*., 2009). Emergence of new storage pests like larger grain borer necessitated change from traditional storage facilities to other options such as use of chemicals, use of hermetic storage, use of host resistant varieties, other cultural practices, for example, timely harvesting and biological control (Hodges, 1994).

2.5.1 Chemical Control

Larger grain borer cause more losses in maize cobs than in shelled grain (Mc Farlane, 1988). Farmers, therefore, prefer to shell their grain; apply insecticides and store in suitable containers to protect against insect pest and pathogen attack during storage (Dales and Golob, 1997). Infestation by *P. truncatus* on farm-stored maize in Tanzania increased weight losses to over 30% in 9 months of storage (Keil, 1988). According to Golob *et al*. (1999) farmers dried the grain in the sun in thin layers to drive away or kill the LGB, subjected the maize cobs to heat and smoke above kitchen fire and some sprayed the cobs with DDT but none was effective.

Synthetic pyrethroid and organophosphorus insecticides are used to control storage pests in many countries in Africa (CABI, 2014). *Prostephanus truncatus* is highly susceptible to synthetic pyrethroids but *Sitophilus* spp. and *Tribolium castaneum* which occur in the same environment are more susceptible to organophosphates. Therefore, to control the whole pest complex, both types of insecticides are applied (Golob, 2002a). According to Farrell and Schulten (2002), immediate shelling, drying and applying of a mixture of 1.6% pirimiphos-methyl and 0.3% permethrin (Actellic super) has been promoted as effective against the larger grain borer. In Tanzania, more than 93% of farmers in both high rainfall and low rainfall zones used Actellic Super to control larger grain borer (Kaliba *et al.,* 1998). This is the same in Kenya where most small scale farmers have adopted the use of Actellic Super Dust to control larger grain borer (Sekyembe *et al*., 1993). Fumigation with phosphine is very effective in large scale stores but it is not available to small scale farmers since its use is restricted to only trained handlers (De Groote *et al*., 2013). Although use of insecticides is effective in control of storage pests, there are challenges facing farmers. To effectively control these pests, insecticides are applied frequently after every 3-4 months (Dales and Golob, 1997). For most small scale farmers, this is expensive to sustain; use of chemicals has adverse effects both to farmers and the environment (FAO, 2011; Weinberg, *et al*., 2008) and hence the need to come up with safe and economically feasible storage pest control.

2.5.2 Biological Control

*Teretrius (*formerly *Teretriosoma) nigrescens* (Lewis) (Coleoptera: Histeridae) is the only predator that has been associated with *P. truncatus* in Central America, Mexico and Costa Rica (Borgemeister *et al*., 2003; CABI, 2014). In laboratory studies, Rees (1985) reported *T. nigrescens* to have successfully controlled the population growth of *P. truncatus* and prevented serious losses in maize. In his study, 10 adults of *T. nigrescens* were able to prevent populations of up to 100 adult *P. truncatus* from increasing. There have been attempts to introduce *T. nigrescens* as a classical biological control for *P. truncatus* in Africa (Borgemeister *et al*., 2003; Giles *et al*., 1996; Hodges, 1994). *Teretrius nigrescens* was first introduced in Togo, West Africa (Hodges, 1994) and later in Kenya (Giles *et al*., 1996). According to Schneider *et al*. (2004), *T. nigrescens* reduced the number of *P. truncatus* caught in pheromone traps considerably in the warm, humid, coastal areas of Togo and Benin.

In Kenya *T. nigrescens* released in cool highland habitats averaging 1700 m asl and lower warm habitat at 900 m asl (Wundanyi and Makueni) resulted in about 80% reduction in LGB flight activity (Giles *et al.,* 1996; Hodges, 1994; Omondi *et al.,* 2011). At lower altitudes, the predator spread 16 km from the release site within 9 months and over 70 km within three years of release. However, at high altitudes the spread has been slower (Hodges, 1994; Omondi *et al.,* 2011). *Teretrius nigrescens* adults and larvae feed on LGB eggs, larvae and pupae (Sekyembe *et al.,* 1993). In Kenya (Hill *et al.,* 2003), Togo (Schneider *et al.,* 2004) and Benin (Borgemeister *et al.,* 1997), the predator successfully controlled *P. truncatus* within few years of release. However, according to Holst and Meikle (2003), *T. nigrescens* may not effectively control *P. truncatus* when the populations are high because it's fecundity is low and intrinsic rate of increase is only two-thirds that of *P. truncatus*. In addition, the predator is more sensitive to insecticides used to control larger grain borer than the pest itself (Golob *et al.,* 1994). Therefore, releasing the predator in maize stores where insecticides are also used may nullify its effect on the pest (Golob *et al.,* 1994). Other biological agents have also been tried in control of *P. truncatus*. In Central America, *Aspergillus* spp efficiently controlled *P. truncatus*, but due to its highly toxic metabolites was excluded from further testing (Laborious *et al*., 1989). In Kenya, Odour *et al.* (2000) reported very low levels of infection of *S. zeamais* and *P. truncatus* by *Beauveria bassiana* (Bals) in farmers maize stores. However, Bourassa *et al.* (2001) in a laboratory study reported high *P. truncatus* mortality caused by 3 strains of *B. bassiana* and *Metarhizium anisopliae.*

2.5.3 Cultural Practices

Good store hygiene, especially removal of infested residues, ensuring maize is cleaned and dried to moisture content below 13% before storage can limit infestation by *P. truncatus*

*(*Sekyembe *et al.,* 1993*)*. Timely harvesting plays an important role in avoiding infestation by post-harvest pests including LGB (FAO, 1999). Maize when left in the field for longer periods after physiological maturity result in losses due to rodents, insect pests, birds and moulds while in the field and during storage (FAO, 1999; FAO, 2011). Mvumi *et al.* (1995) reported 9.1% yield loss due to pest attack in maize when left in the field for four months after physiological maturity in Zimbabwe. Farmers have been using plant or inert materials with insecticidal properties to control storage pests. They mix maize with leaves of tobacco, apply ash from maize cobs or burnt animal dung, subject the maize to heat and smoke above kitchen fire, mix grain and sand/ clay while others use neem oil or neem plant leaves (FAO, 2011; Golob *et al.,* 1999). Although these methods have been used by farmers to control some of the storage pests, they are not effective for control of larger grain borer (Golob *et al.,* 1999). The other challenges are that their safety to the consumer is not known, are not efficient and cost effective for large quantities of grain and use of ash causes tainting and discoloration of the grain lowering its market value (FAO, 2011, Golob, 2002a).

2.5.4 Use of Insect Tolerant Varieties

Use of insect tolerant varieties is environmentally friendly, has relatively low cost, safe and easy to use by farmers. However, due to high costs and other challenges involved when developing and testing them, there are few post-harvest insect tolerant maize varieties in Kenya. They include KH 523-1 LGB, KH 125-04PhPR and KH 125-05PhPR that were developed by KARI Embu and KARI Mtwapa and released in 2011 and 2012, respectively (KEPHIS, 2014).

2.5.5 Hermetic Storage

The hermetic grain storage involves manipulation of gas composition in the air-tight containers to control storage pests. Low oxygen and high carbon dioxide levels in hermetically-sealed containers is achieved through respiratory metabolism of the insects and the grain. High carbon dioxide concentrations and low oxygen prevent development of insects, suppress micro flora activities and reduce grain activity (Moreno *et al*., 2000, Murdock *et al*., 2012). Hermetic storage has been promoted in Asia (Quezada *et al*., 2006; Villers *et al*., 2008), Central America (SDC, 2008a, b) and other countries in the world (FAO, 2008) including Africa as cheap and effective way of controlling storage insect pests (Jones *et al*., 2011; Phiri and Otieno, 2008).

These hermetic storage facilities include; Purdue Improved Cowpeas Storage (PICS), super grain bags, cocoons, metal silos and others. Purdue Improved Cowpeas Storage (PICS) are made of double layer of high density polyethylene (HDPE) bags, inside polypropylene woven or jute bags. Their use in West and Central Africa has been shown to be effective for control of bruchid beetles in cowpeas (Baoua *et al*., 2012a, b; Murdock *et al*., 2012) saving farmers millions of dollars. The International Rice Research Institute (IRRI) promotes use of Super Grain Bags for storage of rice seed. These bags are made up of single layer of high density polyethylene bag that are used as inner layer in other storage bags (jute and Polypropylene) and have been successfully distributed in Asia (Villers *et al*., 2008).

Use of metal silos for grain storage, has been successfully promoted in 16 countries in the world by Food and Agriculture Organization of the United Nations (FAO, 2008) and in Central America by POSTCOSECHA program (Hellin and Kanampiu, 2008) for control of storage insect pests of cereals including larger grain borer. Metal silos are cylindrical air-tight containers made from galvanized iron sheet with joints sealed by capillary soldering using tin-lead (50/50) solder and a soldering iron (CIMMYT, 2011). Metal silos are of different holding capacities of between 100kg- 3,000kgs (CIMMYT, 2009; FAO, 2008; SDC, 2008a). They can be used by farmers and other stakeholders at different levels of the maize value chain depending on the volume of the grain to reduce post-harvest pest losses. In Central America, metal silos are used in combination with Phostoxin (Yusuf and He, 2011) while in Western Australia they are used in combination with carbon dioxide treatments to control storage pests in legumes and cereals (Andrews *et al*., 1994). In Africa, studies have shown metal silos are effective in the control of storage pests including rodents and birds in Kenya, Malawi and Swaziland by various NGOs, FAO and CIMMYT (CIMMYT 2009; FAO, 2008; SDC 2008 a; Tefera *et al.,* 2011 a).

In Kenya, metal silos were introduced by the Catholic Relief Services (CRS) in 2000, mainly in the western region (Nguyo, 2007). They are effective in controlling *S. zeamais* and *P. truncatus* in stored maize for six months without insecticides (CIMMYT, 2011; De Groote *et al.,* 2013). Unlike other hermetic containers being promoted for use by small holder farmers, metal silos are able to store grain for a longer time and prevent attack by rodents, birds and insects (Tefera *et al.,* 2011a). They are relatively expensive (Kimenju and De Groote, 2010) compared to the super grain bags but when well-maintained they have a life span of over 15 years while super grain bags can be used for only 3 years if not perforated (CIMMYT, 2011; FAO, 2003). This technology is affordable to farmers and other stakeholders in the maize value chain because metal silos are available in different sizes of between 100-3000 kgs (CIMMYT, 2009; FAO, 2008). The cost varies depending on size and the country (FAO, 2003). In Kenya, the price of metal silos range from Ksh.3, 000 per 90 kg silo, Ksh.5, 500 for 270 kg silo, Ksh. 8, 600 for 540 kg silo and Ksh.25, 200 for 1800 kg silo (CIMMYT, 2011).

Use of metal silos maintains the quality of the grain and seed if dried to moisture content below 13 %, prevents attack by pests, rodents, mould and birds (Tefera *et al*., 2011a) and require less space. The technology will enable farmers to sell surplus grain at better prices, be food secure, ensure their health and safety and the environment when they eliminate use of insecticides (Tefera *et al*., 2011a). Metal silos also create business opportunities for artisans who engage in production and marketing of locally fabricated metal silos, and create jobs for others (De Groote *et al*., 2013; FAO, 2003; Tefera *et al*., 2011a).

CHAPTER THREE

GENERAL MATERIALS AND METHODS

3.1 Experimental Site

The experiment was conducted at International Maize and Wheat Improvement Center (CIMMYT) and Kenya Agricultural and Livestock Research Organization (KALRO) Kiboko post-harvest insect pest laboratory, located in a semi- arid area at latitude $2^{o}15^{'}$S, longitude $37^{o}75^{'}$ E and 975 m above sea level on the foot of Mwailu Hill. The area experiences a bimodal pattern of rainfall with a mean annual rainfall of 530 mm. The experiment was conducted at ambient conditions with mean temperature of 27 ± 2^{o}C and relative humidity of $58 \pm 5\%$.

3.2 *Prostephanus truncatus* Culture Preparation

Adults of *P. truncatus* were obtained from KALRO/CIMMYT Kiboko post-harvest insect pest laboratory. In the laboratory, *P. truncatus* were reared and cultured on maize seed H513, a hybrid that is susceptible to storage insect pests at ambient conditions (Tefera *et al*., 2010). The grain was cleaned before use by sieving to remove dirt, dust, fine materials, mouldy and broken or shriveled kernels. It was later dried in the sun to a moisture content of 11-12%. The grain was fumigated with Phostoxin tablet (55% *Aluminium phosphide*, 45.0% inert material) in sealed plastic drums for seven days to disinfest it from any possible sources of infestation and the remains of the tablet were removed and incinerated. After fumigation, the grain was thoroughly mixed and aerated for 24 hours before use to avoid residual effect of phosphine gas in the grain. Four hundred grams of the cleaned H513 maize grains were put in an aerated 1.5-liter glass jar. The glass jar lids were 9cm in diameter and were perforated with five small holes of 0.8cm diameter at the four corners and at the center of the lid. A filter paper, 9 cm in diameter was stuck in the inside of the lid to prevent movement of the insects into and out of the glass jar. Two hundred unsexed adults of *P. truncatus* were introduced into the glass jars and covered with perforated lids for ventilation and to avoid insect escape. After ten days of oviposition, all adult insects were removed by sieving to separate the dust, grain and insects using 4.7 mm and 1.0 mm sieves. The grain where the adults had oviposited was kept in clean glass jars for F_1 progeny emergence and put in the rearing shelves in the laboratory (Plate 3.1). This was monitored daily and the emerged progenies were transferred to fresh grain in glass jars with perforated lids. The glass jars were kept at 28 ±2 ^oC, 65 ± 5% relative humidity and in a 12:12, light: dark regime until sufficient numbers of insects were obtained. Humidifiers and heaters (Plate 3.2) were used in the incubation room to maintain these conditions. Temperature and relative humidity in the incubation room was monitored daily with calibrated thermometers, and readings recorded (Tefera, *et al.*, 2010). Each 1.5 litre glass jar was labeled on the outside, indicating the date on which the colony was set up.

Proper sanitation was observed in the rearing room to prevent contamination by mites, psocids, and diseases as described by Tefera *et al.* (2010). The glass jars with the insects were not opened in the colony room nor the insects handled in that area. The work area was kept free of spilled grains and other debris that were capable of harboring insect populations that might infest the stock colony. The work area was also cleaned and sterilized using 70% ethanol before the work began. All equipment (camel hair brushes, sieves, trays and glass jars) which were needed to maintain the insect colony were thoroughly cleaned in hot and soapy water and placed in an oven at 65^oC for 30 minutes before use. Proper personal hygiene was observed and all insect colonies that needed to be discarded were first placed in an oven at 65^oC for at least one hour.

Plate 3. 1 Rearing shelves for *P.truncatus* in the laboratory

Plate 3. 2 Humidifiers, heaters and thermometers in the incubation room

3.3 Grain Preparation

Freshly harvested maize grains of hybrid Duma 41 were bought from farmers, cleaned by sieving to remove dirt, dust, fine materials, mouldy and shriveled kernels. The grains were dried in the sun to 10-11% moisture content and fumigated with Phostoxin tablet (55% *Aluminium phosphide*, 45.0% inert material) in sealed plastic drums for seven days to disinfest it from any possible sources of infestation prior to the start of the experiment. After fumigation, the grain was thoroughly mixed and aerated through sieving before use.

CHAPTER FOUR

EVALUATION OF DIFFERENT SEALING METHODS OF METAL SILOS FOR THE CONTROL OF LARGER GRAIN BORER, *PROSTEPHANUS TRUNCATUS* (HORN) (COLEOPTERA; BOSTRICHIDAE) IN STORED MAIZE

Abstract

Post-harvest losses in stored maize are a major threat to food and income security to small holder farmers in Sub-Saharan Africa. Larger grain borer *(Prostephanus truncatus)* is the most destructive pest causing losses as high as 30% of farm-stored maize in 6 months. Pesticides are available for management of this pest in short periods 3-6 months but they have potential negative effects to human health and the environment. Metal silos are cheap, safe and environmentally friendly. They are reported to be effective in the control of storage pests when properly sealed. To determine the effect of sealing metal silos with different locally available materials for the control *P. truncatus* in stored maize, an on-station trial with four treatments was conducted. The experiment consisted of metal silos with100 kg holding capacity which were loaded with 90 kg of grain and a lighted candle placed on top of the grain. One hundred 10-day old *P. truncatus* were artificially introduced into the grain and the silo lids sealed with rubber band, grease, rubber band combined with grease and without rubber band or grease (control). The treatments were replicated four times, arranged in a completely randomized design and stored in a room roofed with corrugated iron sheets at ambient temperatures of 27±2^{o}C and relative humidity of 58±5%. After thirty five days of storage results exhibited significant ($p<0.05$) differences in weight loss, grain damage and insect mortality. The metal silos sealed using rubber band combined with grease had the least weight loss (0.6%) and grain damage (4.5%) compared to the control which had the highest weight loss (1.9%) and grain damage (6.6%). Metal silo sealed with rubber band combined with grease had higher CO_2 level (2.1% v/v) compared to the control which had the least amount of CO_2 level (0.5% v/v). Insect mortality (100%) was highest in the metal silos sealed

with rubber band, grease and rubber band combined with grease compared to the control which had the least LGB mortality (80%). After incubation, a mean of 3 (F_1) insect progeny emerged in the control and none in the other treatments. Therefore, proper sealing of metal silo with either rubber band or grease and use of lighted candle effectively controlled *P. truncatus* in stored maize.

4.1 Introduction

Maize is a major food security crop and an income earner to many small scale farmers in Africa. Increasing post-harvest losses, rising human population and effects of climate change pose as a threat to food security in most developing countries (Auffhammer, 2011; Jayne and Chapoto, 2006; Tefera, 2012). Songa and Irungu (2010) estimated post-harvest losses at 30% due to post-harvest insect pests, poor grain storage practices and lack of proper storage management technologies. Post-harvest insect pests cause significant quantitative, qualitative and economic losses (Abebe *et al.*, 2009). They are also associated with mycotoxin contamination and poisoning which make grain unsafe for human consumption and animal feed aggravating food insecurity (Tefera *et al.*, 2011a). Maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera; Curculionidae) and *P. truncatus* are among the most destructive pests of stored maize (Tefera *et al.*, 2011b). According to Muhihu and Kibata (1985), *P. truncatus* caused weight losses as high as 35% after storing maize for only 3-6 months while Tefera *et al*. (2011b) reported 67.1% weight loss compared to 6.9% caused by *S. zeamais* in a period of 90 days in a laboratory experiment.

