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On-farm maize storage systems and rodent postharvest losses in six maize growing agro-ecological zones of Kenya

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Abstract Rodents are one of the major postharvest pests that affect food security by impacting on both food availability and safety. However, knowledge of the impact of rodents in on-farm maize storage systems in Kenya is limited. A survey was conducted in 2014 to assess magnitudes of postharvest losses in on-farm maize storage systems in Kenya, and the contribution of rodents to the losses. A total of 630 farmers spread across six maize growing agro-ecological zones (AEZs) were interviewed. Insects, rodents and moulds were the main storage problems reported by farmers. Storage losses were highest in the moist transitional and moist mid-altitude zones, and lowest in the dry-transitional zone. Overall, rodents represented the second most important cause of storage losses after insects, and were ranked as the main storage problem in the lowland tropical zone, while insects were the main storage problem in the other AEZs. Where maize was stored on cobs, total farmer perceived (farmer estimation) storage weight losses were 11.1 ± 0.7 %, with rodents causing up to 43 % of these losses. Contrastingly, where maize was stored as shelled grain, the losses were 15.5 ± 0.6 % with rodents accounting for up to 30 %. Regression analysis showed that rodents contributed significantly to total storage losses ($p < 0.0001$), and identified rodent trapping as the main storage practice that significantly ($p = 0.001$) lowered the losses. Together with insecticides, rodent traps were found to significantly decrease total losses. Improved awareness and application of these practices could mitigate losses in on farm-stored maize.

Keywords Postharvest losses · Rodents · Maize · On-farm storage · Food security · Kenya

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Introduction

Maize is the staple food for over 90 % of the Kenyan population (Laboso and Ng'eny 1996). For this reason, a large part of harvested maize is stored to guarantee supply between harvest seasons. The bulk of storage takes place in on-farm storage systems. These systems are characterized by traditional storage structures (Nukenine 2010) that are prone to invasion by agents of stored food losses including insects and rodents (Lathiya et al. 2007). In Kenya, earlier work by De Lima (1979) identified insects and rodents as the main causes of postharvest losses in durable crops. The black rat otherwise called roof rat (*Rattus rattus)*, the house mouse (*Mus musculus)* and the Natal multimammate mouse (*Mastomys natalensis*) are responsible for most of the postharvest crop damage caused by rodents in East Africa (Makundi et al. 1999). *R. rattus* and *M. musculus* inhabit houses and storage structures whereas *M. natalensis* moves from the fields to frequently invade storage structures at the end of the harvest season due to absence of food in fields (Mdangi et al. 2013).

The actual magnitude of food losses caused by rodents on stored maize is largely unknown. However, a number of studies give estimates of the losses in various parts of the world. Singleton (2003) estimated annual loss of food due to rodents to be equivalent to 11 kg of food per person, which translated to over 77 million metric tons annually, in a world of over 7 billion inhabitants. In India, Cao et al. (2002) estimated the overall grain losses due to rodents in the postharvest stage to be 25–30 % of which the economic cost amounted to $5 billion in stored food and seed grain annually. Studies in Bangladesh and Myanmar estimated household postharvest losses of stored food due to rodent damage at 2.5 % and 17 %, respectively (Belmain et al. 2015), and in east Africa, damage of up to 34 % on maize grain in traditional open cribs was reported in Tanzania (Mdangi et al. 2013). The grain damage by rodents in stores is often associated with removal of the germ, which causes germination failure when the seeds are used for planting, and the contamination of the grain with faeces, hair and urine which results in poor quality and lower market value (Justice and Bass 1979). Moreover, rodents are well-known vectors for diseases that are of public health concern (Cao et al. 2002).

The reduction of postharvest food losses can make a significant contribution towards sustainable food security, and in recent years, this realization has caused renewed interest in mitigating postharvest losses (Affognon et al. 2015). As a first step, appraising the postharvest system and assessment of the kinds and levels of losses, and the factors associated with them is important. Whereas postharvest losses due to rodents are recognized the world over as a serious problem, only a few studies have assessed the levels of losses that farmers routinely experience in farm stores in Africa (Ratnadass et al. 1991; Belmain et al. 2003; Taylor et al. 2012; Mdangi et al. 2013).

In Kenya, apart from the study of De Lima (1979) which reported annual weight losses caused by rodents in small holder systems to be 1.45 %, no further studies have been undertaken, partly because of the general perception that losses due to rodents are insignificant, and probably also because of the difficulties involved in assessing and preventing such losses. The direct measurement of the postharvest losses caused by rodents often presents practical constraints. One constraint is the non-random distribution of rodent infestations on the stored product, which complicates statistical approaches for sampling and loss assessment. Other constraints include the need to distinguish losses due to other pests, and changes in moisture content which have to be measured separately (Greaves 1976). Furthermore, to objectively ascertain grain loss due to rodents, one needs to make the measurements in separate stores where interference is minimal, an option that is expensive and may not provide comparable results to what really occurs in farmer stores (Belmain et al. 2005).

One indirect method involves estimating the population of rodents followed by extrapolation of their daily food consumption (Greaves 1976). A limitation of this method, however, relates to the difficulty of estimating the density of rodent populations in grain stores because their nesting sites and foraging activities may include other habitats (Belmain et al. 2015). In addition, this kind of estimation may not reflect actual losses within farm stores that are usually found in complex environments offering rodents access to several different food sources (Meyer 1994).

An alternative losses assessment approach is the use of surveys to capture farmers' own perception and estimation of the losses in their stores (Abass et al. 2014; Kaminski and Christiaensen 2014). In contexts where the aim is to generate measurements that can be linked to agro conditions, storage practices and the socio-economic circumstances of farmers, surveys done in a representative manner can generate consistent data that reveal what farmers regard as most important (Kaminski and Christiaensen 2014). Furthermore, self-reported loss estimates are more incentive compatible, and give information relevant from a behavioral and operational perspective, as opposed to objective estimates which also face practical and methodological challenges (Kaminski and Christiaensen 2014). In recent years, surveys have been used to attempt to generate nationally representative on-farm postharvest losses estimates in Malawi, Uganda and Tanzania (Abass et al. 2014; Kaminski and Christiaensen 2014) with a high degree of internal consistency of the data.

The aim of the present study was to generate nationally representative data on maize storage practices and level of postharvest losses in on-farm stores in Kenya, and to assess the contribution of rodents to the overall losses. Surveys were used to collect data on storage systems and the magnitude of storage losses farmers incur across the six maize growing agro-ecological zones (AEZs). A regression analysis was further performed to identify the factors that are most responsible for the losses.

Materials and methods

Study area

The study was carried out within six maize growing AEZs of Kenya (Fig. 1) which are located in Central, Coast, Eastern, Nyanza, Rift valley and Western regions of the country (Ong'amo et al. 2006). These AEZs are highland tropics zone (HLT), moist transitional zone (MT), moist mid-altitude zone (MMA), dry mid-altitude zone (DMA), dry transitional zone (DT) and the lowland tropical zone (LLT). The characteristics of the six zones are described in Table 1. The areas of highest potential production are MT followed by HLT zones, which together, represent 64 % of the total production area and account for approximately 80 % of Kenya's maize production. The other zones make up about 30 % of the total maize area but produce only 15 % of Kenya's maize. The remaining 6 % of the maize area which contributes 5 % of the production is located in the 0–0.5 % maize intensity zone (Fig. 1). LLT and DT zones are regarded as the lowest potential areas. DMA and MMA zones are considered as medium potential areas (De Groote 2002).

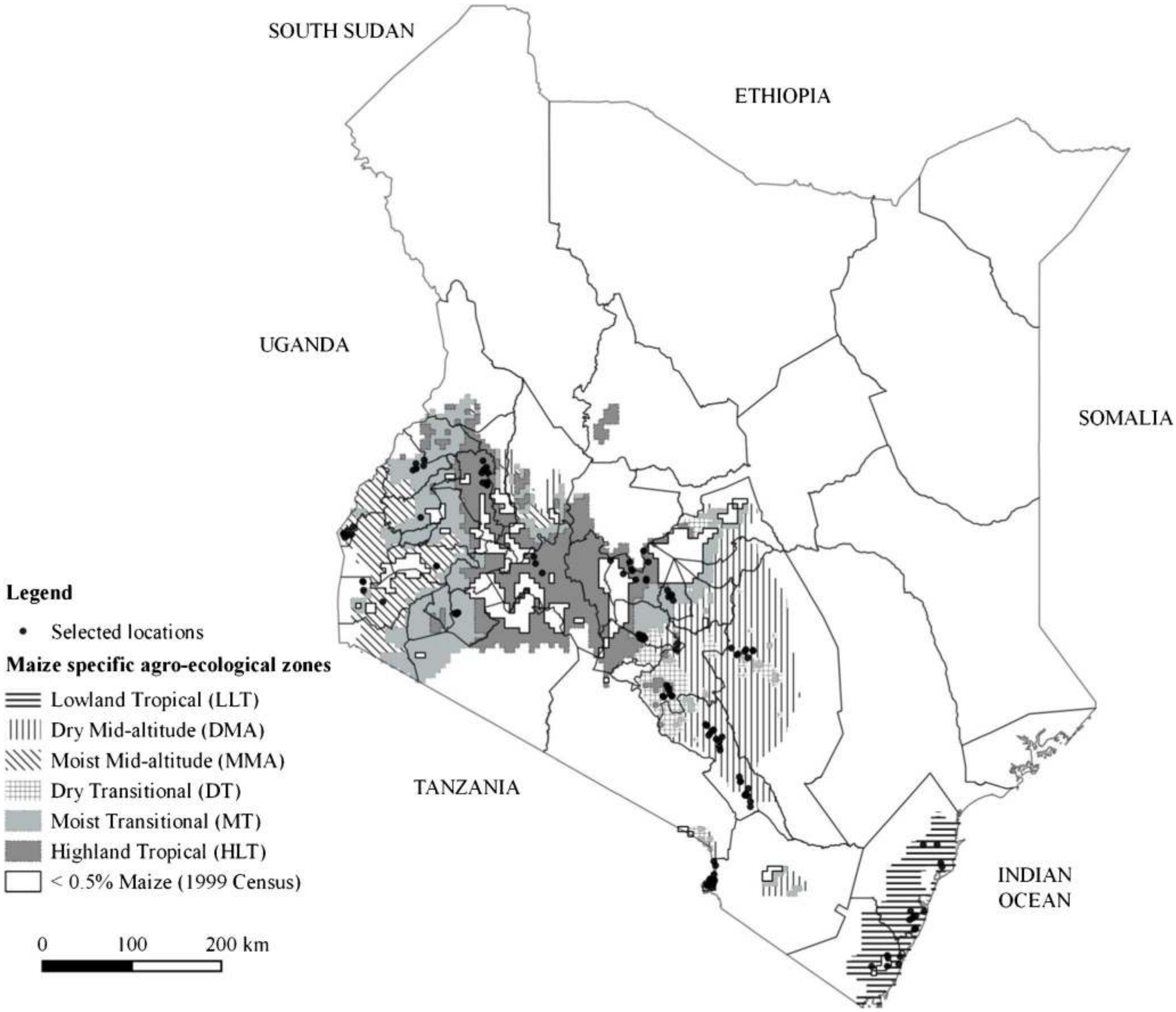

Fig. 1 Map of Kenya showing the various agro-ecological zones and localities surveyed during the study

Sampling and data collection

A total of 630 out of a possible 2.97 million small-scale maize farmers (COMPETE 2010), were interviewed using a structured questionnaire following a 6 × 3 × 35 design (Six AEZs; three sub-counties in each AEZ and 35 respondents per sub-county). According to Krejcie and Morgan (1970), for a population size beyond 1,000,000 a minimum sample size of 400 based on a 0.95 confidence level and a margin of error of 0.05 is regarded as adequate. To identify individual respondents, a combination of random and purposive sampling techniques were employed. Three sub-counties were selected randomly in each AEZ, and 35 maize farmers were purposively selected from each of the sub-counties to give a sample size of 105 respondents per AEZ. Purposive sampling of farmers was applied so as to include only those farmers who harvested maize in 2013 and had subsequently stored part of it. In each household visited, the person who was primarily involved in farming of maize was deliberately identified and interviewed. To achieve this, before commencing the interview, the household head was identified and asked whether he/she was primarily involved in the farming of maize. If the household head was primarily involved, the interview proceeded, otherwise he/she was requested to redirect accordingly. Interviews were conducted by trained enumerators in the national language (Kiswahili) in the presence of a trained local interpreter. Data on demographic and socio-economic characteristics of farmers, maize production, consumption, and storage practices, importance of different maize storage pests, estimate of losses incurred during storage, and coping strategies for the losses were collected. Before estimation of losses, the concept of postharvest losses was explained, and the respondents were trained on how to use the proportional piling method (Watson 1994; Sharp 2007) to give a quantitative estimate

Table 1 Characteristics of the maize-specific agro-ecological zones of Kenya

Agro-ecological zones	Altitude (m ASL[g])	Average total seasonal rainfall (mm)	Daily temperature (°C)	
			Min.	Max.
LLT [a]	<800	<1000	20.0	29.4
DMA [b]	700–1300	<600	16.1	27.9
DT [c]	1100–1800	<600	14.0	25.3
HLT [d]	>1600	>400	10.0	23.0
MT [e]	1200–2000	>500	13.4	23.3
MMA [f]	1100–1500	>500	15.9	28.3

Source: Hassan et al. (1998)

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

[g] Above sea level

of losses. In using this method, farmers were asked to select from 100 dried beans the part corresponding to the losses they experienced for each type of storage pest reported as cause of losses in their stores. Separate estimates were obtained for the long rain crop season (L_{LR}) and the short rain crop season (L_{SR}). In the case where farmers harvested and stored maize during only one crop season, the annual losses were directly equivalent to the losses reported for the one season whereas in the cases where farmers harvested and stored maize during the long and short rain crop seasons, annual losses were calculated using the expression:

$$L(\%) = (L_{LR}QL_R + L_{SR}Q_{SR}) * 100/(Q_{LR} + Q_{SR}) ,$$

where L (%) is the annual loss, L_{LR} is the proportion of maize lost during storage of the long rain harvest, L_{SR} is the proportion of maize lost during storage of the short rain harvest, Q_{LR} is the quantity of maize (kg) stored from the harvest of the long rain season, and Q_{SR} is the quantity of maize (kg) stored from the harvest of the short rain season.