Over the years, farmers have been using organophosphates and pyrethroids on shelled maize (Golob, 2002a) to control post-harvest insect pests. However, over reliance on these pesticides has negative effects on human health, environment and can lead to increased risk of insect resistance to pesticides (Hodges and Meik, 1984). Most small holder farmers cannot afford to use pesticides to control storage pests because they are costly and require frequent applications forcing them to sell their produce soon after harvest at low market prices (Kimenju *et al*., 2009).

Hermetic storage has been explored as a safe and eco-friendly alternative to these challenges. Storage pests are controlled through synergistic effect of low oxygen and high carbon dioxide levels produced by aerobic metabolism of insects, microorganisms and grain respiration in hermetic containers (Quezada *et al*., 2006). Metal silos are among the hermetic containers that have been promoted worldwide to control storage pests (FAO, 2008). They are cylindrical in shape, constructed from galvanized iron sheet and their seams are sealed by capillary soldering using tin-lead (50/50) solder and a soldering iron to ensure that they are airtight (CIMMYT, 2011). Farmers have been filling the metal silos and sealing them with rubber bands. However, the effectiveness of using rubber band as sealing material has not been documented. This study was, therefore, conducted to evaluate the effectiveness of rubber band and other locally available materials in sealing the metal silos for the control of *P. truncatus* in stored maize.

4.2 Materials and Methods

4.2.1 Preliminary trials

Three preliminary trials were conducted before the main experiment to determine the mortality rate of adult *P. truncatus* at different conditions and times.

4.2.1.1 Effect of sealing metal silo lids with different sealing materials on larger grain borer mortality after ten days

Prostephanus truncatus culture and the grain were prepared as described under general methodology in chapter 3 of this thesis. Metal silos with 100 kg holding capacity made of galvanized metal sheet of 24 inch gauge were fabricated locally by a trained tinsmith (Fig 4.1). The metal silo joints were sealed by capillary soldering using tin-lead (50/50) solder and a soldering iron to ensure that they were airtight (CIMMYT, 2011). Four treatments comprising of metal silos loaded with 90 kg of grain each with one 1.5L glass jar containing 400gm of grain and a lighted candle were used. Two hundred (200) newly emerged unsexed 10-day old *P. truncatus* adults were artificially introduced; one hundred (100) into the grain inside the metal silo and another one hundred (100) into the 1.5L glass jar. The glass jar was covered with perforated lid to allow ventilation and prevent escape of insects (Plate 4.1) then placed on top of the grain inside the metal silo. The aim of using glass jar inside the metal silo was to help in fast recovery of all the insects used. A lighted candle was put next to the 1.5 litre glass jar (Plate 4.2) before covering and sealing each metal silo with: (i) treatment 1 (T1), rubber band; (ii) treatment 2 (T2), grease; (iii) treatment 3 (T3), rubber band combined with grease and (iv) treatment 4 (T4), without sealing (control). All treatments were placed on wooden pallets (15 cm high) and arranged in a completely randomized design with four metal silos per treatment. The metal silos were kept for ten days without opening in a room roofed with corrugated iron sheets at ambient temperature of 27±2 ^{o}C and relative humidity of 58±5 %.

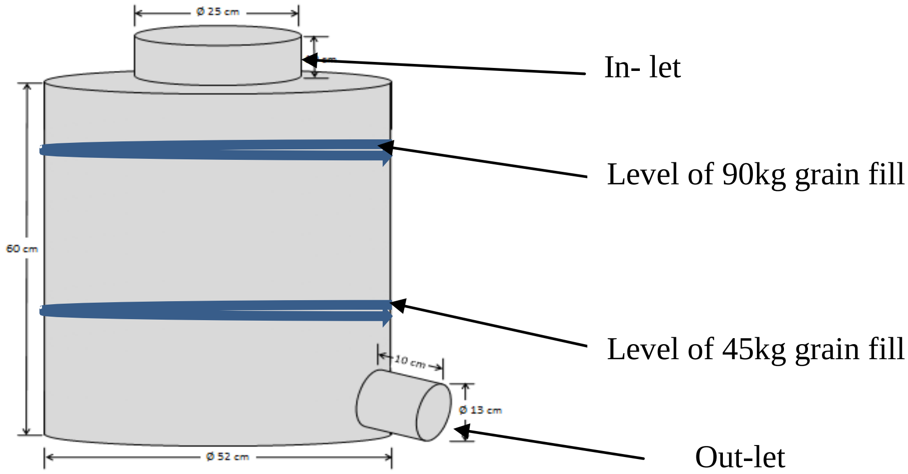

Figure 4. 1. Metal silo with a holding capacity of 100 kg of grain

Plate 4. 1 One and a half (1.5) litre glass jar with 400gram of grain (right) covered with a perforated lid(left).

Plate 4. 2 A lighted candle put next to an aerated 1.5 litre glass jar in a metal silo

4.2.1.2 Mortality rate of adult larger grain borer in metal silos sealed with different materials in different days

A 4x 4 factorial experiment consisting of metal silos sealed with rubber band, grease, rubber band combined with grease and without rubber band or grease (control) was conducted and the grain observed on third, sixth, ninth and twelfth day. The grain and *P. truncatus* culture used in the experiment were prepared as described under general methodology in chapter three of this thesis.

Metal silos loaded with 90 kg of grain, four 1.5L aerated glass jars each containing 400 gm of grain and a lighted candle were used. Five hundred, (500) newly emerged unsexed 10-day old adult *P. truncatus* were artificially introduced; one hundred (100) into the grain inside the metal silo and another hundred (100) in each glass jar. The four aerated glass jars were placed on top of the grain next to a lighted candle in the middle of each metal silo (Plate 4.3) before covering and sealing the metal silos with: (i) Rubber band; (ii) grease; (iii) rubber band combined with grease; and (iv) without sealing. Observations were done on the third, sixth, ninth and twelfth day in all the four treatments. All the metal silos were placed on wooden pallets (15 cm high) and arranged in a completely randomized design with three metal silos per treatment. The metal silos were kept in a room roofed with corrugated iron sheets at ambient temperature of 27 ± 2^{o}C and relative humidity of 58±5%. At each time period, the metal silo was opened and one 1.5litre aerated glass jar removed. A candle was lit and placed on top of the grain each time the metal silo was opened. It was left burning inside the metal silo to deplete oxygen as the metal silo was covered with the lid and sealed.

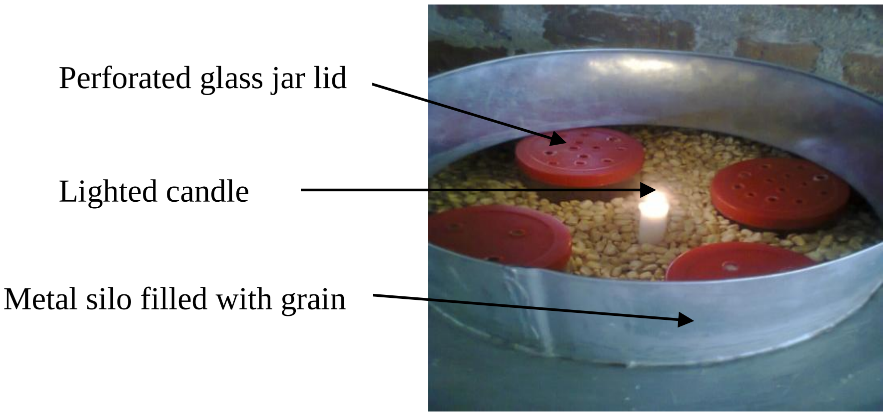

Plate 4. 3 Maize in metal silo with a lighted candle next to aerated 1.5 litre glass jar

4.2.1.3 Mortality rate of larger grain borer in aerated and airtight glass jars under controlled and ambient conditions

A 4x2x2 factorial experiment was conducted in a laboratory using 1.5 litre aerated (glass jar covered with perforated lid) and airtight glass jars, at ambient (30±2^{o}C, 57±5% relative humidity) and controlled conditions (28±2^{o}C and 65±5% relative humidity). These controlled conditions were optimal conditions developed for mass rearing of larger grain borer in the laboratory (Tefera *et al.*, 2010). The grain was observed at four different time periods: third day; sixth day; ninth day; and twelfth day. *Prostephanus truncatus* culture and the grain used to carry out this experiment were prepared as described under general methodology in chapter 3 of this thesis.

The following four treatments comprising of aerated 1.5L glass jar under ambient versus controlled conditions as described in 4.2.1.3 above were used. In each glass jar, four hundred (400) grams of grain was loaded and one hundred (100) newly emerged 10-day old *P. truncatus* artificially introduced into the grain. The observations were done after: (i) three days; (ii) six days; (iii) nine days; and (iv) twelve days. A similar set up using the same treatments was done using airtight 1.5 l glass jars. Each treatment was replicated three times and arranged in a completely randomized design in the laboratory (Plate 4.4).

Plate 4.4 Aerated and air-tight glass jars with maize at ambient conditions in the laboratory.

4.2.2 Evaluation of different sealing methods for metal silo against gas composition, grain damage and *P. truncatus'* survival in stored maize

The site of the experiment and method of preparing grain and *P. truncatus* culture was as described under general methodology in chapter 3 of this thesis.

The following four treatments comprising of metal silo loaded with 90kg of grain, a 1.5 litre glass jar containing four hundred gram (400gm) of grain and a lighted candle were used. Two hundred (200) newly emerged unsexed 10-day old *P. truncatus* adults were artificially introduced; one hundred (100) into the grain in the metal silo and another one hundred (100) into the glass jar. The glass jar was placed on top of the grain in the metal silo next to a lighted candle before covering and sealing it with: (i) Treatment 1 (T1), rubber band (Plate 4.5); (ii) treatment 2 (T2), grease (Plate 4.6); (iii) treatment 3 (T3), rubber band combined with grease (Plate 4.7); (iv) treatment 4 (T4), without sealing (control) (Plate 4.8). All the metal silos were placed on wooden pallets (15 cm high) and arranged in a completely randomized design with four metal silos per treatment. They were stored for five weeks (35 days) in a room roofed with corrugated iron sheets at ambient temperatures of 27±2^{o}C and relative humidity of 58±5%.

Plate 4. 5 100-kg metal silo with the in-let and out-let sealed with rubber band (T1)

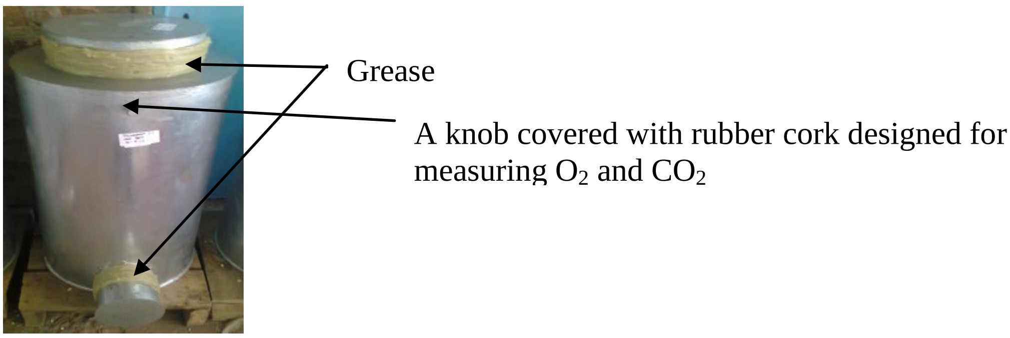

Plate 4. 6 One hundred kilogram metal silo with the in-let and out-let sealed with grease (T2)

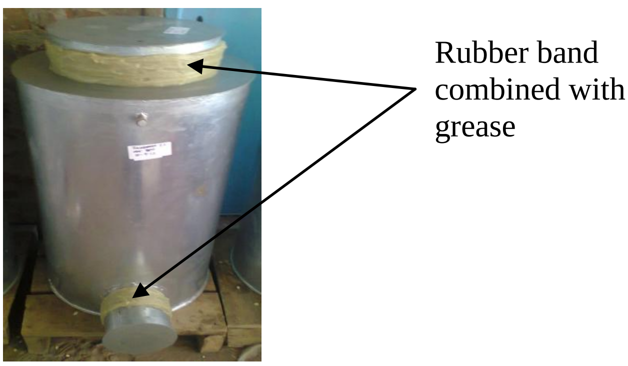

Plate 4. 7 One hundred kilogram metal silo with the in-let and out-let sealed with rubber band combined with grease (T3)

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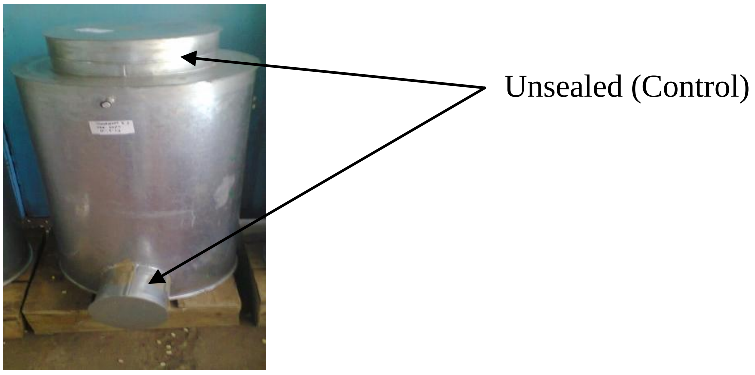

Plate 4. 8 One hundred kilogram metal silo with unsealed in-let and out-let (control) (T4)

4.3 Data collection

4.3.1 Preliminary trials

The contents of each glass jar were separately sieved using 4.7 mm and 1.0 mm sieves (Endecotts Limited, UK) (Plate 4.9), to separate the grains, insects (live and dead) and dust produced following a method by Tefera *et al*. (2011b). Data on percent insect mortality and grain damage were collected in each trial.

4.3.1.1 Insect mortality and grain damage

The number of dead and live *P. truncatus* were separated, counted and recorded separately from each glass jar in each metal silo per treatment. Percent insect mortality was expressed as a proportion of dead insect over the total number of insects used (Tefera *et al*., 2011b).

A sample of 250 grams of the grain was taken separately from each glass jar in each trial to assess grain damage. The total number of damaged grains (holed and windowed kernels) and undamaged grains were counted and their weight recorded. Percent grain damage was determined separately from each glass jar in each metal silo per treatment as described by Tefera *et al*. (2011b).

Plate 4. 9 Sieves (Endecotts Limited, UK) of 4.7mm and 1.0mm used to separate grains, insects and dust.

4.3.2 Evaluation of different sealing methods for metal silo against gas composition, grain damage and *P. truncatus'* survival in stored maize

This main activity was carried out after preliminary trials in section 4.3.1 of this thesis were completed. Grain samples were collected from each metal silo in each treatment using a compartmentalized double tube sampling spear (Seedburo Equipment, Company Chicago, USA) (Plate 4.10) at the start and end of the experiment. A primary sample of five sub-samples was taken from the periphery (South, North, East and West direction) and at the centre of the metal silo from three different levels; top (40 – 50 cm), middle (20 – 40 cm) and the bottom (10 – 20 cm). They were put in a tray and mixed to make a composite sample from which one (1) kilogram of the sample was drawn randomly.

Data on insect mortality and F_1 progeny emergence, grain damage, weight loss, percent dust, oxygen and carbon dioxide level, germination rate, grain nutritional value, moisture content and aflatoxin level of the stored grain were taken.

Plate 4. 10 Compartmentalized double tube sampling spear for sampling grain in the containers.

4.3.2.1 Insect mortality and F_1 progeny emergence

Insect mortality: At the end of the experiment, the contents of each metal silo were separately sieved as shown in Plate 4.11. Those from the glass jars were sieved using 4.7mm and 1.0mm sieves as described in section 4.3.1 to separate the grains, insects (live and dead) and dust. The number of dead and live *P. truncatus* from each glass jar and metal silo per treatment were counted and recorded separately. Insect mortality was determined as described in section 4.3.1.1 above.

F_1 progeny emergence: Grain from each glass jar in each metal silo per treatment was separately put in clean aerated 1.5 litre glass jars after analyzing for grain damage and weight loss. From each metal silo, four hundred (400) gram of grain was taken randomly, separately put in 1.5 litre aerated glass jar and incubated in the laboratory at temperatures of 28 ± 2^oC, relative humidity of 65 ± 5%, in a 12 hrs:12 hrs, light: dark regime for F_1 progeny emergence. The grains were monitored daily for F_1 insect emergence from 40–56 days after incubation.

The emerging F_1 progenies were removed, counted and recorded on each assessment day (Tefera *et al*., 2011b).

Plate 4. 11 Sieving of grain from metal silos at the end of the experiment

4.3.2.2 Percent grain damage, weight loss and dust

A sub- sample of 250g from each metal silo per treatment was obtained by sub-dividing the 1 kg primary sample collected in 4.3.2 above, using a Borner divider. The contents of 1.5 litre glass jars in each metal silo were separately sieved using 4.7 mm and 1.0 mm sieves and a 250 gram sample taken to assess grain damage and weight loss. Grain damage in glass jars and metal silos was determined separately as described by Tefera *et al*. (2011b). The damaged and undamaged grains from each glass jar and metal silo per treatment were counted and weighed separately. Percent weight loss was determined using the count and weigh method (Gwinner *et al*., 1996);

$$\text{Weight loss } \% = \frac{(Wu \times Nd)-(Wd \times Nu) \times 100}{Wu \times (Nd + Nu)}$$

Where:

Wu = weight of undamaged grain,

Nu= number of undamaged grain,

Wd = Weight of damaged kernel and

Nd = Number of damaged kernels.

The weight of the dust obtained from each glass jar and metal silo after sieving was weighed and recorded separately. Percent dust was determined by expressing dust weight as a proportion of the initial sample weight (Tefera et al., 2011b).

4.3.2.3 Oxygen and carbon dioxide measurement

The metal silos were designed to have a small hole fitted with an elastic rubber cork, 5 cm from the neck of the metal silo from where oxygen and carbon dioxide levels were measured (Plate 4.6) using portable Mocon PAC CHECK® Model 325 Headspace analyzer (Mocon, Minneapolis, MN, USA) fitted with a 1.15” 20 gauge needle for sampling through rubber septa (Plate 4.12). Data on oxygen and carbon dioxide levels in the headspace of the metal silos were recorded every week.

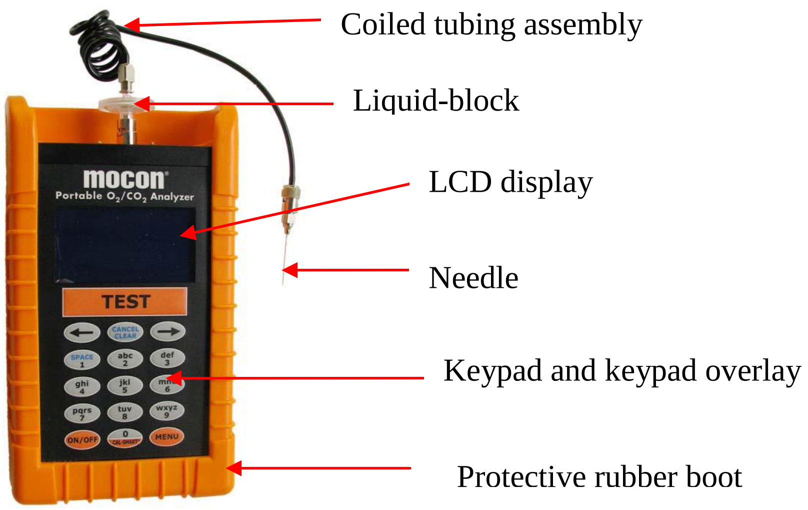

Plate 4. 12 Mocon PAC CHECK® Model 325 used to measure oxygen and carbon dioxide levels

4.3.2.4 Grain germination rate, nutritional analysis and moisture content

Grain germination rate was done by randomly sampling 100 seeds from each metal silo per treatment and sowing them between two humid filter papers in a petri dish. The petri dishes were placed in a room at ambient condition of 25-30^{o}C and watered twice for a week (ISTA, 2004). After seven days, the germinated seeds were counted and expressed as a proportion of the total seeds sown (ISTA, 2004). Grain nutritional analysis was assessed by taking a random sample of 100 gram of grain from each metal silo per treatment. The grain was analyzed for starch, protein, oil and moisture content using Infratec ^{TM} 1241 Grain Analyzer (GRAINtec, 2011) before and after the experiment in three replications. The Infratec™ 1241 Grain Analyzer is a whole grain analyzer which uses the infrared technology and gives instant readings of the set parameters (Plate 4.13).

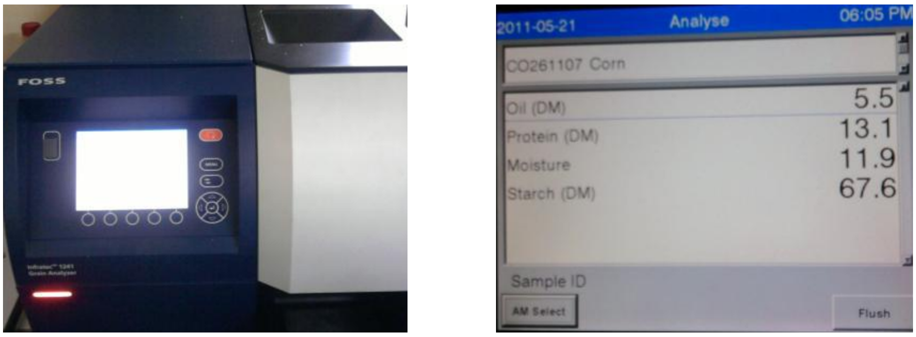

Plate 4. 13 Infratec ^{TM} 1241 Grain Analyzer showing some readings on protein, oil, starch and moisture content (left)

4.3.2.5 Aflatoxin Analysis of the stored grain in the experiment

Aflatoxin level in the grain was analyzed before and after the experiment using direct competitive Enzyme- Linked Immunosorbent Assay (ELISA) (Gathumbi *et al*., 2001). One hundred grams of grain from each metal silo per treatment was sub-sampled from 1kg sample collected in section 4.3.2.1 above, ground to fine powder and thoroughly mixed in a mixer.

Five grams of the ground sample was put in a vial with 25 ml of 70% methanol and vortexed. Methanol extract was de-fatted with 10ml hexane and the mixture centrifuged at 3500 rpm for 10 minutes. Four millilitre (4 ml) supernatant was decanted and diluted to 1:5 in Phosphate Buffer Saline (PBS) and in 1:4 in methanol-PBS (9:1) before ELISA analysis. Micro-titre polystyrene plates were coated by adding 50 microliter (µl) of anti- aflatoxin antibody in bicarbonate buffer in each well and incubated overnight in a moist chamber. The plates were emptied and free protein binding sites blocked by adding 200 µl of 3% bovine serum albumin in PBS for 20 minutes. The plates were washed thrice with distilled water and semi-dried by tapping upside down against an absorbent paper. Four aflatoxin standards with concentration levels; 1 ng/ml, 0.333 ng/ml, 0.111 ng/ml and 0 ng/ml were used. Fifty micro litre (50 µl) of sample extract and 50 µl of aflatoxin standards were added in separate duplicate wells in the plate. Fifty micro litre (50 µl) of diluted aflatoxin-enzyme conjugate solution and 50 µl of diluted antibody solution were added in each well and mixed gently by shaking the plate manually and incubated at room temperature for 30 minutes in the dark.

The liquid was poured, the plate washed thrice with distilled water and semi-dried against an absorbent paper. An enzyme substrate of 50 µl and 50 µl of chromogen was added in each well, mixed gently and incubated for 30 minutes in the dark at room temperature. Enzyme reaction was stopped by adding 100 µl 1 M H_2SO_4 and mixed gently. The absorbance was read using a spectrophotometer ELISA reader (model Uniskan 11 type 364 Labystems, Finland) at 450 nm. The optical density (OD) values of standard dilutions were used to construct a standard curve and the aflatoxin content of each sample was determined by interpolating on the curve. The readings from the calibration curve were multiplied by a dilution factor of 35 to get the actual aflatoxin concentration in the samples in ng/kg. Higher aflatoxin levels confer to light colour that leads to low optical density (OD) value and vice versa.

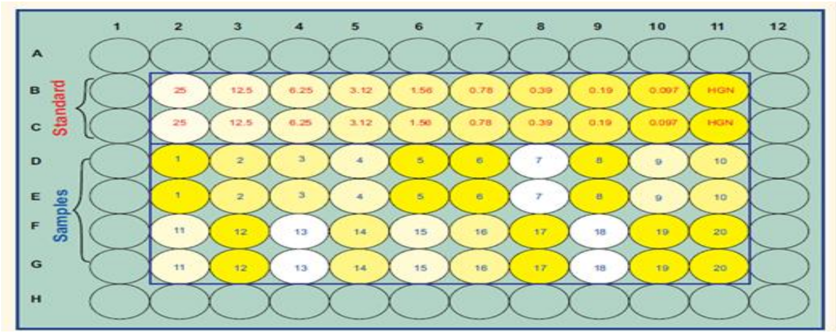

Plate 4. 14 ELISA plate design for analysis of aflatoxin in maize grain

4.4 Data analysis

Data analysis was done using statistical software GenStat 14th Edition. Prior to statistical analysis, the number of emerged F_1 off-spring was transformed using Log_{10} (X+1), where X is the observed value. Percent grain damage, percent weight loss and percent dust produced were angular-transformed (arcsine √proportion) to stabilize the variances. Data on aflatoxin, starch content, percent germination, protein content, oil content, oxygen and carbon dioxide levels were not transformed. One- way analysis of variance (ANOVA) was used to analyze data. Mean separation was done using Fisher's Protected LSD test at 5% probability level to compare the significant differences between treatments. The final results presented in tables and figures are untransformed values.

4.5 Results

4.5.1 Preliminary trials

4.5.1.1 Effect of sealing metal silos with different sealing materials on larger grain borer mortality after ten days

Sealing methods of the metal silos significantly ($F_{3, 12} = 0.001$; $p<0.05$) affected LGB mortality after ten days of storage without opening compared to the control. The highest mortality (100%) was observed in glass jars inside the metal silos sealed with rubber band and rubber band combined with grease. Although a similar trend was observed in the grain stored in the metal silos, mortality was lower in the metal silos than in the glass jars. Metal silo sealed with rubber band did not differ significantly with metal silo sealed with rubber band combined with grease achieving LGB mortality of 90% and 88%, respectively. However, they differed significantly with the metal silos sealed with grease and the control which achieved LGB mortality of 72 % and 10% respectively (Table 4.1). Sealing methods significantly affected grain damage after ten days of storage without opening compared to the control. Grain damage did not differ significantly in the metal silo sealed with rubber band (3.4%) and that sealed with rubber band combined with grease (3.5%). However, grain damage in these silos differed significantly with metal silos sealed with grease (3.9%) and the control (6.8%) (Table 4.1). The damage of grains in glass jars inside the metal silos sealed with rubber band, grease and rubber band combined with grease did not differ significantly (Table 4.1).

Table 4. 1 Grain damage and insect mortality in metal silos sealed with different materials for 10 days

Treatment/ sealing material	Grain damage (%)		Mortality (%)	
	glass jar	metal silo	glass jar	metal silo
Rubber band	3.2a	3.4a	100b	90b
Grease	3.4a	3.9b	86a	72a
Rubber band combined with grease	3.3a	3.5ab	100b	88b
Control (unsealed)	6.1b	6.8c	23c	10c
LSD (5%)	0.2	0.4	2	2.5
CV (%)	3.9	2	1.6	2.5
$F_{3,12,5\%}$	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

4.5.1.2 Mortality rate of the adult larger grain borer in metal silos sealed with different materials on different days

Sealing methods significantly ($F_{3,8}$ =0.001;p <0.05) affected LGB mortality in glass jars in all the days compared to the control. Over time, mortality in the glass jars increased in all the treatments with the highest (100%) recorded on the twelfth day and the least on third day (17%) in the control (Table 4.2). Sealing methods did not significantly affect grain damage in glass jars on the third, sixth and ninth day compared to the control (Table 4.2). Sealing methods significantly ($F_{3,8}$ =0.001; p <0.05) affected insect mortality inside the glass jars and in the metal silos compared to the control on the twelfth day (Table 4.3). Mortality in the glass jars was higher than in the metal silos: glass jars inside the metal silo sealed with rubber band and rubber band combined with grease had 100% mortality each; while those sealed with grease and the control had 94% and 41% respectively. Metal silos sealed with rubber band had 59% LGB mortality, rubber band combined with grease 50%, grease 49% and control 20% (Table 4.3). On the twelfth day, sealing methods did not significantly ($F_{3,8}$ =0.13; p <0.05) affect grain damage in the glass jars and the metal silos (Table 4.3).

Table 4. 2 Grain damage and insect mortality in glass jars inside the metal silos sealed differently on different days

Sealing methods	Grain damage (%)				Mortality (%)			
	Day 3	**Day 6**	**Day 9**	**Day 12**	**Day 3**	**Day 6**	**Day 9**	**Day 12**
Rubber band	8.0a	8.1a	8.7a	6.1a	84b	87a	96ab	100b
Grease	8.0a	7.7a	9.8a	8.8ab	71a	82a	94a	94a
Rubber band combined with grease	7.7a	7.6a	10.2a	7.1ab	80b	87a	99b	100b
Control	8.5a	10a	10.6a	10.9b	17c	22b	27c	41c
LSD (5%)	5.1	2.9	5.9	4.2	5.1	5.5	4.9	3.4
CV %	18.5	9.2	16.7	15	4.3	4.2	3.3	2.2
$F_{(3, 8, 5\%)}$	0.99	0.25	0.89	0.13	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

Table 4. 3 Grain damage and insect mortality in glass jars and metal silos sealed differently on the twelfth day

Sealing methods	LGB Mortality %		Grain damage %	
	Glass jar	**Metal silo**	**Glass jar**	**Metal silo**
Rubber band	100b	59a	6.1a	3.2a
Grease	94a	49a	8.8ab	4.2a
Rubber band combined with grease	100b	50a	7.1ab	4.0a
Control	41c	20b	10.9b	4.5a
$LSD_{(5\%)}$	3.4	25	4.2	2.3
CV (%)	2.2	14	15	15
$F_{(3, 8, 5\%)}$	<0.001	0.03	0.13	0.61

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

4.5.1.3 Mortality rate of larger grain borer in aerated and airtight glass jars under controlled and ambient conditions

Insect mortality: In aerated glass jars, there were significant differences on percent insect mortality under controlled ($F_{3, 8}$ =0.001; p <0.05) and ambient ($F_{3, 8}$ =0.011; p <0.05) conditions. At day three under controlled condition, LGB mortality was the least compared to the mortality at 6, 9 and 12 days (Table 4.4). Similarly under ambient condition, the third day had significantly the least LGB mortality compared to those which were collected thereafter (Table 4.4). Grain damage was significant ($F_{3, 8}$ =0.001; $p < 0.05$) in different time periods of storage under controlled and ambient conditions in aerated glass jars (Table 4.4). In airtight glass jars, percent insect mortality was higher compared to aerated glass jars under both conditions in all the days (Table 4.5). In the airtight glass jars, grain damage was significantly different under controlled conditions but did not differ under ambient conditions (Table 4.5).

Table 4. 4 Insect mortality and grain damage in aerated glass jars under controlled and ambient conditions in different days

Time period in days	**Mortality**		**Grain damage**	
	Controlled condition	**Ambient condition**	**Ambient condition**	**Controlled condition**
3	22a	15a	11.8b	8.3a
6	27b	21b	15.1c	10.3c
9	28b	20b	10.0a	9.6b
12	34c	21b	12.2b	10.0c
LSD $_{(5\%)}$	4.5	3.3	1.0	0.3
C V %	8.4	9	4.2	1.9
F $(_{3, 8, 5\%})$	<0.001	0.011	<0.001	<.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

Table 4. 5 Insect mortality and grain damage in airtight glass jars under controlled and ambient conditions in different days

Time period in days	Mortality		Grain damage	
	Controlled conditions	Ambient conditions	Controlled conditions	Ambient conditions
3	95a	91a	7.4b	7.7a
6	96a	96a	7.6b	7.3a
9	95a	96a	6.6a	7.5a
12	100b	94a	7.8b	7.4a
LSD $_{(5\%)}$	3.8	7.2	0.6	4.3
CV (%)	2.1	4	4.4	15.3
F $(_{3, 8,5\%})$	0.08	0.374	0.008	1

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

4.5.2 Evaluation of the effect of different sealing methods for metal silo on gas composition, grain damage and *P. truncatus'* survival in stored maize

4.5.2.1 Insect mortality and F_1 progeny emergence

Sealing methods significantly affected insect mortality ($F_{3, 12} = 0.001$; $p<0.05$) and F_1 progeny ($F_{3, 12} = 0.001$; $p<0.05$). There was 100% insect mortality and zero (0) F_1 progeny for the tested sealing methods compared to the control which had 80% LGB mortality and the three F_1 progenies, thirty five days after treatment application (Table 4.6).

Table 4. 6 Mean adult mortality and F_1 progeny emergence in maize stored in metal silos sealed with different sealing methods after 35 days

Sealing methods	LGB % mortality	No. of F_1 progeny
Rubber band	100b	0a
Grease	100b	0a
Rubber band combined with grease	100b	0a
Control (unsealed)	80a	3b
LSD $_{(5\%)}$	3.2	1.0
CV (%)	2.1	16.3
F $_{(3, 12, 5\%)}$	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level

4.5.2.2 Percent weight loss, grain damage and dust

Sealing methods significantly affected percent weight loss ($F_{3, 12}$= 0.05; p<0.05) compared to the control. Grains stored in the control suffered the highest weight loss of 1.9% followed by metal silos sealed with grease (1.0%), rubber band (0.9%) and rubber band combined with grease (0.6%) (Fig 4.2). Sealing methods did not significantly affect grain damage ($F_{3, 12}$= 0.25; p<0.05) and percent dust ($F_{3, 12}$= 0.19; p<0.05) (Table 4.7).

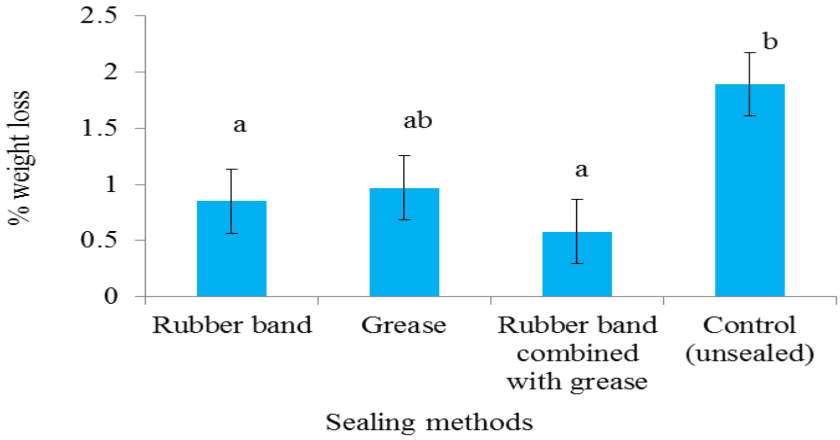

Figure 4.2. Weight loss (%) incurred in metal silos sealed with different sealing methods after 35 days

Table 4. 7 Percent grain damage and dust in metal silos sealed with different sealing methods after 35 days

Sealing method	Grain damage (%)	Dust (%)
Rubber band	5.0a	1.7b
Grease	5.4a	1.7b
Rubber band combined with grease	4.5a	1.6a
Control (unsealed)	6.6b	2.2c
LSD $_{(5\%)}$	1.2	0.2
CV (%)	13.3	9.5
$F_{3,12,5\%}$	0.25	0.191

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

4.5.2.3 Oxygen concentration in metal silos

Sealing methods significantly ($F_{3, 12}$ =0.001; $p < 0.05$) affected oxygen levels in metal silos. The metal silos sealed with rubber band combined with grease had the lowest oxygen mean of 18.1% v/v, rubber band (18.3% v/v), grease (18.7% v/v) and control (20.4% v/v) (Fig 4.3). After thirty five days of storage, oxygen level had decreased from the standard oxygen level of 21 % v/v in normal atmosphere to 16.6% v/v (rubber band combined with grease), 16.8% v/v (rubber band), 17.9% v/v (grease) and in control 20.7% v/v (Fig 4.4).