Data analysis

Qualitative data (maize storage forms, storage places and structures, storage duration, methods used by farmers to protect stored maize, and training on postharvest management) were summarized as contingency tables or graphs. Differences between categories within AEZs as well as the overall sample were determined using the Chi-square test followed by pairwise comparisons using "chisq.multcomp" function with Bonferroni p-values adjustment in the RVAideMemoire package (Hervé 2014) of statistical software R, version 3.2.5. Prior to analysis, data on losses and the proportions of harvested maize taken for various uses (percentage) were tested for normality using the Shapiro-Wilk test (df = 247, statistic =0.801, $p < 0.001$ (total losses in maize cob storage); df = 526, statistic =0.901, $p < 0.001$ (total losses in shelled maize grain storage); df = 247, statistic =0.736, $p < 0.001$ (Insect losses in maize cob storage); df = 526, statistic =0.806, $p < 0.001$ (Insect losses in shelled maize grain storage); df = 247, statistic =0.804, $p < 0.001$ (Rodent losses in maize cob storage); df = 526, statistic =0.767, $p < 0.001$ (Rodent losses in shelled maize grain storage); df = 247, statistic =0.252, $p < 0.001$ (Mould losses in maize cob storage); df = 526, statistic =0.275, $p < 0.001$ (Mould losses in shelled maize grain storage); df = 630, statistic =0.797, $p < 0.001$ (proportion of harvested maize taken for consumption); df = 630, statistic =0.790, $p < 0.001$ (proportion of harvested maize taken for sale); df = 630, statistic =0.242, $p < 0.001$ (proportion of harvested maize taken for other uses)). The data were found to be not normally distributed and were arcsine square root (x/100)-transformed and then subjected to analysis of variance (ANOVA) in SPSS version 20. Means were separated using Duncan's multiple range test at 95 % conficence level.

To identifythe factors associated with the losses, relationships between reported magnitudes of losses, storage practices, storage bio-physical environment, as well the socioeconomic characteristics of the farmers were established using regression analysis. This was performed in STATA 12 (StataCorp LP, TX, USA). A model was fittedwith the explanatory variables grouped in four categories: (i) the respondents' socioeconomic characteristics (gender, age, experience in maize farming and education level), (ii) the storage practices and management characteristics (maize storage forms, storage structures, use of chemicals, cat, trap and training on grain storage protection), (iii) the storage seasons (long rain season, short rain season or both), and (iv) the AEZs. In addition to these variables, presence or absence of rodents in storage was considered for the total maize loss model to see whether contribution of rodents to total losses was significant or not. From the survey, some farmers did not incur any losses and therefore their losses values were constrained to zero. Moreover, the dependent variable was censored at both right and left sides as the losses values were within the (0–1) interval. Due to censoring, an ordinary least squares regression can result in biased parameter estimates. To overcome that situation, Tobit estimator which is the standard procedure to correct for zero censoring (Wooldridge 2012) was performed. However, according to Wooldridge (2012), if error terms are not normally distributed and there is a homoskedastic problem, Tobit estimates are themselves biased. The presence of non-normal distribution and heteroskedasticy of errors were observed when the diagnostic of Tobit regression model was performed through Lagrange Multiplier (LM) tests of non-normality and heteroskedascity as described in Cameron and Trivedi (2010) (Normality test: $NR^2 = 46.593$, $p < 0.0001$ (total losses model) and $NR^2 = 75.977$, $p < 0.0001$ (rodents losses model)) and homoskedasticity test: $NR^2 = 293.376$, $p < 0.0001$ (total losses model) and $NR^2 = 169.342$, $p < 0.0001$ (rodents losses model)). Therefore the censored least absolute deviation (CLAD) regression was used as alternative to the Tobit regression to identify factors that most influenced the magnitude of losses (Powell 1984). The major advantages of this semi-parametric approach are its robustness to unknown conditional heteroskedasticy, and the provision of consistent and asymptotically normal estimates for a wide range of error distributions.

Results

Socio-demographic characteristics of respondents

Socio-demographic characteristics of respondents according to agro-ecological zone are summarized in Table 2. The majority of respondents in the LLT, DMA, HLT and MMA zones were male whereas female respondents were the majority in the DT and MT zones. Overall, out of the 630 respondents there was a balanced gender distribution of 51 % female against 49 % male respondents. Generally, 61.3 % of all respondents were within the age of 25–55 years. More than two thirds had completed the primary level of formal education (69.9 %), although the percentage was lower (45.7 %) in the LLT zone. In addition, close to three quarters of the respondents (73 %) had more than 11 years of experience in maize farming. The harvested maize was mainly used for household consumption (75.6 ± 1.2 %) and income (23.4 ± 1.1 %). A small proportion of the maize (1.5 ± 0.3 %) was used for donations, payments in kind or planting (Fig. 2). Consumption was the predominant end use of the harvested maize in all the AEZs, except the HLT zone where quantities used for home consumption and sale were not significantly different.

Maize storage forms

Maize storage forms varied from one AEZ to another (Table 3). Some farmers stored their maize in cobs during

Table 2 Socio-demographic characteristics of respondents ($n = 630$)

Characteristic	Percentage of respondents in each agro-ecological zone						Overall percentage
	LLT [a] $n = 105$	DMA[b] n = 105	DT n = 105	HLT [d] n = 105	MT [e] n = 105	MMA [f] n = 105	
Gender							
Male	59.0	56.2	25.7	66.7	30.5	56.2	49.0
Female	41.0	43.8	74.3	33.3	69.5	43.8	51.0
Age (years)							
< 18	0.0	0.0	0.0	1.0	0.0	1.9	0.5
18–24	4.8	1.9	1.0	6.7	5.7	14.3	5.7
25–40	39.0	30.5	24.8	35.2	43.8	27.6	33.5
41–55	24.8	22.9	34.3	34.3	27.6	22.9	27.8
> 55	31.4	44.8	40.0	22.9	22.9	33.3	32.5
Education level							
No formal education	30.5	10.5	11.4	7.6	12.4	1.0	12.2
Not completed primary school	23.8	26.7	6.7	15.2	14.3	21.0	17.9
Completed primary school	23.8	35.2	54.3	31.4	46.7	35.2	37.8
Completed secondary school	21.9	27.6	27.6	45.7	26.7	42.9	32.1
Maize farming experience (years)							
1–5	10.5	3.8	3.8	30.5	13.3	21.0	13.8
6–10	24.8	13.3	9.5	10.5	10.5	10.5	13.2
11–15	8.6	8.6	9.5	16.2	22.9	25.7	15.2
> 15	56.2	74.3	77.1	42.9	53.3	42.9	57.8

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

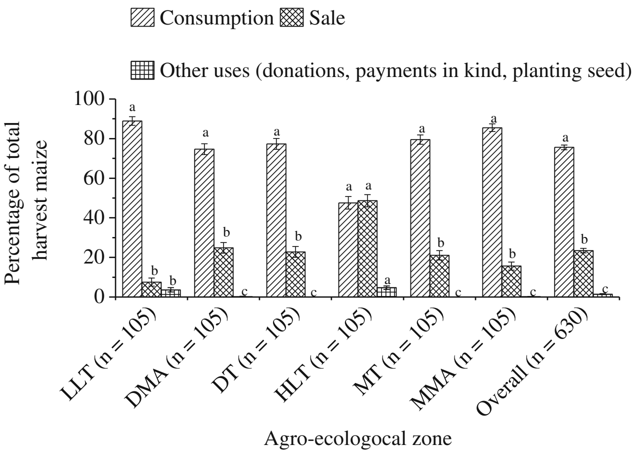

Fig. 2 End uses of maize harvested by farmers. n: sample size; LLT: Lowland tropical zone ($F_{2,\ 312}$ = 703.65, $p < 0.001$); DMA: Dry mid-altitude zone ($F_{2,\ 312}$ = 323.80, $p < 0.001$); DT: Dry transitional zone ($F_{2,\ 312}$ = 352.82, $p < 0.001$); HLT: Highland tropical zone ($F_{2,\ 312}$ = 99.99, $p < 0.001$); MT: Moist transitional zone ($F_{2,\ 312}$ = 441.89, $p < 0.001$); MMA: Moist mid-altitude zone ($F_{2,\ 312}$ = 675.64, $p < 0.001$); Overall sample ($F_{2,\ 1887}$ = 1709.45, $p < 0.001$). For each agro-ecological zone and the overall, same letters indicate no significant differences among categories at $p < 0.05$

the whole storage period, while others stored it as shelled grains. Other farmers stored in both forms whereby the maize was stored in cobs for the first few months before shelling. In the LLT zone, cob storage was the predominant form of maize storage (72.4 %), whereas in the DMA, HLT, MT and MMA zones storage in the form of grain was predominant (69.5 %, 82.9 %, 55.24 % and 92.4 %, respectively). However in the DT zone, maize storage as shelled grain or both cobs and shelled grain was the commonest practice among farmers. Farmers stored maize cobs either with the husk or without the husk (dehusked) while some stored both dehusked and undehusked forms at the same time. Generally, storage of maize as dehusked cobs was the commonest practice ($\chi 2$ (2) = 236.02, $p < 0.001$). In the LLT zone, storage of maize as husked or dehusked cobs was common practice, whereas in the other AEZs farmers predominantly stored cobs in the dehusked form. Overall, however, storage of maize as grain was the commonest practice across the AEZs ($\chi 2$ (2) = 217.40, $p < 0.001$).