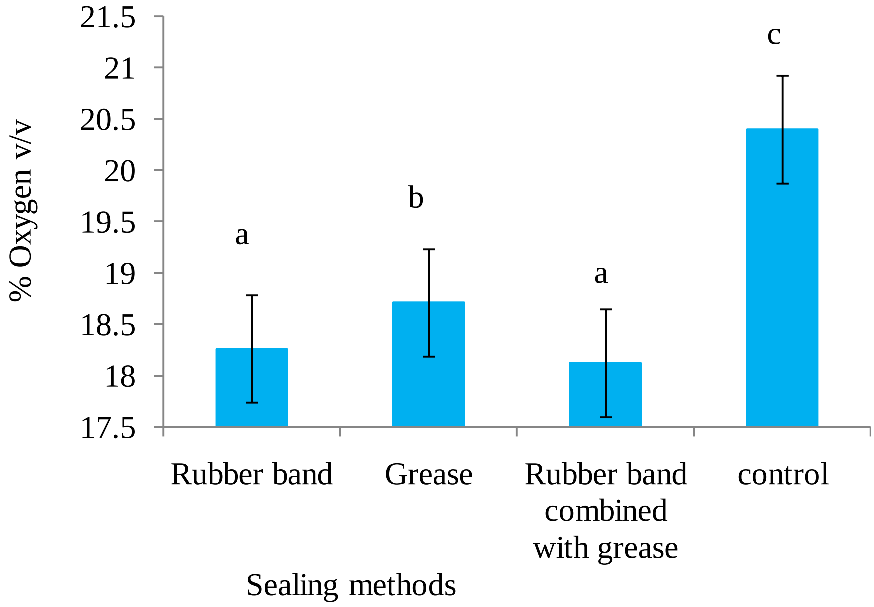

Figure 4.3. Mean oxygen levels in metal silos sealed with different sealing methods after 35 days

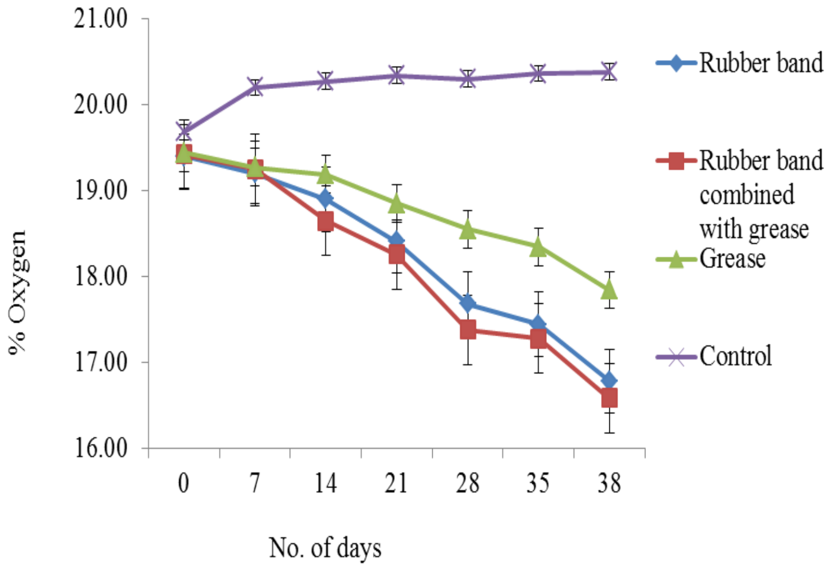

Figure 4.4. Weekly oxygen trend in metal silos sealed with different sealing methods after 35 days

4.5.2.4 Carbon dioxide concentration in metal silos

Sealing methods significantly ($F_{3, 12}$ =0.001; p <0.05) affected carbon dioxide level after thirty five days of storage. Metal silos sealed with rubber band combined with grease had the highest CO_2 mean of 2.1% v/v, rubber band (1.9% v/v), grease (1.1% v/v) compared to the least in control (0.5% v/v) (Fig 4.5). The level of CO_2 increased from the normal level of 0.038% v/v in the atmosphere to over 1% v/v when the candle was lit in all the treatments. The level of CO_2 increased in metal silo sealed with rubber band combined with grease to 3.3% v/v; rubber band, (2.9% v/v; and grease, 1.7% v/v in a period of 35 days. However, in control, the CO_2 level decreased from 0.8% v/v to 0.5% v/v (Fig 4.6).

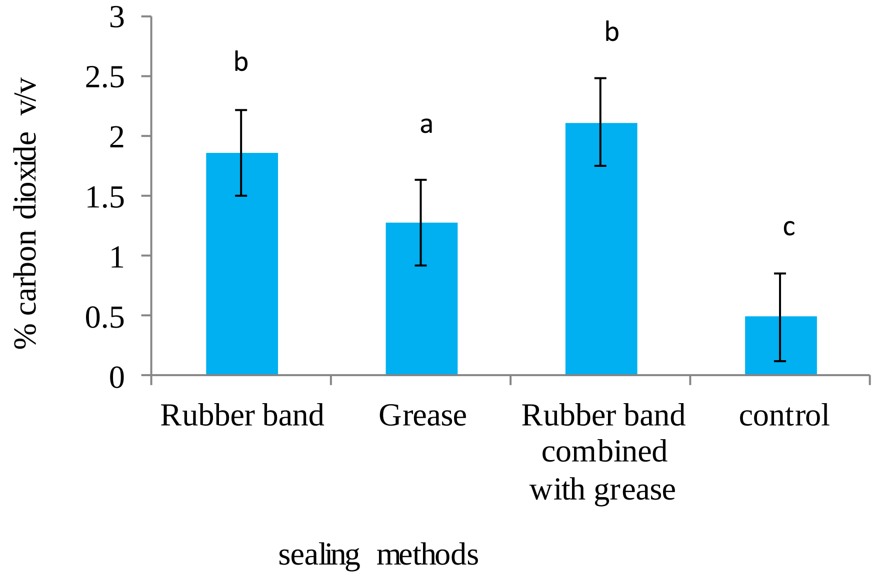

Figure 4.5. Mean carbon dioxide level in metal silo sealed with different sealing methods after 35 days

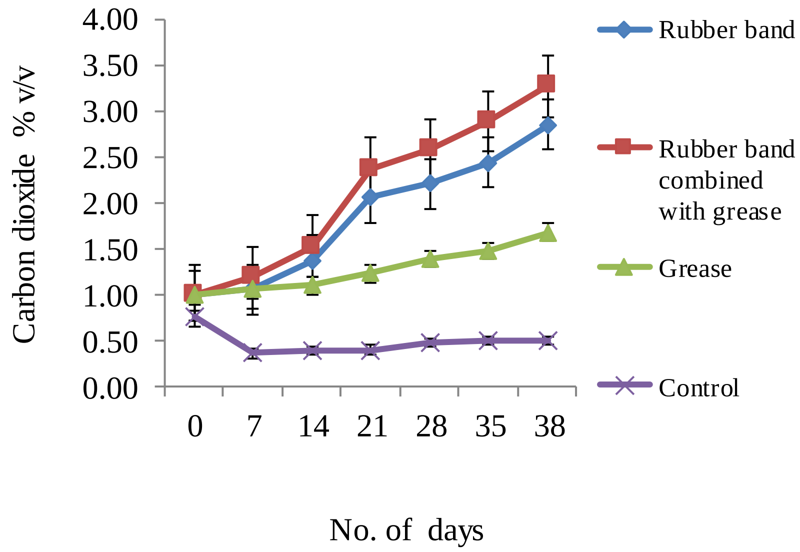

Figure 4.6. Weekly carbon dioxide trend in metal silos sealed with different sealing methods after 35 days

4.5.2.5 Grain nutritional content, moisture content and germination rate

Grain nutritional content was measured in terms of grain moisture content, oil content, starch content, protein content and aflatoxin levels. Sealing methods did not affect grain moisture ($F_{3,\ 12}$= 0.974; p<0.05), oil content ($F_{3,\ 12}$= 0.941; p<0.05), starch ($F_{3,\ 12}$= 0.978; p<0.05), protein content ($F_{3,\ 12}$= 0.319; p<0.05) and aflatoxin levels ($F_{3,\ 12}$= 0.714; p<0.05) after storing maize grain in metal silos for thirty five days (Tables 4.8 and 4.9). Germination rate was not significantly ($F_{3,\ 12}$= 0.252; P<0.05) affected by the sealing methods but it reduced from 86% - 79% after storing the grain for thirty five days (Table 4.9).

Table 4. 8 Percent protein, oil and starch content in grain stored in metal silo sealed with different sealing methods after 35 days of storage

Treatment	**Protein (%)**		**Oil (%)**		**Starch (%)**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**
Rubber band	10.3b	10.3b	5.5a	5.5a	69.1a	69.0a
Grease	10.2a	10.2a	5.5a	5.5a	68.9a	68.9a
Rubber band combined with grease	10.2a	10.2a	5.4a	5.5a	69a	69a
Control	10.3b	10.3b	5.5a	5.5a	69a	69a
LSD 5%	0.3	0.2	0.2	0.2	0.7	0.4
CV (%)	1.5	1	2	2.1	0.6	0.3
$F_{3,12,5\ \%}$	0.02	0.32	0.33	0.94	0.88	0.98

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

Table 4. 9 Comparison of moisture content, germination rate and aflatoxin (ppb) level in grain stored in metal silo sealed with different methods after 35 days

Treatment	Moisture (%)		Germination (%)		Aflatoxin (ppb)	
	Initial	Final	Initial	Final	Initial	Final
Rubber band	10.5a	9.9a	86a	79a	0.68a	0.69a
Grease	10.6a	9.9a	86a	79a	0.96a	0.92a
Rubber band combined with grease	10.6a	10.0a	85a	78a	0.93a	0.96a
Control	10.5a	10.2a	86a	83a	1.27a	1.29a
LSD 5%	0.2	0.3	4.7	5.5	0.7	1.35
CV (%)	1.2	1.8	3.5	5.1	11.4	10.9
$F_{3,12,5\,\%}$	0.98	0.17	0.96	0.01	0.44	0.15

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

4.6 Discussion

Hermetic containers are effective in the control of post-harvest insect pests due to the synergistic effect of low oxygen and high carbon dioxide levels in the inter-granular atmosphere in the container. This deprives the insect of water and leads to their death due to desiccation (Murdock *et al.,* 2012; Calderon and Navarro, 1980). All insects died (100%) in metal silos that were sealed with rubber band, grease and rubber band combined with grease after thirty five days of storage and over 90% died in airtight glass jars within twelve days. As a result, no F_1 progeny emerged in the metal silos which had higher levels of carbon dioxide and low oxygen compared to the control. It is probable that the sealing method deprived the insects air exchange hence there was little oxygen after the candle was lit leading to their death by the 12th day. Moreno *et al.* (2000) reported 100% mortality of *S. zeamais* and no insect emerged after 12 days of storing maize grain under hermetic conditions. According to Sekyembe *et al*. (1993), under favourable conditions, LGB larvae hatch from eggs in 3-7 days. However, in this study, F_1 progeny could not emerge in metal silos probably because the females were unable to oviposit after oxygen level was decreased and carbon dioxide increased during storage. LGB mortality rate in the control was noted to be high (80%) after thirty five days of storage. This we attribute to the elevated CO_2 level (0.8 % v/v) as a result of using lighted candle inside the metal silo at the start of the experiment. Low emergence of F_1 progeny in the control indicates that some adult females were able to oviposit the eggs since the oxygen was depleted over a slow rate compared to the silos that were sealed. A study by Baoua *et al.* (2012b) reported that *Callosobruchus maculatus* eggs under hermetic condition were tolerant to low O_2 and high CO_2 levels unlike the adults and larvae. The eggs were able to develop when conditions were rendered favourable. Other than the elevated CO_2 and low O_2 level in metal silos, other factors could have contributed to the high insect mortality in hermetically sealed metal silos and airtight glass jars. Reuss and Pratt (2001) and Whittle *et al.* (1994) reported the presence of carbon monoxide gas in the headspace of stored canola and dry grains in sealed vessels. Similar observations were reported by Whittle *et al.* (1994) when canola, field peas, oats and paddy rice were kept in sealed glass vessels. Although in the control there was low mortality 80% of insects, it demonstrates the silos' ability to store grain for thirty five days without insecticides.

A negative correlation between gas composition (low oxygen and high carbon dioxide levels), weight loss, grain damage and percent dust was observed in the metal silos. Metal silos sealed with rubber band, grease and rubber band combined with grease had lower weight losses, grain damage and dust compared to the unsealed metal silos (control). This could be attributed to slowed insect feeding activity when O_2 level in the sealed metal silos fell below the normal level (21%) in comparison with the control. Murdock *et al.* (2012), in their study observed slowed insect feeding activity when oxygen fell below ambient level and completely ceased when oxygen fell to 1-4% in PICS bags. In this study, grain damage was relatively higher than normal a phenomena that could be explained by the fact that this maize was bought from different farmers who handled their grain differently and hence some had high numbers of discoloured and damaged kernels. However, it is worth noting that the number of insect damaged kernels (holed and windowed) in the sealed metal silos was far much lower compared to those in the control at the end of the experiment. Similarly percent dust in the metal silos was also low.

Oxygen (O_2) level in metal silos sealed with rubber band, grease and rubber band combined with grease was reduced to below the normal level (21% v/v) while carbon dioxide (CO_2) increased with time to over 10 times the normal CO_2 level (0.038% v/v) in the atmosphere. According to Calderon and Navarro (1980) and Murdock *et al*. (2012), metabolic activities of the insects, microorganisms and grain respiration utilize oxygen and elevate carbon dioxide level in hermetic containers. The amount of oxygen consumed and carbon dioxide produced in hermetic containers is dependent on the level of insect infestation and the rate of grain respiration. In this study, the elevated CO_2 level was as a result of using lighted candle inside the metal silos in combination with metabolic activities of the insects and grain respiration. Navarro *et al*. (1994) reported reduced oxygen level of below 10% v/v in 180 days when 2 insects/ kg were used and 5% v/v in less than 90 days when 8 insects/ kg of grain were used in a liner with an oxygen ingress rate of 0.24% /day. Baoua *et al*. (2012b) also reported reduced oxygen level to 3% v/v and increased carbon dioxide level of 5% v/v when an average of 24 insects/kg of grain were used in Purdue Improved Cowpeas Storage (PICS) bags. Since most farmers do not disinfest their grain before storing, an insect infestation level of 1 insect/kg of grain was used in this study to mimic low levels of insect infestation that is likely to occur while the crop is still in the field.

The low level of insect infestation may have contributed to the slow rate of O_2 depletion and CO_2 production in metal silos compared to observations by Baoua *et al*. (2012b) in PICS bags. Moisture content of the grain before storage plays a key role in determining the rate of grain respiration. Studies by Ragai and Loomis, (1954) and Reuss *et al*. (1994) reported that maize grain with high moisture content (23%) produced higher CO_2 level compared to when the moisture content was low (15%) because of high respiration rate. The moisture content of the grain used in this study was 10-11% and this could have also lowered the rate of grain respiration and insect metabolism activities which led to less oxygen utilization and carbon dioxide production during storage.

The grain moisture content and germination rate did not differ in this study. This agree with studies by Baoua *et al*. (2012 b) and Moreno *et al*. (2000) who reported that hermetic storage preserved grain quality, germination and grain moisture content for a long time unlike in non-hermetic storage. In this study, it was clear that metal silos can effectively control storage pests when the grain is cleaned and dried to the right moisture content (below 13.5%) without even sealing the metal silo as long as lighted candle is used inside the metal silo at the start of storage. In this study, initial germination rate was low (86%) and did not change after storing the grain for 35 days. Aflatoxin level did not vary with treatments over the period of storage. However, it is important to note that, the level of aflatoxin was below the 1.75 ppb which is below 20 ppb set by Food and Drug Administration (www.fda.gov) and 10 ppb tolerance level set by Kenya Bureau of standards in grain for human consumption.

4.7 Conclusion

From this study, metal silos can preserve grain quality and effectively control *P. truncatus* without use of insecticides when the lids are properly sealed with rubber band or grease and the maize dried to moisture content below 13.5%. Use of lighted candle inside metal silos assists in raising carbon dioxide level while depleting oxygen right from the start of storage and eventually lead to increased insect mortality, reduced grain damage and weight loss and prevent F_1 progeny emergence after opening the metal silo. In addition, the metal silos without seals are able to store grain for at least 35 days without insecticides.

CHAPTER FIVE

EFFECT OF GRAIN VOLUME AND LIGHTED CANDLE ON OXYGEN DEPLETION AND CARBON DIOXIDE ACCUMULATION IN METAL SILOS FOR THE CONTROL OF *PROSTEPHANUS TRUNCATUS*

Abstract

In Africa, post-harvest losses in on-farm stored grain are estimated at 4-10% annually due to insect pests, rodents, birds and moulds. To avoid these losses most small scale farmers sell their produce immediately after harvest at lower market prices and buy later at higher prices accelerating poverty levels in the region. Adoption of metal silos to store on-farm maize will ensure food and income security to small holder farmers who can store their maize for a longer period and sell their produce at a higher price in the market. To enable farmers manage their metal silos appropriately during storage, an on-station trial was conducted to determine the effect of grain volume and use of lighted candle in metal silos for the control of *P. truncatus* in stored maize. The experiment consisted of: metal silo loaded with 90 kg of grain and a lighted candle placed on top of the grain before covering it with the lid and sealing the metal silo using the rubber band; metal silo loaded with 45 kg of grain and a lighted candle placed on top of the grain; metal silo loaded with 90 kg of grain and sealed with rubber band without lighting the candle; metal silo loaded with 45kg of grain and sealed with rubber band without lighting candle and polypropylene woven bag loaded with 90 kg of grain and tied tightly with rubber band and sisal rope (control) were compared. Ninety days after storage, grain stored in all metal silos regardless of grain volume and candle lighting suffered the least weight loss (0.3% to 1.1%) and damage (4.1% to 10.5%) compared to grain in polypropylene bags which suffered the highest weight loss (7.3% to 25.3%) and damage (28.9% to 37.5%).

Hundred percent (100%) insect mortality was recorded in all the metal silos irrespective of grain volume and candle lighting while in the control, the number of live *P. truncatus* increased from 100 to 1786, ninety days after storage. First filial generation (F_1) emerged in the metal silos without lighted candle from 40-56 days at 28±2°C, 65 ± 5% relative humidity in a 12:12, light: dark regime. Germination rate of the grain stored in polypropylene bags significantly reduced from 66% to 49% unlike in metal silos after ninety days of storage. Therefore, metal silos irrespective of grain volume, can effectively control *P. truncatus* in stored maize when properly sealed with rubber band and lighted candle used to deplete oxygen at the start of storage period with the grain moisture content below 13.5%.

5.1 Introduction

Post-harvest losses in developing countries are 1-5% higher than in developed countries (FAO, 2011). In the recent past, tremendous efforts have been made towards increasing maize production to meet an increasing annual demand of 2.6% in developing countries (FAOSTAT, 2009). However, these efforts have been challenged by inefficient storage systems, available to small holder farmers, aggravating food insecurity. According to Cao *et al*. (2002), an estimated 20% of the food is lost during storage and this translates to $25.8 billion. The amount of losses incurred during storage is dependent on the type of storage container, duration of storage and other management options adapted before and during storage (FAO, 2011). *Prostephanus truncatus* and *Sitophilus zeamais* are the most destructive pests of stored maize in sub-Saharan Africa (Boxall, 2002b; Tefera *et al*., 2011a, b). Introduction of *P. truncatus* in Africa led to huge losses being incurred on dried cassava and on-farm stored maize (Boxall, 2002b; Wright *et al*., 1993). This caused the farmers to shift from traditionally storing their unshelled maize in cribs (Hellin *et al*., 2009) to use of organophosphates and pyrethroids on shelled maize to reduce the losses (Golob, 2002a). Although pesticides are effective in the control of storage pests for a short duration (mostly ninety days), their use has negative effects on human health, environment and increases the risk of insect resistance to pesticides (Hodges and Meik, 1984). Since pesticides are expensive and require frequent applications, most small scale farmers cannot afford, forcing them to sell their produce soon after harvest at low prices than what they will pay while buying the same grain later (Kimenju *et al*., 2009). This necessitated exploration of other alternatives to reduce post-harvest losses in stored cereals. Among the recently explored technology, is the use of hermetic containers for control of storage pests by small scale farmers.