Maize storage structures

Table 4 and Fig. 3 show the structures used for maize storage in the various AEZs. Maize cobs were stored in traditional granaries (large cylindrical baskets made of bent sticks placed on raised platforms constructed in the homestead, and covered with grass thatch roof or wooden platform with a wall made of mud constructed above the fire place in the kitchen),

Table 3 Proportions of farmers using different forms of maize storage across the various agro-ecological zones (n = 630)

Maize storage	Percentage of respondents in each agro-ecological zone						Overall percentage
	LLT [a] n = 105	DMA [b] n = 105	DT [c] n = 105	HLT [d] n = 105	MT [e] n = 105	MMA [f] n = 105	
Storage forms							
Cobs	72.4a	2.9c	1.0b	14.3b	3.8b	4.8b	16.5c
Grain	24.8b	69.5a	40.0a	82.9a	55.2a	92.4a	60.8a
Both cobs and grain	2.9c	27.6b	59.1a	2.9c	41.0a	2.9b	22.7b
$\chi 2$ (2)	79.6	71.54	55.254	117.94	44.4	164.8	217.4
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Forms of cob storage[g]							
Husked cobs	45.6a	6.3b	1.6b	0.0b	2.1b	0.0b	16.2b
De-husked cobs	40.5a	93.8a	96.8a	100.0a	97.9a	100.0a	79.0a
Mixture of husked and de-husked cobs	13.9b	0.0b	1.6b	0.0b	0.0b	0.0b	4.9c
$\chi 2$ (2)	13.696	52.75	114.29	36	88.128	16	236.02
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences between categories at $p < 0.05$

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

[g] Considers the sum of farmers who stored maize as cobs, and farmers who stored maize as cobs at one stage and thereafter as grain

Table 4 Storage structures used by farmer to store maize across the agro-ecological zones

Maize storage structure	Percentage of respondents in each agro-ecological zone						Overall percentage
	LLT [a]	DMA [b]	DT [c]	HLT [d]	MT [e]	MMA [f]	
Maize cobs (n = 247)[g]							
Traditional granaries	94.9a	3.1b	0.0c	0.0b	4.3b	50.0a	33.2a
Traditional cribs	0.0b	3.1b	9.5abc	0.0b	0.0b	12.5a	3.2c
Improved cribs with grass thatch	1.3b	21.9ab	25.4a	0.0b	0.0b	0.0a	9.7bc
Improved cribs with iron sheet roof	1.3b	56.3a	34.9a	77.8a	85.1a	25.0a	39.3a
Bag	0.0b	46.9a	3.2bc	0.0b	0.0b	0.0a	6.9bc
Directly on the floor in room	0.0b	12.5ab	0.0c	5.6b	8.5b	12.5a	4.1bc
Mat/pallet put on the floor in room	2.5b	15.6ab	20.6ab	16.7b	8.5b	12.5a	11.3b
Hanging on rope	0.0b	0.0b	14.3abc	0.0b	0.0b	0.0a	3.6c
$\chi 2$ (7)	491.23	49.549	53.176	73.556	211.76	11.444	249.42
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.1204	<0.001
Shelled maize grain(n = 526)[h]							
Bag	100.0a	100.0a	100.0a	96.7a	100.0a	99.0a	99.2a
Directly on floor in room	6.9bc	5.9b	0.0c	2.2b	0.0b	1.0c	2.1c
On mat/pallet put on the floor in room	44.8ab	6.9b	22.1b	2.2b	5.0b	36.0b	16.4b
Directly on the floor in improved cribs	0.0c	6.9b	0.0c	0.0b	1.0b	0.0c	1.5c
Directly on floor in traditional granary	0.0c	1.0b	0.0c	0.0b	0.0b	0.0c	0.2c
Metal silo	0.0c	3.9b	0.0c	0.0b	0.0b	1.0c	1.0c
Hermetic plastic bags	0.0c	0.0b	0.0c	0.0b	0.0b	2.0c	0.4c
Plastic container	0.0c	0.0b	0.0c	1.1b	0.0b	0.0c	0.2c
Platform	0.0c	1.0b	0.0c	0.0b	0.0b	0.0c	0.2c
Tomato crate	3.5c	0.0b	0.0c	0.0b	0.0b	0.0c	0.2c
$\chi 2$ (9)	180.56	696.69	766.31	731.7	848.79	659.78	3752.3
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences between categories at $p < 0.05$

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

[g] Sample sizes for individual AEZs are LLT: n = 79; DMA: n = 32; DT: n = 63; HLT: n = 18; MT: n = 47; MMA: n = 8

[h] Sample sizes for individual AEZs are LLT: n = 29; DMA: n = 102; DT: n = 104; HLT: n = 90; MT: n = 101; NMA: n = 100

traditional cribs (raised cylindrical structures made of bent sticks and covered on top with grass thatch), improved cribs with grass thatch (raised rectangular structures with walls made of spaced sisal stems, wooden rafters or timber, and with grass thatch roof), improved cribs with iron sheet roof (raised rectangular structures with walls made of spaced sisal stems, wooden rafters, timber or wire mesh between poles, and with iron sheet roof), or in bags. Other farmers placed the cobs directly on the floor on a mat or on pallets, or on a hanging rope inside a designated storage room in the living house. Among these storage methods, traditional granaries were predominantly used for cob storage in the LLT and MMA zones, whereas improved cribs with iron sheet roofing were common in the other AEZs for cob storage. Overall, the predominant storage structures for maize cobs were the improved cribs with iron sheet roofing (39.3 %) and the traditional granaries (33.2 %).