Hermetic storage has been promoted as a safe, cost effective and environmentally friendly alternative to pesticides use for control of storage pests in Asia (Quezada *et al*., 2006; Villers *et al*., 2008) and currently in Africa (Jones *et al*., 2011; Phiri and Otieno, 2008). Purdue Improved Cowpeas Storage (PICS), super grain bags and metal silos have been used by small holder farmers to control storage pests in stored cereals (CIMMYT, 2011; FAO, 2008; Navarro and Donahayo, 2005). In these hermetic containers, the synergistic effect of low oxygen and high carbon dioxide level produced by aerobic metabolism by insects, microorganisms and grain respiration arrests insect development and eventually lead to their death as a result of desiccation (Calderon and Navarro 1980; Murdock *et al*., 2012). Metal silos unlike PICS and super grain bags can be of different holding capacities ranging from 0.1t to 3t (CIMMYT, 2009; FAO, 2008; SDC, 2008a) and have a longer life span of over 10 years if well maintained while super grain bags can be used for only 3 years if not perforated (CIMMYT, 2011; FAO, 2003; Kimenju and De Groote, 2010). In Central America and Western Australia, metal silos are reported to be effective in controlling storage pests in combination with *aluminum phosphide* and carbon dioxide treatments, respectively (Andrews *et al*., 1994; Yusuf and He, 2011).

In Kenya, metal silos effectively controlled *S. zeamais* and *P. truncatus* in maize stored for six months without prior treatment with insecticides (CIMMYT 2011; De Groote *et al*., 2013). For metal silos to effectively control storage pests; the grain should be dried to moisture content below 13.5%, completely fill the metal silo with the grain, use lighted candle to deplete oxygen and the loading inlet and outlet should be tightly tied or sealed using rubber strips (SDC, 2008; Tefera *et al*., 2011a). In Senegal, empty oil-metal drums effectively controlled cowpea bruchids, *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae) when they were completely filled and kept closed for at least two months (Boys *et al*., 2004). However, farmers reported challenges of drum rusting that resulted in grain damage (Boys *et al*., 2004). To overcome similar challenges, metal silos are made from galvanized iron sheet to avoid rusting (SDC, 2008a,b; Tefera, *et al*., 2011a). In sub-Saharan Africa, most small holder farmers sell part of their grain at different times of the year to meet their needs. This way they may not have enough grain to fill the metal silo throughout the storage period. There is no documentation on whether grain volume and use of lighted candle in metal silo can affect its effectiveness in controlling storage pests. This study, therefore reports on the effect of grain volume and use of lighted candle in metal silos for control of *P. truncatus* in stored maize.

5.2 Materials and methods

5.2.1 Preliminary trial

From the sealing method experiment, (chapter four of this thesis), insect mortality was highest (100%) and no F_1 progeny emerged in metal silos that were sealed with rubber band, grease and rubber band combined with grease after 35 days of storage. There was also minimal change in gas composition inside the metal silos, despite use of lighted candle as routinely practiced by farmers. With these results, a preliminary experiment was conducted to determine the effect of lighted candle on gas composition, grain damage and mortality rate of *P. truncatus* in maize stored in the metal silos for different periods of time.

5.2.1.1 Effect of lighted candle on gas composition, grain damage and mortality rate of *P. truncatus* in metal silos on different days

The experiment was carried out at Kiboko (see section 3.1 of this thesis). Preparation of grain and *Prostephanus truncatus* culture was done as described under general methodology in chapter 3 of this thersis.

A 4x2 factorial experiment was conducted using metal silos with lighted candle versus non-lit candle and grain observed at four time periods: day 3; day 6; day 9 and day 12. The following four treatments were conducted under lit and non-lit candles. The treatments consisted of metal silos loaded with 90 kg of grain and three aerated 1.5litre glass jars inside each metal silo. Four hundred (400) newly emerged ten-day old *P. truncatus* adults were artificially introduced in each treatment; 100 adults into the grain inside the metal silo and another 100 into each 1.5litre glass jar. The glass jars, each containing four hundred (400) grams of grain, were placed on top of the grain inside the metal silo next to a lighted candle. The candle was burning inside the metal silos as the silos were covered with lids and sealed using rubber band. The treatments were arranged in a completely randomized design with two metal silos per treatment and observed for three, six, nine and twelve days.

A similar design using the same treatments was done without lighted candle. All metal silos were placed on wooden pallets (15 cm high) and stored in a room roofed with corrugated iron sheets at ambient temperature of 27±2^{o}C and relative humidity of 58±5%.

5.2.2 Effect of grain volume and lighted candle on gas composition, grain damage and insect mortality

Grain and *P. truncatus* culture were prepared as described under general methodology in chapter 3 of this thesis.

The following five treatments comprising of metal silos with a holding capacity of 100 kg (Fig 4.1) and polypropylene bags of 90 kg were used: (i) treatment 1 (T1), metal silo loaded with 90 kg of grain, one aerated 1.5 litre glass jar containing four hundred (400) grams of grain, placed next to a lighted candle on top of the grain inside the metal silo before sealing it with rubber band (Plate 5.1a); (ii) treatment 2 (T2), metal silo loaded with 45 kg of grain, one aerated 1.5 litre glass jar containing four hundred (400) grams of grain, placed next to a lighted candle on top of the grain inside the metal silo before sealing it with rubber band (Plate 5.1b); (iii) treatment 3 (T3), metal silo loaded with 90 kg of grain, one aerated 1.5 litre glass jar containing four hundred (400) grams of grain, placed on top of the grain inside the metal silo and sealed with rubber band without lighting candle (Plate 5.2a); (iv) treatment 4 (T4), metal silo loaded with 45kg of grain, one aerated 1.5 litre glass jar containing four hundred (400) grams of grain, placed on top of the grain inside the metal silo and sealed with rubber band without lighting the candle (Plate 5.2b); and (v) treatment 5 (T5), woven polypropylene bag loaded with 90 kg of grain and tightly tied with sisal rope and used as a control (local practice) (Plate 5.3).

Two hundred (200) 10-day old *P. truncatus* adults were artificially introduced into each treatment; one hundred introduced into the grain inside each metal silo and polypropylene bag and another one hundred into each 1.5 liter glass jar. In the polypropylene bag, the 1.5 litre glass jar was placed on top of the grain inside the bag before tying the bag with sisal rope. All treatments (silos and bags) were placed on wooden pallets (15 cm high), arranged in a completely randomized design with four metal silos and four bags per treatment (Plate 5.4). They were kept for three months in a room roofed with corrugated iron sheet at ambient temperature of 27±2^{o}C and relative humidity of 58±5%.

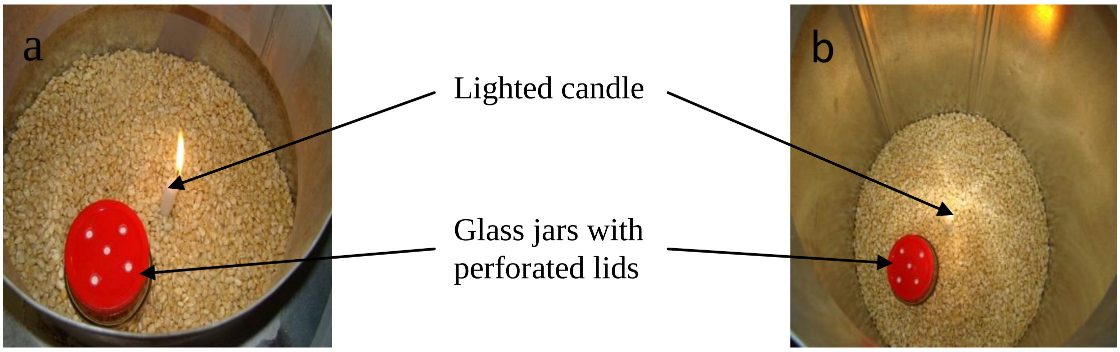

Plate 5. 1 Metal silo with a lighted candle next to an aerated glass jar with (a) 90 kg of grain (T1) and (b) 45 kg of grain

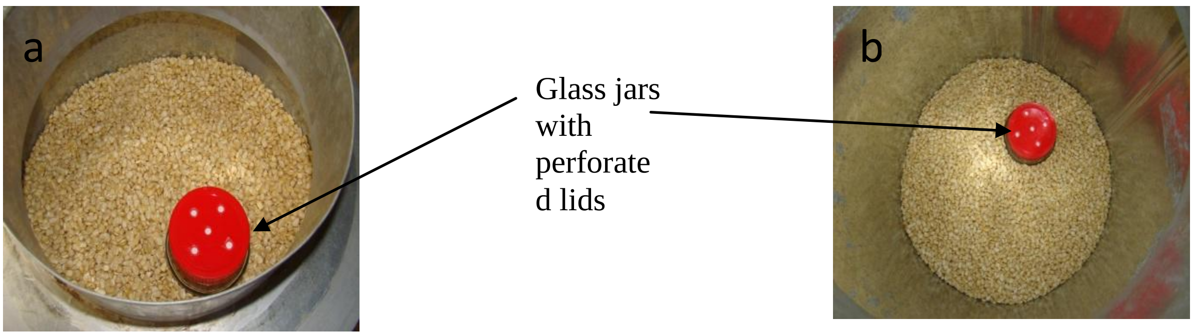

Plate 5. 2 Metal silo without a lighting candle with (a) 90kg of grain (T3) and (b) 45kg of grain (T4)

Plate 5. 3 Polypropylene bag with 90kg of grain (T5)

Plate 5. 4 Experimental layout in the laboratory

5.3 Data collection

5.3.1 Preliminary trial

5.3.1.1 Effect of lighted candle on gas composition and mortality rate of *P. truncatus* in metal silos on different storage periods

A composite sample of 1kg was obtained from each metal silo using a compartmentalized double tube sampling spear as described in section 4.3.2 on the third, sixth, ninth and twelfth day. The contents of each metal silo and glass jar were sieved separately as described in section 4.3.2.1 of this thesis. Data on insect mortality, grain damage, weight loss and percent dust were taken in the metal silos and the glass jars as described in chapter four, section 4.3.2. The level of oxygen and carbon dioxide in the metal silos was recorded every day.

5.3.2 Effect of grain volume and lighted candle on gas composition, grain damage and insect mortality

Composite samples of 1 kg were obtained separately from each metal silo and polypropylene bag using a compartmentalized double tube sampling spear as described in section 4.3.2 at the start and end of the experiment. After sampling, the contents of each metal silo, polypropylene bag and glass jar were then sieved separately as described in section 4.3.2.1 and data on insect mortality and F_1 progeny emergence, grain damage, weight loss, percent dust, germination rate, grain nutritional value and moisture content taken as described in chapter four of this thesis. The level of oxygen and carbon dioxide in the metal silos and polypropylene bags were recorded every week using portable Mocon PAC CHECK® Model 325 Headspace analyzer (Mocon, Minneapolis, MN, USA) as described in chapter four. In the polypropylene bags, the needle was pricked through the bag into the grain and data on O_2 and CO_2 taken.

5.4 Results

5.4.1 Preliminary trial

5.4.1.1 Effect of lighted candle on gas concentration and the mortality rate of *P. truncatus* and in metal silos in different days

5.4.1.1.1 Insect mortality

Change in gas concentration significantly ($F_{7,\ 40}$= 0.001; p<0.05) affected insect mortality. Glass jars inside the metal silos with lighted candle had the highest insect mortality (83% to 100%) while those without candle had the least (43% to 76%) from third to twelfth day (Table 5.1a). In metal silos with lighted candle, insect mortality was higher (45%- 98%) compared to those without lighted candle (21%-65%) (Table 5.1b).

5.4.1.1.2 Percent weight loss, grain damage and dust

Percent weight loss, grain damage and dust in the glass jars were affected significantly ($F_{7, 40}$= 0.001; p<0.05) at different days of storage. Glass jars inside the metal silos without candle had the higher weight loss (0.5% to 1.4%), grain damage (4.8% to 6.1%) and dust (0.3% to 0.8%) than those in metal silos with lighted candle which had a weight loss of 0.2% to 0.4%), grain damage (1.5% to 4.0%) and dust (0.3% to 0.6%) from third to twelfth day (Table 5.1a). In metal silos with lighted candle, grain damage (1.8% to 4.0%), weight loss (0.3% to 0.4%) and dust (0.3% to 0.6%) were lower than in the metal silos without lighted candle; grain damage (4.0% to 5.8%), weight loss (0.8 % to 1. 2%) and dust (1.0% to 1.2%) (Table 5b).

Table 5. 1a. Insect mortality, weight loss, grain damage and dust in glass jars inside the metal silos with and without lighted candle in different days

Condition	Time period in days	LGB Mortality %	Grain Weight loss %	Grain Damage %	Dust %
Without lighted candle	3	43a	1.4a	5.8a	0.3a
	6	57b	1.2a	6.1a	0.7a
	9	62c	0.9a	5.2a	0.7a
	12	76d	0.6a	4.8a	0.8a
With lighted candle	3	83e	0.4a	4.0a	0.3a
	6	95f	0.3a	3.6a	0.3a
	9	98fg	0.3a	2.9a	0.4a
	12	100g	0.3a	1.5a	0.6a
	CV	3.9	14.2	5.8	8.2
	$LSD_{5\%}$	6.8	0.3	0.6	0.22
	$F_{7, 40, 5\%}$	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

Table 5. 1b. Insect mortality, weight loss, grain damage and dust in metal silos with and without lighted candle in different days

Condition	Time period in days	LGB Mortality %	Weight loss %	Grain Damage %	Dust %
Without lighted candle	3	21a	1.0a	5.8a	1.0a
	6	40b	1.2a	4.7a	1.1a
	9	56cd	1.1a	5.7a	1.1a
	12	65d	0.8a	4.3a	1.2a
With lighted candle	3	45bc	0.4a	4.0a	0.6a
	6	70d	0.5a	3.9a	0.5a
	9	92e	0.3a	2.4a	0.3a
	12	98e	0.3a	1.8a	0.3a
	CV	14.4	5.1	22	12
	$LSD_{5\%}$	10	0.3	1.8	0.07
	$F_{7, 40, 5\%}$	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

5.4.1.1.3 Carbon dioxide and oxygen level in metal silos

Metal silos with lighted candle had the highest carbon dioxide level on the third day (1.25% v/v), sixth (1.28% v/v), ninth (1.40% v/v) and twelfth day (1.54% v/v) whereas metal silos without candle had the least carbon dioxide level on third (0.49% v/v), sixth (0.67% v/v), ninth (0.71% v/v) and twelfth day (0.62% v/v) (Fig 5.1).

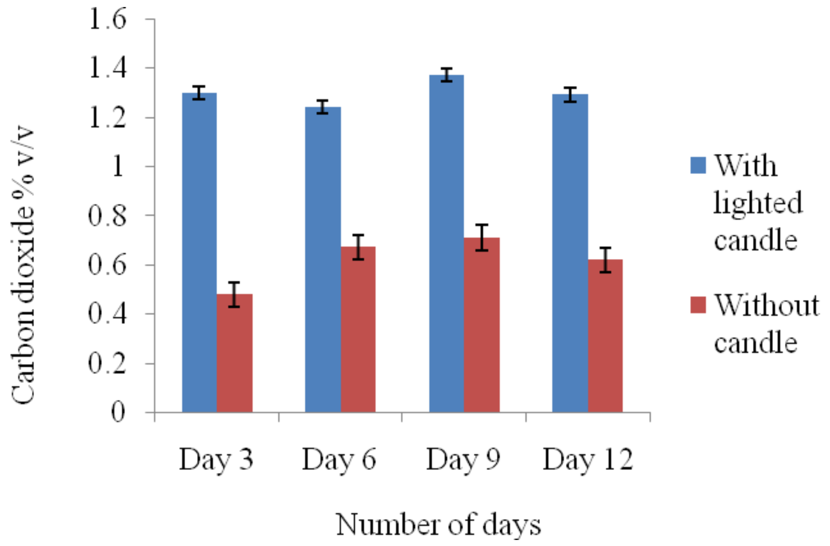

Figure 5. 1. Carbon dioxide level in metal silos with and without lighted candle on the third, sixth, ninth and twelfth day.

Metal silos with lighted candle had lower oxygen levels than in the metal silos without candle in days; 3, 6, 9 and 12. Oxygen level on third day (20.77% v/v) was higher in metal silos without lighted candle than on sixth day (20.47% v/v), ninth day (20.21% v/v) and twelfth day (20.33% v/v). Similar trend was observed in metal silos with lighted candle on the third (19.74% v/v), sixth (19.63% v/v), ninth (19.48% v/v) and twelfth (19.44 % v/v) (Fig 5.2).

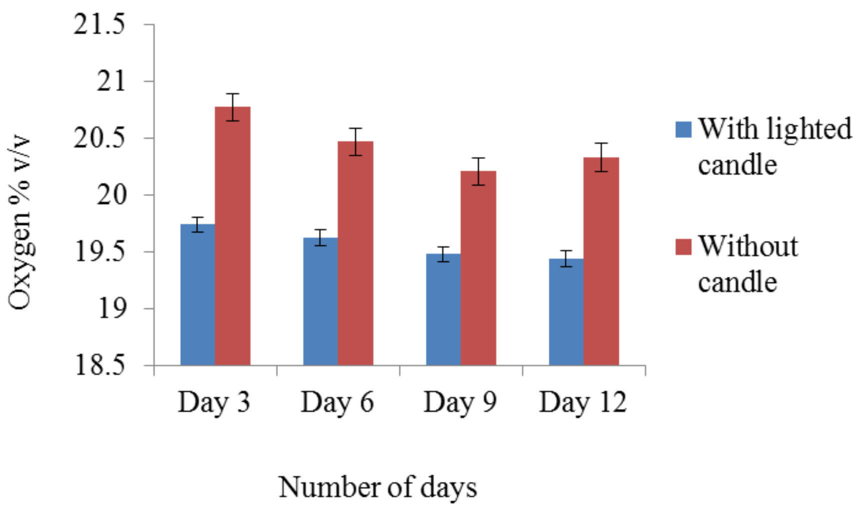

Figure 5.2. Oxygen level in metal silos with and without lighted candle on the third, sixth, ninth and twelfth day

5.4.2 Effect of grain volume and lighted candle on gas composition, grain damage and insect mortality

5.4.2.1 Insect mortality and F1 progeny emergence

Insect mortality ($F_{4,\ 15}$= 0.001; p<0.05) and F_1 progeny emergence ($F_{4,\ 15}$= 0.001; p<0.05) were significantly affected in the metal silos compared to the control (polypropylene bag) after storing maize for ninety days. Irrespective of grain volume, there was 100% mortality in all the glass jars and in the metal silos with and without lighted candle. In the control, the number of live *P. truncatus* increased from 100 to 1537 in the glass jar and from 100 to 1786 in the polypropylene bag after ninety days of storage (Table 5.2). Control had the highest mean of F_1 progeny that emerged from the grain in the glass jar (56) and in the polypropylene bag (191) after storage (Table 5.2). Metal silos without lighted candle had 6 to 7 F_1 progenies while none emerged in metal silos with lighted candle (Table 5.2). A total of four thousand, six hundred and two (4602) *Sitophilus zeamais* and one thousand six hundred and fifteen (1615) *Tribolium castaneum* had invaded the grain in the control after ninety days of storage.

Table 5. 2 Mean number of dead and live LGB and F_1 progeny in the maize stored in metal silos and polypropylene bags for 90 days.

Treatments	**Glass jars**			**Metal silos**		
	Dead LGB	**Live LGB**	**F_1 progeny**	**Dead LGB**	**Live LGB**	**F_1 progeny**
Metal silo with 90 kg and lighted candle	100a	0a	0a	100a	0a	0a
Metal silo with 45 kg and lighted candle	100a	0a	0a	100a	0a	0a
Metal silo with 90 kg without candle	100a	0a	0a	100a	0a	6b
Metal silo with 45 kg without candle	100a	0a	0a	100a	0a	7b
Polypropylene bag (control)	247b	1537b	56b	534b	1786b	191c
LSD 5%	37.8	8.7	0.4	13	6.5	2
CV %	19.4	1.6	2.3	4.6	1.2	24
$F_{(4,15\ 5\%)}$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

5.4.2.2 Percent grain damage, weight loss and dust

Grain volume and lighted candle significantly affected grain damage ($F_{4, 15}$= 0.001; p<0.05), weight loss ($F_{4, 15}$= 0.001; p<0.05) and percent dust ($F_{4, 15}$= 0.001; p<0.05) in glass jars, metal silos and polypropylene bags after ninety days of storage (Table 5.3). The least weight loss (0.3% to 1.2%), dust (0.03% to 0.7%) and grain damage (4.1% to 10.5%) were observed in the metal silos regardless of grain volume and candle lighting (Table 5.3). However, grain stored in polypropylene bags suffered the highest percent weight loss (7.3% to 25.3%), dust released (1.1% to 39.5%) and damage (28.9% to 37.5%) after 90 days of storage (Plate 5.7).

Table 5. 3 Grain damage, dust and weight loss caused by *P. truncatus* in glass jars and metal silos after 90 days of storage

Treatments	**Glass jars**			**Metal silos/ polypropylene bag**		
	weight loss %	**Damage %**	**Dust %**	**weight loss %**	**Damage %**	**Dust %**
Metal silo with 90 kg and lighted candle	0.3a	4.1a	0.03a	0.4a	6.3a	0.4a
Metal silo with 45 kg and lighted candle	0.5a	4.2a	0.04a	0.2a	6.3a	0.4a
Metal silo with 90 kg without candle	0.6a	5.8a	0.1a	1.1a	8.4a	0.6a
Metal silo with 45 kg without candle	0.7a	6.8a	0.1a	1.0a	10.5a	0.7b
Polypropylene bag (control)	25.3b	37.5b	39.5b	7.3b	28.9b	1.1c
LSD 5%	5.1	11.7	4.2	5.0	10	0.2
CV %	29.2	28.6	19.4	4.8	27.8	9.5
$F_{4,15,5\%}$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

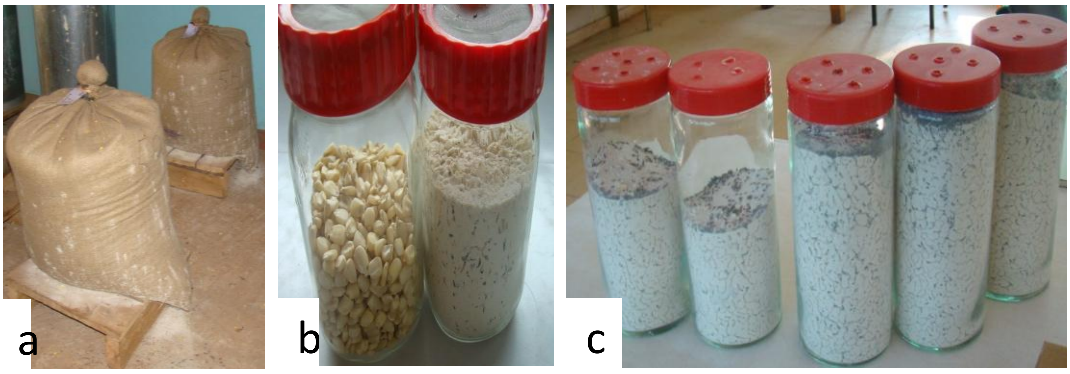

Plate 5. 5 Dust Produced as a result of feeding by *P. truncatus* on maize grain
a) Dust produced in polypropylene bags by *P. truncatus*
b) Comparison of dust produced in glass jars kept in metal silos (left) and polypropylene bags (right) after 90 days of storage
c) Dust produced in polypropylene bags after 90 days of storage.

5.4.2.3 Oxygen and carbon dioxide level

Grain volume and lighted candle significantly ($F_{4, 15}$ =0.001; p <0.05) affected Oxygen and Carbon dioxide level in metal silos after ninety days of storage. The metal silos loaded with 90 kg and 45 kg of grain with lighted candle had the least oxygen (below 18% v/v) and the highest CO_2 (above 3% v/v). A contrasting trend was observed in a metal silo loaded with 90 kg and 45kg of grain without lighted candle (> 20% O_2 and <0.5% CO_2). Polypropylene bag, however, had the highest O_2 (20.9%) and least CO_2 (0.05%) after ninety days of storage (Table 5.4).

Table 5. 4 Mean oxygen and carbon dioxide level in metal silos and polypropylene bags with maize grain stored for 90 days

Treatments	Oxygen (%)	Carbon dioxide (%)
Metal silo with 90 kg and lighted candle	18.0b	3.0d
Metal silo with 45 kg and lighted candle	17.7a	3.3e
Metal silo with 90 kg without candle	20.3c	0.6c
Metal silo with 45 kg without candle	20.5c	0.4b
Polypropylene bag (control)	20.9d	0.05a
		0.1
LSD 5%	0.2	2.2
CV %	0.4	<0.001
$F_{4,15,5\%}$	<0.001	

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

5.4.2.4 Grain moisture content and germination rate

There were significant differences which were observed in the final moisture content ($F_{4, 15}$ = 0.001 p<0.05) and the germination rate ($F_{4, 15}$ = 0.001 p<0.05) between the control and metal silo treatments ninety days after storage. Germination rate in the control decreased from 66% to 49% while moisture content increased from 10.4% to 11% after ninety days of storage. Grain volume and use of lighted candle did not significantly affect moisture content and germination after ninety days of storage in metal silos (Table 5.5).

Table 5. 5 Comparison of moisture content and germination rate of maize stored in metal silos and polypropylene bags for 90 days

Treatment	Moisture		Germination	
	Initial	**final**	**Initial**	**final**
Metal silos with 90 kg and lighted candle	10.5a	10.5a	65a	61a
Metal silos with 45kg and lighted candle	10.6a	10.5a	65a	59a
Metal silos with 90kg without candle	10.4a	10.4a	64a	62a
Metal silos with 45 kg without candle	10.4a	10.3a	66a	64a
Polypropylene bags	10.4a	11b	66a	49b
LSD 5%	0.2	0.2	6.9	6.5
CV %	1.1	1	7	7.4
$F_{4,15, 5\%}$	0.391	<0.001	0.96	<0.001

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

5.4.2.5 Grain nutritional content

Grain nutritional content was not affected by the amount of grain stored with or without lighted candle compared to grain stored in the polypropylene bags (Table 5.6).

Table 5. 6 Comparison of oil, starch and protein content in maize stored in metal silos and polypropylene bags for ninety days

Treatment	Protein		Oil		Starch	
	Initial	**final**	**Initial**	**final**	**Initial**	**final**
Metal silos with 90 kg and lighted candle	10.5	10.4	5.3	5.3	68.7	68.7
Metal silos with 45kg and lighted candle	10.7	10.5	5.4	5.3	68.8	69.0
Metal silos with 90kg without candle	10.6	10.6	5.3	5.4	69.0	68.6
Metal silos with 45 kg without candle	10.6	10.6	5.4	5.4	68.7	69.0
Polypropylene bags	10.6	10.7	5.4	5.5	68.9	68.6
LSD 5%	0.2	0.3	0.2	0. 1	0.4	0.4
CV %	1.3	1.7	2.0	1.7	0.4	0.4
$F_{4, 15, 5\%}$	0.199	0.17	0.39	0.01	0.45	0.02

Means followed by the same letter(s) within a column are not significantly different from each other at 5% probability level.

5.5 Discussion

The results from this study showed that the metal silos are effective in the control of LGB when maize grain is stored for 90 days. Use of lighted candle in the metal silos during storage affected the levels of CO_2 and O_2 in the metal silos quickly killing the adult females before they could oviposit the eggs. Hence no progeny emerged in the metal silos with lighted candle after exposing the grain to favourable temperature of 28 ± 2^{o}C, relative humidity of 65 ± 5% in the incubation room. Synergistic effect of low O_2 and high CO_2 in hermetic containers deprives insects of air and water leading to their death (Murdock *et al.*, 2012). Irrespective of grain volume, change in gas composition inside the metal silos led to 100% insect mortality after ninety days of storage. In this study, it is likely that there was carbon monoxide gas produced during incomplete combustion that may have occurred when the candle was lit in an enclosed metal silo. In other studies, the presence of carbon monoxide gas in the head space of hermetic containers used to store grain and legumes have been reported (Reuss and Pratt, 2001; Whittle *et al*., 1994). Contrary to the metal silos with lighted candle, F_1 progeny emerged in metal silos without candle after the grain was exposed to temperature of 28 ± 2^o C and relative humidity of 65 ± 5% in the incubation room (Tefera *et al*., 2011b). It is supposed that there was a slow rate of CO_2 which was produced in metal silos without lighted candle as a result of metabolic activities of the insects and the respiration of grain compared to the CO_2 which was produced by the lighted candle, metabolic activities of the insects and the respiration of the grain in the metal silos with lighted candle. Thus enabling the adult females to oviposit the eggs in the metal silos without lighted candle before they were exposed to the lethal levels of CO_2 which was produced during storage. Studies by Murdock *et al*. (2012) and Baoua *et al*. (2012b) reported that although *Callosobruchus maculatus* adults died when the CO_2 level increased, the eggs were tolerant to low O_2 and high CO_2 levels. In this case, the eggs were able to survive the lethal conditions and were able to develop when they were exposed to favourable temperature of 28 ± 2^{o}C and relative humidity of 65 ± 5 % during incubation.

Percent weight loss and grain damage in metal silos with lighted candle was lower than in metal silos without candle. This may be attributed to high CO_2 and low O_2 level which slowed down insect feeding in metal silos with lighted candle compared to the metal silos without candle and the polypropylene bags. According to Murdock *et al*. (2012), insect feeding was slowed down when oxygen fell below ambient level and the insects practically ceased feeding when it fell to 1-4 %. Although in this study oxygen and carbon dioxide levels did not reach those reported by Murdock *et al*. (2012) in PICS bags, damage by insects in the metal silos was lower compared to the control (polypropylene bag). Grain volume and use of lighted candle in the metal silos affected LGB insects and hence the level of grain damage. Metal silos without lighted candle had the higher damage level than those with lighted candle after ninety days of storage. Similarly, the level of damage was slightly higher in the metal silos with 45kg of grain compared to those with 90 kg. It is probably that, there was a slower rate in the change of gas composition in metal silos without candle, thus giving the insects more time to feed than in metal silos with lighted candle. In metal silos with less volume, there was more oxygen in the headspace and this took time to deplete thus enabling the insects to feed more than in the higher grain volume. This agrees with similar observations by Pattison, (1970) and Navarro *et al.* (1994) where they reported that, partially filled drums have large headspace and insects can cause grain damage before oxygen levels are reduced to a level that would prevent insect development. According to USDA (2009) hermetic containers should be filled as close to the brim as possible to avoid large air space to grain ratio which may not reduce oxygen to levels that can effectively control pest populations. The number of insect damaged grains was low in all the metal silos except in the control (polypropylene bag) where the grain was invaded by *Sitophilus zeamais* and *Tribolium casteum.*The invasion was a result of the insects gaining access to the grain when the polypropylene bag was damaged by the larger grain borer.

Use of lighted candle inside the metal silo during grain storage assisted in quickly depleting oxygen and elevating carbon dioxide level in metal silos. The metal silos with lighted candle had higher CO_2 and lower O_2 levels compared to the metal silos without candle, both in preliminary and the main trial. The higher level of CO_2 in metal silos with lighted candle was as a result of combustion, insect metabolic activity and grain respiration compared to the metal silos without lighted candle where CO_2 production depended on grain respiration and insect metabolic activities only. During combustion, oxygen in the metal silo was used as carbon dioxide and water were being produced; $C_3H_8 + 5O_2 \rightarrow 3CO2 + 4H_2O$ + Heat and light. The presence of water which was produced during combustion raised humidity in the grain which in turn increased biological activities in the metal silo depleting O_2 faster and raising CO_2 level than in the metal silos without candle and the control. According to studies by Ragai and Loomis (1954) and Reuss *et al*. (1994), respiration rate is higher in the grain with higher moisture content than in low moisture content, thus raising the amount of CO_2 which was produced.

Metal silo with 45 kg had less volume of grain and more oxygen in the headspace of the container than that with 90kg hence higher CO_2 was produced during combustion. The grain moisture content and percent germination were not affected in all metal silos with and without lighted candle except in the control. There was germination loss in polypropylene bag after ninety days of storage as a result of high insect infestation and damage by *P. truncatus* and other storage pests leading to an increase in grain moisture content. The initial germination rate of the grain before the experiment was low (65-66%) because the maize was meant for consumption and not for seed. The weather during that season was wet and humid which could have contributed to discolouration of most of the kernels. According to studies done by Baoua *et al.* (2012b) and Moreno *et al.* (2000), hermetic storage preserved grain quality, germination and moisture for a long time which was similar to the grain stored in metal silos.

5.6 Conclusion

Metal silos, irrespective of grain volume, can preserve grain quality, moisture content, germination and effectively control *P. truncatus* without use of insecticides when properly sealed with rubber band. The maize should, however, be dried to moisture content below 13.5 % and candle lit at the beginning of storage. Lighted candle inside the metal silos lead to fast accumulation of carbon dioxide level and depletion of oxygen right from the start of storage period thus controlling pests effectively.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General Discussion

In this study, oxygen gas was decreased below the ambient level of 21% v/v in the atmosphere in the metal silos with and without lighted candles when sealed with either rubber band or grease. Carbon dioxide increased over 10-50 times above the normal CO_2 level of 0.038% v/v in the atmosphere in all the metal silos irrespective of grain volume, sealing material and use of lighting candle. Change of gas composition inside the metal silos was as a result of combustion, grain respiration and insect metabolic activities (Moreno *et al.*, 2000). During combustion, oxygen in the metal silo was used, carbon dioxide level raised and moisture produced: $C_3H_8 + 5O_2 \rightarrow 3CO2 + 4H_2O$ + Heat and light.

The presence of water which was produced during combustion raised humidity in the grain which in turn increased biological activities in the metal silo depleting O_2 faster and raising CO_2 level than in the metal silos without candle and in the polypropylene bags (control). The level of oxygen depletion and carbon dioxide accumulation in hermetically sealed metal silos was observed to be lower compared to the levels reported in PICS bags (Baoua *et al*., 2012b). This could have been a result of low moisture content (10-11%) of the grain and the low insect infestation level (1insect/kg of grain) used in the study. One (1) insect/ kg of grain was used to mimic low level of insect infestation that may occur when the crop is still in the field before farmers harvest their grain. The level of insect infestation in hermetic storage affected the level of oxygen consumption and carbon dioxide production. Baoua *et al*. (2012b) reported oxygen depletion in PICS bags to 3% v/v and carbon dioxide rise to 5% v/v when an average infestation rate of 24 insect/kg of grain was used. Navarro *et al*. (1994) reported decreased oxygen levels of below 10% in 180 days when 2 insects/ kg were used and 5% in less than 90 days when 8 insects/ kg of grain in a liner with an oxygen ingress rate of 0.24% /day. A study by Moreno *et al*. (2000) reported that, in hermetic storage, insects were the main consumers of oxygen while grain respiration was the least. Grain respiration rate is minimal when the grain moisture content is low which translate to low O_2 consumption and CO_2 production. According to Ragai and Loomis (1954) and Reuss *et al*. (1994), maize with higher moisture content of 23% had higher respiration rate and produced more CO_2 gas than at 15% moisture content.

Low oxygen and high carbon dioxide levels in hermetically sealed metal silos led to100% insect mortality after storing the grain for over one month and no offspring (F_1) emerged after incubating the grain in favourable conditions. According to Navarro *et al*. (2007) and Yakubu *et al*. (2011), synergistic effect of low oxygen and high carbon dioxide levels in hermetic storage is key for insect control. At low oxygen and high carbon dioxide levels, insects were deprived of water and because they continued to respire, they died as a result of desiccation (Murdock *et al*., 2012; Navarro *et al*., 1994). Elevation of carbon dioxide gas affected adult *P. truncatus* and over 95 % mortality was achieved when they were exposed to 60% (2.4 % v/v) CO_2 and above for three days (Suss *et al*., 1993). Other than the elevated CO_2 and low O_2 level in the metal silos, other factors could have contributed to high insect mortality both in the metal silos and in the airtight glass jars in the study. Reuss and Pratt (2001) and Whittle *et al*. (1994) reported the presence of carbon monoxide gas (CO) in the headspace of stored canola and dry grains in hermetic containers. Canola, field peas, oats and paddy rice have been reported to produce carbon monoxide in sealed glass vessels (Whittle *et al*., 1994).