Across the six AEZs, farmers who stored maize as shelled grain primarily used ordinary bags for storage (99.2 %), but some stored directly on the floor (2.1 %), or on mat/ pallet on the floor (16.3 %) in a designated storage room in the living house. Some farmers stored the shelled maize directly on the floor of the crib or granary (1.7 %) whereas a few farmers stored in hermetic containers such as metal silos (1.0 %) and

Fig. 3 Maize storage structures across agro-ecological zones. a and b:traditional granaries; c: traditional crib; d: improved crib with grass thatch roof; e: improved crib with iron sheet roof; f: maize cobs stored on the floor in room; g: bagged maize grain stored in special room; h: bagged maize grain stored in crib; i: maize grain packed in plastic hermetic bags and stored in crib

hermetic plastic bags (0.4 %). Figure 4 shows the storage places for the bagged maize grain. With the exception of the HLT zone where bagged maize was predominantly stored in cribs or granaries, bagged maize was mostly stored in a special store room in the living houses. Overall, 73.2 % of farmers stored bagged maize in their living houses whereas only 25.1 % stored in cribs and granaries. The typical maize storage durations varied from one AEZ to another (Fig. 5). For maize cobs, 1–4 months storage was predominant in DMA, DT and MT zones whereas longer storage periods of 5–8 months were predominant in the LLT zone (Fig. 5 (i)). In HLT and MMA zones, there were no significant differences between the different storage period intervals for cobs storage ($\chi2$ (2) = 5.33, p = 0.069 (HLT) and $\chi2$ (2) = 1.75, p = 0.416 (MMA)). For shelled maize, storage durations spanning 1–4 months were predominant in DMA and DT. In the other

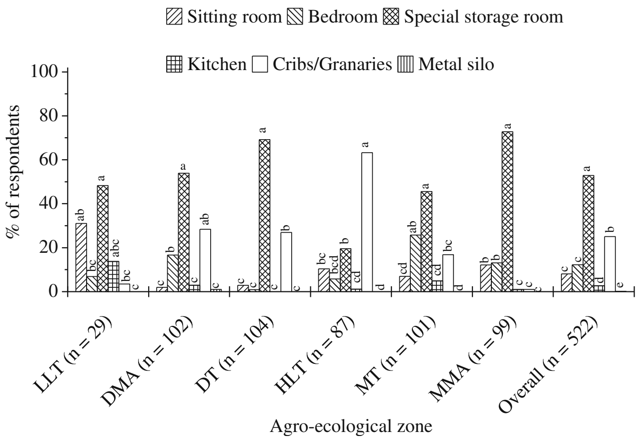

Fig. 4 Places used by farmers for storage of bagged maize grain. n: sample size; LLT: Lowland tropical zone ($\chi2$ (5) = 29.6, $p < 0.001$); DMA: Dry mid-altitude zone ($\chi2$ (5) = 126.78, $p < 0.001$); DT: Dry transitional zone ($\chi2$ (5) = 240.88, $p < 0.001$); HLT: Highland tropical zone ($\chi2$ (5) = 148.93, $p < 0.001$); MT: Moist transitional zone ($\chi2$ (5) = 86.43, $p < 0.001$); MMA: Moist mid-altitude zone ($\chi2$ (5) = 243.27, $p < 0.001$); Overall sample ($\chi2$ (5) = 601.48, $p < 0.001$). Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences among categories at $p < 0.05$

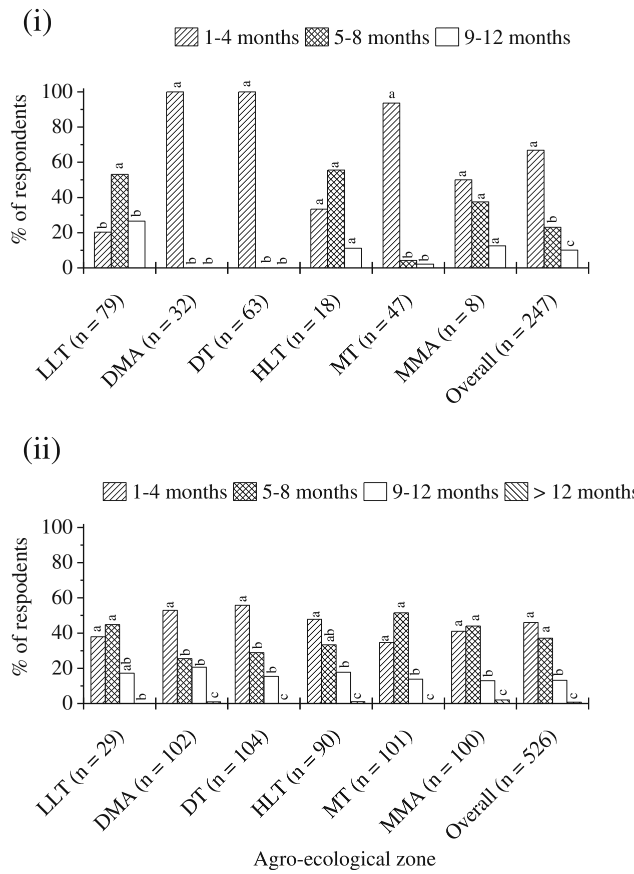

Fig. 5 Storage duration of maize stored as cobs (i) ($\chi2$ (2) = 14.47, $p < 0.001$ (LLT); $\chi2$ (2) = 64, $p < 0.001$ (DMA); $\chi2$ (2) = 126, $p < 0.001$ (DT); $\chi2$ (2) = 5.33, $p = 0.069$ (HLT); $\chi2$ (2) = 76.89, $p < 0.001$ (MT); $\chi2$ (2) = 1.75, $p = 0.416$ (MMA); $\chi2$ (2) = 130.72, $p < 0.001$ (Overall sample)) and maize stored as grain (ii) ($\chi2$ (3) = 14.44, $p < 0.001$ (LLT); $\chi2$ (3) = 56.196, $p < 0.001$ (DMA); $\chi2$ (3) = 67.23, $p < 0.001$ (DT); $\chi2$ (3) = 43.6, $p < 0.001$ (HLT); $\chi2$ (3) = 62.37, $p < 0.001$ (MT); $\chi2$ (3) = 51.6, $p < 0.001$ (MMA); $\chi2$ (3) = 263.58, $p < 0.001$ (Overall sample)) in the various agro-ecological zones. n: sample size; LLT: Lowland tropical zone; DMA: Dry mid-altitude zone; DT: Dry transitional zone; HLT: Highland tropical zone; MT: Moist transitional zone; MMA: Moist mid-altitude zone. Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences among categories at $p < 0.05$

AEZs, there was no significant difference between storage periods lasting 1–4 months and 5–8 months (Fig. 5 (ii)). Overall, the commonest storage period for cobs spanned 1–4 months whereas for shelled grains storage periods between 1–4 months and 5–8 months were the commonest.

Storage problems

Figure 6 gives the frequencies of storage problems as experienced by farmers (Fig.6 (i)) and the ranking of the problems across the agro-ecological zones (Fig. 6 (ii)). In the LLT zone, all the farmers surveyed experienced storage problems, while in the HLT, MMA, DMA, DT and MT zones, 83–98 % of farmers reported problem-free storage. In general, the problem of storage pests (insects, rodents and moulds) was reported by 92 % of farmers surveyed. In all the AEZs and for the overall sample, the report of insect and rodent infestations in stores by the farmers was statistically equal. The problem of moulds was reported by 13 % of farmers across the country and was the least problem reported by farmers in all AEZs compared to insect and rodent problems ($\chi2$ (2) = 363.19, $p < 0.001$). Storage pest problems were ranked by farmers according to their perception of the level of damage caused by the respective pests in their stores. In LLT, the majority of farmers ranked rodents as the main storage problem, followed by insects and lastly moulds. In the other AEZs, insects were ranked as the main storage problem followed by rodents and then moulds. Overall, insects were the most important storage problem followed by rodents ($\chi2$ (2) = 452.98, $p < 0.001$).

Control of storage pests

Table 5 and Table 6 summarize the methods used by farmers to protect maize stored as cobs and maize stored as shelled grain against storage pests, respectively. The proportion of farmers who did not apply any measures to control insects or rodents varied from one AEZ to another. With regard to insects in maize stored as cobs (Table 5), about half of the farmers in the MT zone did not apply any measures while in the HLT zone, all the farmers applied control methods, specifically insecticides and indigenous treatments. For rodents 70 % of farmers in all the AEZs except HLT and MT zones applied some control measures; only 50 % of farmers in the HLT zone and fewer than 25 % in the MT zone, applied some

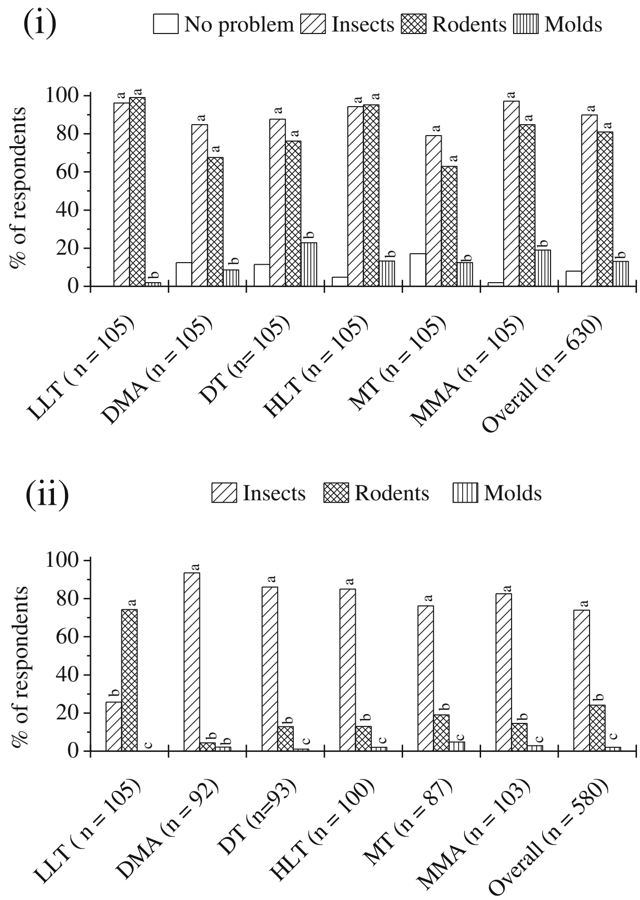

Fig. 6 Problems encountered by farmers in the storage of maize (i) ($\chi2$ (2) = 97.65, p < 0.001 (LLT); $\chi2$ (2) = 62.53, p < 0.001 (DMA); $\chi2$ (2) = 40.33, p < 0.001 (DT); $\chi2$ (2) = 68.65, p < 0.001 (HLT); $\chi2$ (2) = 49.37, p < 0.001 (MT); $\chi2$ (2) = 55.23, p < 0.001 (MMA); $\chi2$ (2) = 363.19, p < 0.001 (Overall sample)), and the proportion of farmers ranking a particular problem as the main or "number one" storage problem in the agro-ecological zones (ii) ($\chi2$ (2) = 89.65, p < 0.001 (LLT); $\chi2$ (2) = 149.83, p < 0.001 (DMA); $\chi2$ (2) = 118.13, p < 0.001 (DT); $\chi2$ (2) = 121.94, p < 0.001 (HLT); $\chi2$ (2) = 54, p < 0.001 (MT); $\chi2$ (2) = 114.25, p < 0.001 (MMA); $\chi2$ (2) = 452.98, p < 0.001 (Overall sample)) n: sample size; LLT: Lowland tropical zone; DMA: Dry mid-altitude zone; DT: Dry transitional zone; HLT: Highland tropical zone; MT: Moist transitional zone; MMA: Moist mid-altitude zone. Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences among categories at p < 0.05

control measure against rodents during cob storage. Overall, 33 % and 26 % of the farmers who stored their maize as cobs did not apply any methods against insects and rodents, respectively. In shelled maize grain storage (Table 6), over 92 % of the farmers in DMA, DT, HLT, MT and MMA zones applied some form of protection to counter insects whereas about a third of the farmers in LLT did not apply any methods to control insects. Overall, only 7 % of the farmers surveyed across the AEZs failed to apply any methods to counter insects when the maize was stored as shelled grain. For rodent control in shelled maize grain storage, over 88 % of farmers in LLT, MT and MMA applied some form of control while 30 % of the farmers in DMA and HLT did not apply any control methods. Overall, about 15 % of farmers who stored maize as grain did not apply any technology to counter rodent infestation.

Use of pesticides (insecticides and rodenticides) was the main method used for insects ($\chi2$ (5) = 254.39, p < 0.001 (cob storage); $\chi2$ (8) = 2545.31, p < 0.001 (grain storage)) and rodents ($\chi2$ (5) = 326.350, p < 0.001 (cob storage); $\chi2$ (6) = 1133, p < 0.001 (grain storage)) control across the country. Insecticides used included Actellic Super dust (pirimiphos-methyl 1.6 % *w*/w + permethrin 0.3 % w/w), Actellic Gold dust powder (thiamethoxam 0.36 % w/w + pirimiphos methyl 1.6%w/w), Skana Super grain dust (malathion 2.0 % w/w + permethrin 0.3 % w/w), Spintor 0.125 % dust (spinosad 0.125 % w/w), Sumicombi 1.8 % dust (1.5 % w/w fenitrothion +0.3 % w/w fenvalerate) and Super Malper dust (malathion 1.6 % w/w + permethrin 0.4 % w/w). Apart from chemical insecticides, other methods used were application of cow dung, wood ashes, plant leaves, exposing to sun, admixing with hot pepper, smoking, grain treatment with boiled water, and storage in hermetic plastics bags (Ng'ang'a et al. 2016) and metal silos (De Groote et al. 2013; Gitonga et al. 2015). The hermetic plastic bags were PICS (Purdue Improved Crop Storage) triple-layer bags (Murdock et al. 2012). Rodenticides used included Red Cat powder (Zinc Phosphide 54 % w/w), Mortein Doom Rat Kill (Brodifacoum 0.005 % w/w), Indocide (indomethacin) and Baraki Pellets (Difethialone 0.125 % w/w). Farmers in all the agro-ecological zones also kept cats, and used traps and baits for rodent control. Some farmers reported hunting to mitigate rodent attack. Generally all the farmers interviewed reported that their stores were cleaned and old stocks removed before loading the new harvest.

Farmers training on grain storage and protection technologies

The proportion of farmers without training on stored maize protection was significantly higher than the proportion of farmers with training, in all AEZs (Fig. 7). On average, only 16 % of farmers across the AEZs had received training. The majority (96 %) of the training on proper grain storage practices was given by government extension agencies, whereas 4 % of the training was given by non-governmental organizations.

Losses during maize storage

Table 7 shows the levels of losses reported by farmers. For maize stored as cobs, rodents and insects caused losses that varied from 1.3–9.7 % and 3.3–8.3 %, respectively, whereas

Table 5 Methods used by farmers to protect maize cobs against storage pests (n = 247)

Control method	Percentage of respondents in each agro-ecological zone						Overall percentage
	LLT [a] (*n* = 79)	DMA [b] (*n* = 32)	DT [c] (*n* = 63)	HLT [d] (*n* = 18)	MT [e] (*n* = 47)	MMA [f] (*n* = 8)	
Insects control							
No control method	27.9	34.4	34.9	0.0	51.1	25.0	32.8
Insecticides	38.0a	62.5a	65.1a	88.9a	21.3a	50.0a	49.0a
Wood/Cow dung ashes	7.6bc	9.4b	0.0b	27.8ab	0.0b	25.0a	6.5bc
Plant leaves	24.1ab	3.1b	0.0b	0.0b	0.0b	0.0a	8.1b
Exposure to sun	1.3c	3.1b	1.6b	0.0b	34.0a	37.5a	8.9b
Hot pepper powder	5.1c	3.1b	0.0b	0.0b	0.0b	0.0a	2.0c
Put fire under granary (smoking)	36.7a	3.1b	0.0b	0.0b	0.0b	0.0a	12.2b
$\chi2$ (5)	56.281	64.778	198.29	59.286	56.154	10.333	254.39
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.066	<0.001
No control method	5.1	28.1	6.4	50.0	76.6	25.0	25.9
Rodenticides	79.8a	53.1a	74.6a	44.4a	4.3ab	50.0a	57.1a
Cat	49.4a	50.0a	14.3b	22.2ab	17.0a	62.5a	32.8b
Rat trap	44.3a	15.6ab	6.4bc	5.6b	4.3ab	0.0b	19.0c
Plastering the wall and floor of the granary	10.1b	0.0b	0.0c	0.0b	0.0b	0.0b	3.2d
Hunting	6.3b	0.0b	0.0c	0.0b	0.0b	0.0b	2.0d
Bait	0.0b	0.0b	0.0c	5.6b	0.0b	0.0b	0.4d
$\chi2$ (5)	122.16	52	170.6	21.143	24	18.333	326.35
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences among categories at $p < 0.05$