During combustion in the metal silos with lighted candles, incomplete combustion may have occurred producing CO which is lethal to human and insects. Similar conditions may have caused insect mortality in airtight glass jars and metal silos in preliminary trials. In this study, F_1 progeny emerged after incubation in the metal silos without lighted candles. Consequently, it is supposed that the adult females were able to oviposit when they were exposed to none lethal conditions during the early days of storage. However, with time oxygen was reduced and carbon dioxide elevated to levels that were lethal to the adults. According to Baoua *et al*. (2012a) adults of *C. maculatus* were more susceptible to low O_2 and high CO_2 levels in PICS bags while eggs and larvae were tolerant and survived those conditions. Moreno *et al*. (2000) observed that eggs were not able to develop in low O_2 and high CO_2 in PICS bags, but F_1 progeny emerged when the grain was exposed to favourable conditions (28 ± 2^o C, 65 ± 5% relative humidity).

Percent weight loss and grain damage were lower in hermetically sealed metal silos with lighted candle and in air tight glass jars than in unsealed metal silos, aerated glass jars and polypropylene bags. Elevated CO_2 and low O_2 levels slow down insect feeding activities in metal silos with lighted candles leading to lower weight losses and grain damage compared to metal silos without candles and the polypropylene bags. Murdock *et al*. (2012), in his study observed slowed insect feeding activity when oxygen fell below ambient level (21% v/v) and was completely ceased when it fell to 1-4% v/v in PICS bags. The number of insect damaged grains was lower in sealed metal silos and airtight glass jars than in aerated glass jars, unsealed metal silos and the polypropylene bags at the end of the storage period. The grain in the polypropylene bags was highly damaged and was also invaded by *Sitophilus zeamais* and *Tribolium casteum* unlike in the metal silos.

The grain moisture content and germination rate were not affected by grain storage in the metal silos except in polypropylene bags. This agrees with studies by Baoua *et al*. (2012b) and Moreno *et al*. (2000) who reported that hermetic storage preserved grain quality, germination and grain moisture content for a long time unlike in non-hermetic storage. In this study, it is demonstrated that metal silos can effectively preserve grain quality and germination rate when; the grain is cleaned and dried to the right moisture content (below 13.5%), the metal silo is properly sealed with rubber band or grease, with or without a lighted candle inside the metal silo at the start of storage period, for at least a month without opening the metal silo.

In both experiments, the grain germination rate was generally low with an average of 86% in the first and 65% in the second experiment. This is probably because the maize was bought from farmers who use it for consumption and not as seed. In the polypropylene bags (non-hermetic storage), germination rate decreased from 66% to 49% and moisture content increased from 10.4 to 11% after ninety days of storage whereas in metal silos there was no significant change in the germination rate and moisture content of the grain. The loss in germination in the grain stored in polypropylene bags could be as a result of high insect infestation and damage by *P. truncatus*, *S. zeamais* and *T. castaneum* leading to increase in grain moisture content. Grain quality in form of starch, protein and oil content did not change. Aflatoxin levels did not change either. The level of aflatoxin was less than 1.75 ppb below the acceptable 20 ppb set by Food and Drug Administration (www.fda.gov) and 10 ppb tolerance level set by Kenya Bureau of standards in grain for human consumption.

6.2 Conclusion

- Sealing methods involving use of rubber band, grease and rubber band combined with grease influence the effectiveness of the metal silos in controlling *P. truncatus* for up to 90 days with 100% insect mortality.
- Irrespective of grain volume, metal silos can preserve grain quality and effectively control *P. truncatus* without use of insecticides when; maize is cleaned and dried to moisture content below 13.5%, lighted candles are used in the metal silo and the lids are properly sealed with either rubber band, grease or rubber band combined with grease.
- Use of lighted candle in the metal silos enhances insect mortality by quickly lowering oxygen and elevating carbon dioxide at the beginning of storage leading to preserved grain quality with little or no damage due to insects.

6.3 Recommendations

- From this study, we recommend use of rubber band, grease or rubber band combined with grease for sealing the metal silos. These are available locally to seal the in-let and the out-let of the metal silos while storing grain. This should be accompanied by clean grain of 13.5% moisture content at the beginning of grain storage.
- The metal silos with the grain should not be opened for at least a month and a lighted candle must be used every time the silo is opened to help quickly elevate carbon dioxide and reduce oxygen levels.
- Further studies should be carried out to determine whether use of metal silo has an effect on aflatoxin levels of the grain. This was not achieved in the study because there was no control with known amount of aflatoxin to compare with other treatments.

- Further studies should be undertaken to determine the level of carbon monoxide gas produced after maize is stored in metal silos especially when lighted candles are used. It is also important to determine if there are any other factors playing a role on insect mortality after storing grain in metal silos.

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.

Andrews, A.S., Annis, P.C., Newman, C.R. 1994. Sealed storage technology on Australian farms. In: Highley, E. (Ed.), Proceedings of the 6th International Working Conference on Stored-product Protection, pp. 27-36.

Anonymous, 2003. The status of the larger grain borer in Kenya. Report of the Larger Grain Borer Task Force, July 2003.

Anthony O. E. 2006.Options for *Striga m*anagement in Kenya. Kenya Agricultural Research Institute KARI Technical Note No. 19, March 2006.

Ariga, J. and Jayne, T.S. 2011. 'Fertilizer in Kenya: Factors Driving the Increase in Usage by Smallholder Farmers', in Punam Chuhan-Pole and Manka Angwafo (eds) Yes Africa Can: Success Stories from a Dynamic Continent, World Bank, Washington, 269–88

Auffhammer, M. 2011. Agriculture: Weather dilemma for African maize. Nature Climate Change, 1 27-28.

Babangida L. Y. and Yong, H. 2011. Design, development and techniques for controlling grains post-harvest losses with metal silo for small and medium scale farmers. *African Journal of Biotechnology* Vol. 10 (65), pp. 14552-14561.

Baoua, I.B., Amadou, L., Margam, V. and Murdock, L.L. 2012a. Comparative evaluation of six storage methods for postharvest preservation of cowpea grain. *Journal of Stored Products Research* 49, 171-175.

Baoua, I.B., Margam, V., Amadou, L. and Murdock, L.L. 2012b. Performance of triple bagging hermetic technology for postharvest storage of cowpea grain in Niger. *Journal of Stored Products Research* 51, 81-85.

Beintema, N.M. and Stads, G.J. 2004. Sub-Saharan African Agricultural Research. Recent Investment Trends. *Outlook on Agriculture*. Vol. 33, No. 4, 2004. Pp 239-246.

Bett, C., and Nguyo, R. 2007. Post-harvest storage practices and techniques used by farmers in semi-arid eastern and central Kenya, El-Minia, Egypt.

BioNET-EAFRINET, 2011.Mauremootoo, R.J., Rassman, K. and Cindy B. 2011. *Prostephanus truncatus* Keys and fact sheets. BioNET-EAFRINET UVIMA Project (Taxonomy for Development in East Africa). http://keys.lucidcentral.org/keys/v3/eafrinet/maize_pests/key/maize_pests/Media/Html/*Prostephanus_truncatus*_Horn_-_Larger_Grain_Borer. Accessed 28th July 2014.

Boeye J., Laborius G.A and Schulz F.A. 1992. The response of *Teretriosoma nigrescens* Lewis (Coleoptera: Histeridae) to the pheromone of *Prostephanus. Truncatus* (Horn) (Col., Bostrichidae). *Angewandte Schaedlingskunde Pflanzenschutz Umweltschutz* 65(8), 153-157.

Bokusheva, R., Finger, R., Fischler, M., Berlin, R., Marín, Y., Pérez, F., Paiz, F. 2012.Factors determining the adoption and impact of a postharvest storage technology. *Food Security* 4, 279-293

Borgemeister, C., Djossou, F., Adda, C., Schneider, H., Djomamou, B., Degbey, P., Azoma, K. and Markham, R.H. 1997. Establishment, spread and impact of *Teretriosoma nigrescens* (Coleoptera; Histeridae), an exotic predator of the larger grain borer *Prostephanus truncatus* (Coleoptera: Bostrichidae) in south-western Benin. *Environmental Entomology* 26, 1405-1415.

Borgemeister, C., Holst, N. and Hodges, R.J. 2003. Biological control and other pest management options for larger grain borer *Prostephanus truncatus*. In: Neuenschwander, P., Borgemeister, C., Langewald, J. (Eds.), Biological Control in IPM Systems in Africa. CABI Publishing, Oxford, UK, pp. 311-328.

Bourassa, C., Vincent, C., Lomer, C.J., Borgemeister, C.and Mauffette, Y. 2001. Effects of entomopathologenic hyphomycetes against the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera; Bostrichidae) and its predator, *Teretriosoma nigrescens* Lewis (Coleoptera; Histeridae). *Journal of Invertebrate Pathology* 77, 75- 77.

Boxall, R.A. 2002b. Damage and loss caused by the larger grain borer *Prostephanus truncatus.* Integrated Pest Management Reviews 7, 105-121.Cape Town, South Africa.

Boys, K., Fulton, J., Faye, M. and Lowenberg-DeBoer. J. 2004. Adoption and economic impact implications of storage technology and improved cowpea varieties in the north central peanut basin of Senegal.

CABI, 2014. *Prostephanus truncatus* (Larger Grain Borer) datasheet. Crop Protection Compendium, 2014 Edition. CAB International Publishing. Wallingford, UK. www.cabi.org/cpc. Accessed on 28 June 2014.

Calderon, M., and Navarro, S. 1980. Synergistic effect of CO_2 and O_2 mixtures on two stored grain insect pests. In: Shejbal, J.ed., Controlled Atmosphere Storage of Grains, Amsterdam Elsevier, 79-84.

Cao D., Hart K. and Pimentel D. 2002. Post-harvest Crop Losses (Insects and Mites), chapter 299, Encyclopedia of pest Management. Pimentel, D (Ed.) CRC Press.

CFIA, 2006. Biology Document BIO1994-11: The biology of *zea mays* (L.) (Maize). A companion document to the directive 94-08 (Dir 94-08), assessment criteria for determining environmental safety of plant with novel traits. http://www.inspection.gc.ca/english/plaveg/bio/dir/dir9411e.shtml. Accessed May 11th, 2013.

CIMMYT, 2009. Annual Report. Effective Grain Storage for Better Livelihoods of African Farmers Project. CIMMYT-Nairobi, Kenya, p. 35.

CIMMYT, 2011. Effective Grain Storage for better Livelihoods of African Farmers Project. Completion report June 2008 to February 2011.CIMMYT (International Maize and Wheat Improvement Center). (2009). Annual Report. Effective Grain Storage for Better Livelihoods of African Farmers Project. CIMMYT-Nairobi, Kenya, p. 35.

Dales, M.J., Golob, P. 1997. The protection of maize against *Prostephanus truncatus* (Horn), using insecticide sprays in Tanzania. *International Journal of Pest Management* 43, 39-43.

De Groote, H., Bett, C., Okuro, O.J., Odendo, M., Mose, L. and Wekesa, E. 2002. Direct estimation of maize losses due to stem borers in Kenya, preliminary results from 2000 and 2001. Proceedings of the 7th Eastern and Southern Africa Regional Maize Conference, Nairobi, Kenya, 11-15 February 2002.

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

Demianyk, C.J. and Sinha, R.N. 1988. Bioenergetics of the Larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae), feeding on corn. *Annals of the Entomological Society of America*, 81(3): 449-459.

Demissie, G., Tefera, T. and Tadesse, A. 2008. Importance of husk covering on field infestation of maize by *Sitophilus zeamais* Motsch. (Coleoptera: Curculionidea) at Bako, Western Ethiopia. Afr. J. Biotechnol. 7:3774-3779.

Dendy, J., Dobie, P., Saidi, J.A., Smith, J. and Uronu, B. 1989. Trapping the larger grain borer *Prostephanus truncatus* in maize fields using synthetic pheromones. *Entomologia Experimentalis et Applicata* 50, 241-244.

Dick, K. 1989. A review of insect infestation of maize in farm storage in Africa with special reference to the ecology and control of *Prostephanus truncatus*. Overseas Development Natural Resources Institute (p. 42). Chatham: Bulletin 18.different moisture contents. Postharvest Biology and Technology 39, 321- 326.

Dunstan, W.R. and Magazini, A.I. 1981. Outbreaks and new records, United Republic of Tanzania: the larger grain borer on stored products. FAO Plant Protection Bulletin 29, 80-81.

FAO, 1977. Analysis of an FAO survey of post-harvest crop losses in developing countries. AGPP MISC/27. Rome: FAO.

FAO, 1999. Insect damage Post-harvest Operations. Mohammed N.S., Danilo, M. and Beverly L.Insect damage: damage on post-harvest pg 38. INPhO- Post _harvest Compendium.www.fao.org/...post-harvest-compendium http://www.fao.org/fileadmin/user_upload/inpho/docs/Post_Harvest_Compendium_-_Pests-Insects.pdf. Accessed 23rd July 2014.

FAO, 2003. Maize Post-harvest Operations. INPhO- Post _harvest Compendium. www.fao.org/...post-harvest-compendium. http://www.fao.org/fileadmin/user_upload/inpho/docs/Post_Harvest_Compendium_-_MAIZE.pdf. Accessed 18 July 2014.

FAO, 2008. Household metal silos, key allies in FAO's fight against hunger by Agricultural and Food Engineering Technologies Service (AGST), FAO of the United Nations. Viale delle Terme di Caracalla 00153 Rome (Italy) http://typo3.fao.org/fileadmin/user_upload/ags/ publications/silos_E_light.pdf. Accessed 08-Aug-2012.

FAO, 2010. Reducing post-harvest losses in grain supply chains in Africa: Lessons learned and practical guidelines. FAO/World. FAO Headquarters, Rome Italy, 18-19 March 2010.

FAO, 2011.Missing Food: The case of Post-harvest Losses in Sub-Saharan Africa. World Bank/ FAO April, 2011. Report No. 60371-AFR.

FAOSTAT, 2009. Food and Agricultural Commodities Production. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/site/339/default.aspx. accessed July 14th 2014.

FAOSTAT, 2012.Global information and Early warning system. Food and Agricultural Commodities Production. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/site/339/default.aspx. accessed July 14th 2014.

Farrell, G., and Schulten, G. G. M. 2002. Larger grain borer in Africa; a history of efforts to limit its impact. Integrated Pest Management Reviews, 7, 67–84.

Gathumbi, J. K., Usleber, E., Maertlbauer, E. 2001. Production of ultra-sensitive antibodies against aflatoxin B1. *Letters in Applied Microbiology* 32, 349-351.

GenStat for Windows 14th Edition. 2011. VSN International, Hemel Hempstead, UK.

Giles P.H. and Leon O, 1975. Infestation problems in farm-stored maize in Nicaragua. In: Proceedings of the 1st International Working Conference on Stored Products Entomology, Savannah, Georgia, USA, 1974: 68-76.

Giles, P.H., Hill, M.G., Nang'ayo, F.L.O., Farrell, G. and Kibata, G.N. 1996. Release and establishment of the predator *Teretriosoma nigrescens* Lewis for the biological control of *Prostephanus truncatus* (Horn) in Kenya. *African Crop Science Journal* 4, 325-337.

Golob, P. and Hodges, R.J. 1982. A study of an outbreak of *Prostephanus truncatus* (Horn) in Tanzania. Tropical Products Institute Report No. G164, 23 pp.

Golob, P., Marsland, N., Nyambo, B., Mutambuki, K., Moshy, A., Kasalile, E.C., Tran, B. H. M., Birkinshaw, L. and Day, R. 1999. Coping strategies adopted by small-scale farmers in Tanzania and Kenya to counteract problems caused by storage pests, particularly the Larger Grain Borer. Final Technical Report Project R 6952.

Golob, P. 2002a. Chemical, physical and cultural control of *Prostephanus truncatus*. *Integrated Pest Management Reviews* 7, 245-277.

Gwinner, J., Harnisch, R. and Muck,O. 1996. Manual on the prevention of post-harvest seed losses, post-harvest project, GTZ, D-2000, Hamburg, FRG, p. 294.

Haines, C.P. 1991. Insects and Arachnids of Tropical Stored Products: Their Biology and Identification (A Training Manual), 2nd edition. Chatham, UK: Natural Resources Institute.

Hassan,R., Ransom, J.K. and Ojiem, J. 1995. The spatial distribution and farmers strategies to control *striga* in maize: Survey results from Kenya, In J.e.a. (ad), ed. Proc.of the Fourth Eastern and Southern Africa Regional Maize conference, Harare, Zimbabwe, 28, March- 1 April 1994, CIMMYT, Harare, Zimbabwe.

Hellin, J. and Kanampiu, F. 2008. Metal silos and food security in El Salvador. Appropriate Technology 35, 69-70.

Hellin, J., Kimenju, S., De Groote, H. 2009. Value chain analysis in Kenya and Malawi: Project report submitted to SDC. International Maize and Wheat Improvement Centre (CIMMYT), Nairobi, Kenya.

Hill, M.G., Nang'ayo, F.L.O. and Wright, D.J. 2003. Biological control of the larger grain borer *Prostephanus truncatus* (Coleoptera: Bostrichidae) in Kenya using a predatory beetle *Teretrius nigrescens* (Coleoptera: Histeridae). *Bulletin of Entomological Research* 93, 299-306.

Hodges, R. J., Dunstan, W. R., Magazini, I., and Golob, P. 1983. An outbreak of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in East Africa. Protection Ecology, 5, 1983–194.

Hodges, R.J. and Meik, J. 1984. Infestation of maize cobs by *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) .Aspects of biology and control. *Journal of Stored Products Research*, 20(4): 205-213.

Hodges, R., Meik, J. and Denton, H. 1985. Infestation of dried cassava (*Manihot esculenta* Crantz) by *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Journal of Stored Products Research.* 21: 73-77.

Hodges, R.J. 1994. Recent advances in the biology and control of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). In: Proceedings of 6th International Working Conference on Stored-Product Protection. Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R. (Eds.), pp. 929-934. Canberra, Australia, 17-23 April, 1994.

IITA. 2007b. Maize http://www.iita.org/cms/details/maize_project_details.aspx? zoneid =63& articleid =273.Accessed on June 13th 2013.

Infonet-Biovision, 2012. Larger Grain Borer. Daniel Wanyama, Kenya Institute of Orgnic Farming (KIOF). http://www.infonet-biovision.org/default/ct/91/pests. 5th edition. Accessed on 14/July.

ISTA, 2004. International Rules for Seed Testing. Edition 2004, Zurich, Switzerland.