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

losses attributed to mould were less than 1 % across the AEZs. The total perceived losses varied between 6 and 17 %, and on average were 11.2 ± 0.7 %. There were significant differences among the AEZs for the losses due to rodents ($F_{5, 241} = 38.38$, $p < 0.001$), insects ($F_{5, 241} = 4.72$, $p < 0.001$), moulds ($F_{5, 241} = 3.77$, $p = 0.003$) and total losses ($F_{5, 241} = 7.79$, $p < 0.001$). Rodent infestation caused significantly higher losses in the LLT zone as compared to the other AEZs whereas insect infestation caused highest and lowest losses in the MMA and DT zones, respectively. Within the AEZs, significant differences were observed among the losses caused by rodents, insects and moulds ($F_{2, 234} = 296.38$, $p < 0.001$ (LLT); $F_{2, 93} = 30.45$, $p < 0.001$ (DMA); $F_{2, 186} = 29.67$, $p < 0.001$ (DT); $F_{2, 51} = 19.66$, $p < 0.001$ (HLT); $F_{2, 138} = 15.73$, $p < 0.001$ (MT); $F_{2, 21} = 5.71$, $p = 0.01$ (MMA)). Moreover, the magnitude of losses due to moulds were the lowest in all the AEZs. Losses from rodents were significantly higher than those caused by insects in the LLT zone alone.

For the maize stored as shelled grain, losses due to rodents and insects varied from 2.7–8.7 % and 7.4–12.9 %, respectively, whereas losses caused by moulds were lower than 1 %. Total losses varied between 10 and 20 % (average 15.5 ± 0.6 %) and the effect of AEZ was highly significant ($F_{5, 520} = 16.82$, $p < 0.001$ (rodent); $F_{5, 520} = 3.14$, $p = 0.008$ (insects); $F_{5, 520} = 3.29$, $p = 0.006$ (moulds); $F_{5, 520} = 6.44$, $p < 0.001$ (total losses)). Similar to maize stored as cobs, perceived losses due to rodents were highest in the LLT zone whereas losses due to insect infestation were highest in the MMA zone. Comparisons within the AEZs showed that there are significant differences among the losses caused by rodents, insects and moulds in all the AEZs ($F_{2, 84} = 69.71$, $p < 0.001$ (LLT); $F_{2, 303} = 119.60$, $p < 0.001$ (DMA); $F_{2, 186} = 29.67$, $p < 0.001$ (DT); $F_{2, 267} = 191.72$, $p < 0.001$ (HLT); $F_{2, 300} = 60.22$, $p < 0.001$ (MT); $F_{2, 297} = 91.49$, $p < 0.001$ (MMA)). Moulds caused the lowest losses in all the AEZs. No significant differences were observed between levels of

Table 6 Methods used by farmers to protect shelled maize grain against storage pests (n = 526)

Control method	Percentage of respondents in each agro-ecological zone						Overall percentage
	LLT [a] (n = 29)	DMA [b] (n = 102)	DT [c] (n = 104)	HLT [d] (n = 90)	MT [e] (n = 101)	MMA [f] (n = 100)	
Insects control							
No control method	31.0	7.8	6.7	4.4	3.0	5.0	6.8
Insecticides	69.0a	88.4a	92.3a	91.1a	97.0a	54.0a	83.7a
Wood/ Cow dung ashes	6.9b	4.9b	1.0b	6.7b	1.0c	52.0a	12.7b
Plant leaves	13.8b	1.0b	1.0b	0.0b	1.0c	1.0b	1.5c
Exposure to sun	0.0b	2.0b	1.0b	3.3b	9.9b	37.0a	10.1b
Hot pepper powder	0.0b	2.0b	0.0b	0.0b	0.0c	0.0b	0.4c
Put fire under granary/ smoking	3.5b	0.0b	0.0b	0.0b	0.0c	0.0b	0.2c
Use of boiled water	0.0b	0.0b	0.0b	0.0b	1.0c	0.0b	0.29c
Use of metal silo	0.0b	3.9b	0.0b	0.0b	0.0c	1.0b	1.0c
Use of hermetic plastic bags	0.0b	0.0b	0.0b	0.0b	0.0c	2.0b	0.4c
χ2 (8)	113.33	601.29	739.09	578.4	676.05	281.27	2545.3
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Rodents control							
No control method	6.9	29.4	11.5	30.0	7.9	4.0	15.4
Rodenticides	68.9a	53.9a	68.3a	54.4a	60.4a	62.0a	60.8a
Cat	44.8a	54.9a	19.2b	32.2ab	54.5a	68.0a	45.8b
Rat trap	24.1ab	6.9b	4.8c	17.8bc	18.8b	5.0b	11.2c
Hunting	3.5b	0.0b	0.0c	5.6 cd	0.0c	0.0b	1.1d
Bait	0.0b	0.0b	0.0c	13.3bc	0.0c	0.0b	2.3d
Book gum/ stick pad	3.5b	0.0b	0.0c	13.3bc	0.0c	2.0b	0.6d
Use of metal silo	0.0b	3.9b	0.0c	0.0d	0.0c	1.0b	1.0d
χ2 (6)	61.33	240.11	302.56	93.88	233.51	293.06	1133
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences among categories at $p < 0.05$

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

losses caused by rodents and insects in LLT and DT whereas in the other zones, the magnitudes of losses caused by insects were significantly higher than those caused by rodents.

On average, irrespective of the AEZ and maize storage forms, farmers perceived losses due to rodents, insects and moulds to be 4.7, 8.6, and 0.5 %, respectively, and were significantly different for the three loss agents ($F_{2,\ 2316} = 637.94$, $p < 0.001$). A comparison, however, showed that when maize was stored as cobs, insects and rodents caused similar magnitudes of losses ($F_{2,\ 738} = 181.64$, $p < 0.001$) whereas for maize stored as shelled grain the losses caused by insects were significantly higher than those caused by rodents ($F_{2,\ 1575} = 489.11$, $p < 0.001$) as observed for the average overall losses. Generally, losses were higher in maize stored as shelled grain and total losses exceed 5 % in all AEZs irrespective of the form of storage. Total losses exceeded 15 % in LLT and MMA zones for maize stored as cobs, and in LLT, HLT, MT and MMA zone for maize stored as shelled grain. Lowest losses were found in the DT and DMA zones for both forms of maize storage.