Jayne, S. and Chapoto, A. 2006. Emerging structural maize deficits in Eastern and Southern Africa: implications for national agricultural strategies. Policy synthesis No. 16. Food Security Research Project. Ministry of agricultural and Cooperatives, Agricultural Consultative Forum, Michigan State university and the market Access, Trade, and Enabling Policies (MATEP) Programme, Lusaka, Zambia.

Jiang, X.Q., Wilkinson, D.R. and Berry, J.A. 1990. An outbreak of maize chlorotic mottle virus in Hawaii and possible association with thrips. *Phytopathology* 80:106.

Jones, M., Alexander, C. and Lowenberg-DeBoer, J. 2011. Profitability of Hermetic Purdue Improved Crop Storage (PICS) Bags for African Common Bean Producers. Working Paper No.11-3. Dept. of Agricultural Economics, Purdue University,West Lafayette, Indiana.

Josphert, N.K., McConchie, R., Xie, X., and Simon, N. N. 2012. The significant role of post-harvest management in farm management, Aflatoxin mitigation and Food security in sub Saharan Africa. *Greener Journal of Agricultural Sciences* Vol.2 (6) pp.279-288.

Kaliba, A.R., Verkuijil, H., Mwangi, W., Byamungu, D.A., Anandajayasekeram, P. and Moshi, A.J. 1998. Adoption of maize production technologies in western Tanzania. Mexico: CIMMYT.

Kanyanjua, S.M., Ireri, L., Wambua, S. and Nandwa, S.M. 2002. Acidic soils in Kenya: Constraints and remedial options. KARI Technical Note No. 11 June 2002.

Kega, V.K., Warui, C.W. 1983. Prostephanus truncatus in Coast Province Kenya.*Tropical Stored Products Information* 46-2.

Keil, H. 1988. Losses caused by the Larger Grain Borer in farm stored maize in the Arusha Region of Tanzania. pp. 28-52 in G.G.M. Schulten and A.J. Toet (Eds.). Proceedings of the Workshop on the Containment and Control of the Larger Grain Borer, Arusha, Tanzania, 16-21 May 1988. pp. 28-52.

KEPHIS, 2014. Updated variety list in Kenya. http:// www. Kephis.org. accessed 20th July 2014.

Kimenju, S.C., De Groote, H. and Hellin, H. 2009. Preliminary Economic Analysis: Cost effectiveness of the use of improved storage methods by small scale farmers in east and southern Africa countries. International Maize and Wheat Improvement Center (CIMMYT), p.17.

Kimenju, S. and De Groote, H. 2010. Economic analysis of alternative maize storage technologies in Kenya. Paper presented at the Joint 3rd African Association of Agricultural Economists (AAAE) and 48th Agricultural Economists Association of South Africa (AEASA) Conference, Cape Town, South Africa, September 19–23. Maize against the maize weevil, *Sitophilus zeamais* (Coleoptera: Curculionidae). *Stored Prod. Res*. J. 45(1): 67-70.

Krall, S. 1984. A new threat to farm-level maize storage in West Africa: *Prostephanus truncatus* (Coleoptera: Bostrichidae). *Tropical Stored Products Information* 50, 26-31.

Laborious, G.A., Bõye, J., Leliveldt, B and Schulz, F.A. 1989.Evaluation of biological methods to control the larger grain borer *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Africa with special reference to the predator

Teretriosoma nigrescens Lewis (Coleoptera: Histeridae). In: Intergrated pest management of in tropical and sub-tropical cropping systems. Proceedings (of the International DLG Symposium), Bad Durkheim, Federal Republic of Germany, february 8-15 1989. Frankfurt, Deutsche Landwirtschafts-Gesellschaft e.V. and Ede, CTA,3, 939-959.

Malek, M. and Parveen, B. 1989. Effect of insects infestation on the weight loss and viability of stored paddy. Bangladesh *Journal of Zoology*. 17: 1, 83-85.

Mallya, G.A. 1992. *Prostephanus truncatus* (HORN), the larger grain borer (LAB), and its control in Tanzania. In: Implementation of and further research on biological control of the larger grain borer. Proceedings of an FAO/GTZ Coordination meeting. Lome, Togo, 5-6 November 1990.

McFarlane, J.A**.** 1988. Storage methods in relation to post-harvest losses in cereals. *Insect Science and its Application*. 9: 6, 747-754.

MOA, 2012. Report on Maize Lethal Necrosis Disease, Multidisplinary Team Report, Ministry of Agriculture, Kenya (July 2012).

Moreno- Martinez, Jimenez, S., Mario, E. 2000. Effect of *Sitophilus zeamais* and *Aspergillus chevalieri* on the oxygen level in maize stored hermetically. *Journal of stored products Research* 36 (2000) 25-26.

Muhihu, S.K. and Kibata, G.N. 1985. Developing a control programme to combat an outbreak of *Prostephanus truncatus* Horn (Coleoptera: Bostrichidae) in Kenya. *Tropical Science*, 25: 239 -248.

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

Mvumi, B., Giga, D. and Chiuswa, D. 1995. The maize (*Zea mays* L.) post-production practices of smallholder farmers in Zimbabwe: findings from surveys. JASSA, *Journal of Applied Science* in Southern Africa. 1: 2, 115-130.

Nang'ayo, F.L.O., Hill, M.G., Wright, D.J. 2002. Potential hosts of *Prostephanus truncatus* (Coleoptera: Bostrichidae) among native and agroforestry trees in Kenya. *Bulletin of Entomological Research*, 92(6):499-506; 36.

Nansen, C.and Meikle, W.G. 2002. The biology of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera:Bostrichidae). *Integrated Pest Management Reviews*, 7: 91-104.

Navarro, S. Donahaye, E.J. and Fishman, S. 1994. The future of hermetic storage of dry grains in tropical and subtropical climates. In: Proceedings of the 6th International working Conference on Stored-Product Protection, 17-23 April 1994 Canberra Australia 1: 130-138.

Navarro, S. and Donahaye, J. 2005. Innovative environmentally friendly technologies to maintain quality of durable agricultural produce. In: Shimshon, B.Y. (Ed.), Environmentally Friendly Technologies for Agricultural Produce Quality. CRC Press, Boca Ratón, Florida, pp. 203-260.

Navarro, S., De Bruin, T., Montemayer, A. R., Finkelman, S., Rindner, M., Dias, R. 2007. Use of biogenerated atmospheres of stored commodities of quality preservation and insect control, with particular reference to cocoa beans. Integrated Protection of Stored Products, IOBC/wprs Bulletin, Vol. 30 (2) 2007, 197-204.

Ngamo, L. S. T., Ngassoum, M. B., Mapongmetsem, P. M., Maliasse, F., Hauburg, E., Lognay, G. 2007. Current post-harvest practices to avoid insect attacks on stored grains in northern Cameroon. *Agricultural Journal* 2, 242–247.

Nguyo, R. 2007. Grain Storage: Keeping weevils at bay with metal silos. In: Rootheart, R., Taylor, P. (Eds.). Creating Sustainable Agricultural Impact for smallholders: MATF Innovative Partnerships and approaches, 4th MATF Experience sharing workshop. Mombasa, Kenya. pp 19-23.

Niblett, C. L. and Claflin, L.E. 1978. Corn lethal necrosis, a new virus disease of corn in Kansas. *Plant Disease* 62: 15-19.

Nyoro, J., Ayieko, M. and Muyanga, M. 2007. The compatibility of trade policy with domestic policy interventions affecting the grains sector in Kenya. Tegemeo Institute, Egerton University.

Odour, G.I., Smith, S.M, Chandi, E.A., Karanja, L.W, Agano, J.O and Moore, D. 2000. Occurrence of Beauveria bassiana on insect pests of stored maize in Kenya. *Journal of Stored Products Research* 36, 177-185.

Omondi, B.A., Nanqing, J., Berg, J. and Fritz, S.2011.The flight activity of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and *Teretrius nigrescens* Lewis (Coleoptera: Histeridae) in Kenya. *Journal of Stored Products Research* 47 (2011) 13-19.

Onwueme, I.C. and Sinha, T.D. 1991. Field crops production in Tropical Africa. Technical Centre for Agricultural and Rural Co-operation.

PaDIL – Plant Biosecurity Toolbox. Larger grain borer *Prostephanus truncatus*. http://www.padil.gov.au/pbt. Accessed on 12 Jun 2011.

Pande, N. and Mehrotra, B.S. 1988. Rice weevil (*Sitophilus oryzae* Linn.): vector for toxigenic fungi. *National Academy Science Letters*. 11: 1, 3-4.

Pantenius, C. 1988. Storage losses in traditional maize granaries in Togo. *Insect Science and its Application*. 9 (6), 725-735.

Pattinson, I.1970. Grain Storage at Village Level. FFHC Action Program Report TAN/II.,FFHC/FAO, Rome.

Phiri, N.A. and Otieno, G. 2008. Managing pests of stored maize in Kenya and Malawi. *Journal of Stored Products Research* 21, 141-150.

POSTCOSECHA, 2011. Five (5) Year Ex-Post Impact Study. Fischler, M., Bokusheva, R. and Finger, R. Agri-Food and Agri Environmental Economics Group, Institute for Environmental Decisions, ETH Zurich, Switzerland, Yuri Marín, Francisco País, Karen Pavón, and Francisco Pérez, Nitlapan, Managua, Nicaragua. POSTCOSECHA Programme Central America. Final Report March 2011. Pg 128. Swiss Agency for Development and Cooperation SDC.

Proctor, D.L. (ed.) 1994. Grain storage techniques. Evolution and trends in developing countries. FAO Agricultural Services Bulletin No. 109. FAO, Rome.project, GTZ, D-2000, Hamburg, FRG. p. 294.

Quezada, M., Moreno, J., Vazquez M, Mendoza, M., Mendezalbores, A., Moreno, M.E. 2006. Hermetic storage system preventing the proliferation of *Prostephanus truncatus* Horn and storage fungi in maize with different moisture contents. *Postharv. Biol*. Tech. 39(3): 321-326.

Ragai, H. and Loomis, W.E. 1954. Respiration of maize grains. *Plant Physiology*, 29, 49-55

Rees, D.P. 1985. Life history of *Teretriosoma nigrescens* Lewis (Coleoptera: Histeridae) and its ability to suppress populations of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Journal of Stored Products Research*, 21(3):115-118.

Rees, D.P., Rodriguez, R., Herrera, F.L. 1990. Observations on the ecology of *Teretriosoma nigrescens* Lewis (Col. Histeridae) and its prey *Prostephanus truncatus* (Col.: Bostrichidae). *Tropical Science*, 30:153-165.

Reuss, R., Damcevski, K. and Annis, P.C. 1994. The impact of temperature, moisture content, grain quality and their interactions on changes in storage vessel atmospheres. In Highley E, Wright E.J, Banks H.J, Champ B.R (Eds) Stored Products Protection, Proccedings of the 6th Inter. working conference on stored products protection Canberra Austratlia Cab International, Vol.1 pp 178-182.

Reuss, R. and Pratt, S. 2001.Accumulation of carbon monoxide and carbon dioxide in stored canola. *Journal of Stored Products Research,* 37(2001)23-34.

Sambarashe, M., Chitamba, J.and Sipiwe, G. 2013. Screening of stored maize (*Zea mays* L.) Varieties Grain for Tolerance against Maize Weevil, *Sitophilus zeamais* (Motsch.), *International Journal of Plant Research*, Vol. 3 No. 3, 2013, pp. 17-22.

Santos, J.P., Maia, J.D.G., and Cruz, I. 1990. Damage to germination of seed corn caused by maize weevil (*Sitophilus zeamais*) and Angoumois grain moth (*Sitotroga cerealella*). *Pesquisa Agropecuaria Brasileira*. 25: 12, 1687-1692.

Scheets, K. 1998. Maize chlorotic mottle machlomovirus and wheat streak mosaic rymovirus concentrations increase in the synergistic disease maize lethal necrosis. *Virology* 242:28–38.

Schneider, H., Borgemeister, C., Setamou, M., Affognon, H., Bell, A., Zweigert, M.E., Poehling, H., Schulthess, F. 2004. Biological control of the larger grain borer *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) by its predator *Teretrius nigrescens* (Lewis) (Coleoptera: Histeridae) in Togo and Benin. *Biological Control* 30, 241-255.

Scholz, D., Borgemeister, C., Meikle, W. G., Markham, R.H., Poehling, H.M. 1997. Infestation of maize by *Prostephanus truncatus* initiated by male-produced pheromone. *Entomologia Experimentalis et Applicata*, 83(1):53-61; 37.

SDC, 2008a. Latin America Section: Fighting Poverty with Metal Silo and Job Creation. Berne. Switzerland.

SDC, 2008b. Manual for manufacturing metal silos for grain storage. Swiss Agency for Development and Cooperation.

SDC, 2012. Food Security in Central America: Small silos that make a big difference. SDC, Report 2012.

Sekyembe S., Maurer G., Gatimu J., Nkanya J. and Injairu S.C. 1993. Training manual for the control of the greater (larger) grain borer (*Prostephanus truncatus*, Horn). Produced by the Agriculture and Food Protection Department, Food and Agriculture Organisation of the United Nations. http://www.fao.org/wairdocs/.HTM. Accessed on 28th July 2014.

Semple, R. L., Hicks, P. A. Lozare, J. V., and Castermans, D. A. 1992. Regional training course on integrated pest management strategies in grain storage systems, conducted by the National Post Harvest Institute for Research and Extension (NAPHIRE), Department of Agriculture, June 6–18, 1988, Philippines. A REGNET (RAS/86/189) Publication in Collaboration with NAPHIRE.

Semple, R.L. and Kirenga, G.I. 1994. Facilitating Regional Trade of Agricultural Commodities in Eastern, Central and Southern Africa. Phytosanitary Standards to Restrict the Further Rapid Spread of the Larger Grain Borer (LGB) in the Region. Technical Data Sheets. Dar es Salaam University Press, 288 pp.

Short, C., Mulinge, W. and Witwer, M. 2012. Analysis of incentives and disincentives for maize in Kenya. Technical notes series, MAFAP, FAO Rome.

Smale, M and Jayne, T. 2003. Maize in Eastern and Southern Africa: "Seeds" of Success in Retrospect. EPTD Discussion Paper No. 97. IFPRI, Washington, D.C.

Songa, W. and Irungu. J. 2010. Post0harvest Challenges to food security in Kenya. Republic of Kenya Ministry of Agriculture.

Suma, P. and Russo, A. 2005. On the presence of *Prostephanus truncatus* (Horn) (Coleoptera Bostrychidae) in Italy. *Bollettino di Zoologia Agraria e di Bachicoltura*, 37(2):135-139.

Süss, L.,Locatelli D.P., and Boriani, M. 1993. Effect of Carbon dioxide on *Prostephanus truncatus* (Horn).Institute of Agricultural Entomology, University of Milan, via Celoria 2, I-20133 Milano, Italy.

Tefera T., Mugo, S., Tende, R. and Likhayo, P. 2010. Mass rearing of stem borers, maize weevil, and larger grain borer insect pests of maize. CIMMYT: Nairobi, Kenya.

Tefera, T., Kanampiu, F., De Groote, H., Hellin, J., Mugo, S., Kimenju, S. Beyene,Y., Prasanna, M.B., Bekele, S.and Marianne, B. 2011a.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 (2011) 240-245.

Tefera, T., Mugo, S., and Likhayo, P. 2011b. Effects of insect population density and storage time on grain damage and weight loss in maize due to the maize weevil *Sitophilus zeamais* and the larger grain borer *Prostephanus truncatus*. *African Journal of Agricultural Research*, 6, 2249–2254.

Tefera, T. 2012. Post-harvest losses in African maize in the face of increasing food shortage. International Society for Plant Pathology 2012.*Food Sec*. (2012) 4:267-277.

Tooke, F.G.C. and Scott, M.H. 1994. Wood boring beetles in South Africa. Department of Agriculture. Technical Bulletin No. 247 (Entomology Series No. 14).

USDA, 2009. Complete guide to home canning. Principles of home canning. http://www.nchfp.uga.edu/publicationslpublication_usda.html. Accessed on 28/3/2015.

USDA, 2013. Global Agricultural Information Network. Corn Update report for Kenya.

Villers, P., Navarro, S. and De Bruin, T. 2008. Development of Hermetic Storage Technology in Sealed Flexible Storage Structures. In: Daolin., G., Navarro, S., Jian, Y., Cheng, T., Zuxun, J., Yue, L., Haipeng, W. (Eds.), pp. 36-37. Proceedings of the 8th International Conference on Controlled Atmosphere and Fumigation in Stored Products. California Garden Hotel, Chengdu, China. September 21-26. 2008, Sichuan Publishing Group, Sichuan, China.Villers, P., Gummert, M., 2009, "Seal of Approval", Rice Today, Jan-March 2009.

Wangai, A.W., Redinbaugh, M. G., Kinyua, Z. M., Miano, D. W., Leley, P. K., Kasina, M., Mahuku, G., Scheets, K., Jeffers, D. 2012. First Report of Maize chlorotic mottle virus and Maize Lethal Necrosis in Kenya. *Plant Disease* 96:10- 1582.

Weinberg, Z.G., Yan Y., Chen Y., Finkelman S., Ashbell G and Navarro S. 2008. The effect of moisture level on high-moisture maize (Zea mays L.) under hermetic storage conditions—in vitro studies. *Journal of Stored Products Research* 44 (2008) 136–144.

Whittle, C.P, Waterford, C.J, Annis, P.C. and Banks, H.J. 1994. The production and accumulation of Carbon monoxidein stored grain. *Journal of Stored Products Research* 30. 23-26.

World Bank, 2009. Eastern Africa: A Study of the Regional Maize Market and Marketing Costs. Economic and Sector Work, Report No. 49831-AFR. Washington, DC: World Bank.

Wright, M.A.P., Akou, E. D. and Stabrawa, A. 1993. Larger grain borer project, Togo. Infestation of dried cassava and maize by *Prostephanus truncatus*: entomological and socio-economic assessments for the development of loss reduction strategies. Natural Resources Institute Report R1941.141p.

Yakubu, A., Bern, C. J., Coats, J. R. and Bailey, T.B. 2011. Hermetic on-farm storage for maize weevil control in East Africa. *African Journal of Agricultural Research,* 6(14): 3311-3319.

Yusuf, B.L. and He, Y. 2011.Design, development and techniques for controlling grains post-harvest losses with metal silo for small and medium scale farmers. *African Journal of Biotechnology* 10, 14552-14561.

Yuya, A., Tadesse, A., Azerefegne, F. and Tefera, T. 2009. Efficacy of combining Niger seed oil with malathion 5% dust formulation on maize against the maize weevil, *Sitophilus zeamais* (Coleoptera: Curculionidae). *Journal of Stored Products Research* 45(1):67-70.