Factors affecting maize postharvest losses due to rodents

From the CLAD regression model (Table 8), factors that significantly influenced the magnitude of losses due to rodents in maize farming were experience, use of improved cribs with roof in iron sheet or thatch, use of rodenticides, use of traps and type of AEZs. In all AEZs, lower levels of losses by rodents were positively associated with experience in maize

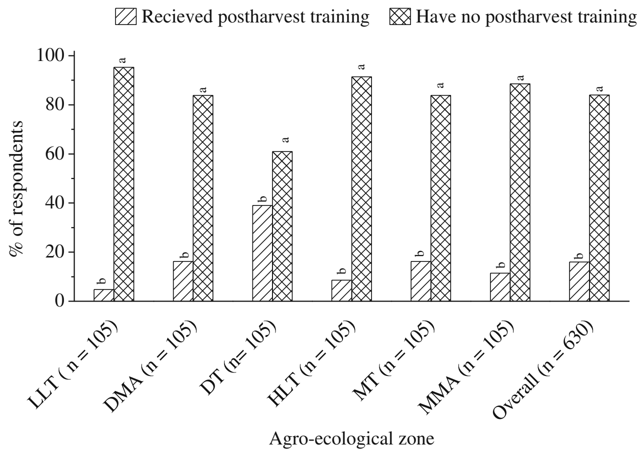

Fig. 7 Proportion of farmers who have or have not received training on grain storage and protection technologies in the various agro-ecological zones. n: sample size; LLT: Lowland tropical zone ($\chi2$ (1) = 85.95, $p < 0.001$); DMA: Dry mid-altitude zone ($\chi2$ (1) = 48.01, $p < 0.001$); DT: Dry transitional zone ($\chi2$ (1) = 5.03, $p = 0.025$); HLT: Highland tropical zone ($\chi2$ (1) = 72.09, $p < 0.001$); MT: Moist transitional zone ($\chi2$ (1) = 48.01, $p < 0.001$); MMA: Moist mid-altitude zone ($\chi2$ (1) = 62.49, $p < 0.001$); Overall sample ($\chi2$ (1) = 290.77, $p < 0.001$). Within each agro-ecological zone as well as the overall sample, same letters indicate no significant differences among categories at $p < 0.05$

farming ≥16 years (p = 0.093) and use of traps as rodent control measures (p = 0.001). The model results also showed that higher levels of losses were associated with the use of improved cribs with iron sheet roof (p = 0.079) or thatch (p = 0.040), the use of rodenticides (p = 0.009) and the LLT zone while lower losses were associated with all the other AEZs. With regard to the total losses, lower levels were associated with the use of insecticides (p = 0.088), cat ($p < 0.0001$) and traps (p = 0.001) for rodent control, and the agro conditions of the DT zone (p = 0.063). The presence of rodents in stores ($p < 0.0001$), the storage of maize during both the long and short rain seasons (P = 0.092), and the agro conditions of MT (p = 0.089) and MMA zones (p = 0.005) were associated with higher levels of total losses.

Discussion

On-farm maize storage systems

On-farm storage losses are recognized as a serious problem that affects the food security of many rural households, and a myriad of factors among them socio-economic, cultural, agro-climatic, influence the level of losses (World Bank 2011). An assessment of the magnitudes of these losses, and the postharvest systems linked to them, is a first step in their mitigation. A number of studies in Africa reported that agro-ecological zones influence the storage practices of farmers even within the same country (Hell et al. 2000; Udoh et al. 2000; Ngamo et al. 2007; Nukenine 2010). In this study, this observation was made, for instance, in the low popularity of crib storage in the LLT zone as compared to the other AEZs. Traditional granaries, specifically wooden platform with walls made of mud constructed above the fire place in the kitchen rooms were the dominant storage structures in the LLT zone. Cribs, which can be constructed entirely from locally available plant materials (Nukenine 2010), have the advantages of allowing free air circulation for adequate drying of maize during storage particularly in humid zones (Hell et al. 2000; Udoh et al. 2000). The LLT zone is hot and humid. It is probable that the temperature ranges in the LLT zone help to reduce the moisture content of the harvested maize in the field thereby eliminating the need to have cribs. However, the choice of storage structures is an interaction of a host of environmental, economic, and socio-cultural factors. For instance, some studies in West Africa showed low adoption of the cribs among farmers who considered them costly, labour intensive and not offering sufficient privacy (FAO 1992). Gitonga et al. (2015), in their study covering the six maize AEZs of Kenya, reported that the most important factors that farmers considered when choosing a storage facility were effectiveness against storage pests followed by security of the stored grain and durability of the storage facility. But in the present study, the observed trends in use of specific storage structures were also related to availability and exposure to storage technologies, and level of yields. The LLT zone lies along the coast where high relative humidity persists, and environmental temperatures are high (20–29 °C) compared to the other AEZs (10–28 °C). In addition, the LLT zone, together with MA and DT zones is also a low yield zone (< 1.5 tons/ha) while the HLT and MT zones are high yielding (> 2.5 tons/ha) and MMA zone moderately yielding (1.44 tons/ ha) (Hassan 1998). These together with other factors related to socio-cultural aspects might explain why the traditional platforms raised over the fire place were predominant in the LLT zone and not in other zones.

In all the AEZs, use of bags (polypropylene or sisal) for storage of shelled maize and use of granaries and cribs for storage of maize in cobs were the most common storage practices. A very low use rate of hermetic storage plastic bags technologies was observed in the study, and was only reported by some farmers in the MMA zone. Probable reasons for this low popularity could be low farmer exposure to such technologies and lack of availability. Adoptions studies, for example, of triple-layer plastic in West and Central Africa (Moussa et al. 2014) consistently showed that a key constraint to farmers' use of this technology was local availability. It should also be noted that introduction and dissemination of the hermetic grain storage bags in East Africa was still at an early stage at the time of the study, and therefore marketing and promotion campaigns or the supply chains for the technology were not yet well established (Hodges and Stathers 2015). Nevertheless, results also showed that on-farm maize storage is mainly in the form of shelled maize but the shelled maize,

Table 7 Storage losses incurred by farmers on maize during storage across the agro-ecological zones

Maize storage form	Perceived weight losses (%)			
	Rodents	Insects	Moulds	Total[g]
Maize cobs (n = 247)				
LLT [a]	9.7 ± 0.7a* A**	6.0 ± 0.5abcB	0.0 ± 0.0bC	15.5 ± 1.0a
DMA [b]	1.3 ± 0.2cB	5.6 ± 0.8bcA	0.8 ± 0.6abC	7.7 ± 1.1b
DT [c]	2.2 ± 0.2bcA	3.3 ± 0.4cA	0.6 ± 0.2aB	6.0 ± 0.5b
HLT [d]	5.0 ± 1.2bA	8.3 ± 1.8abA	0.1 ± 0.1abB	13.3 ± 2.8ab
MT [e]	2.6 ± 0.6cB	5.5 ± 1.3bcA	0.4 ± 0.2abC	11.3 ± 2.6b
MMA [f]	3.3 ± 1.3bcAB	13.4 ± 5.1aA	0.1 ± 0.1bB	16.9 ± 5.7ab
Average losses	4.8 ± 0.4 A	5.5 ± 0.4 A	0.4 ± 0.1B	11.2 ± 0.7
Shelled grain (*n* = 526)				
LLT [a]	8.7 ± 1.0aA	7.4 ± 1.2bA	0.0 ± 0.0cB	16.1 ± 1.8ab
DMA [b]	3.2 ± 0.4cB	9.9 ± 1.0abA	0.2 ± 0.2cC	13.2 ± 1.2bc
DT [c]	2.7 ± 0.3cA	7.6 ± 0.9bA	0.3 ± 0.1abcB	10.6 ± 0.9c
HLT [d]	6.6 ± 0.5aB	10.0 ± 0.7abA	0.5 ± 0.2abC	17.2 ± 1.1a
MT [e]	3.8 ± 0.6cB	11.2 ± 1.3abA	0.9 ± 0.3abC	16.6 ± 1.6abc
MMA[f]	6.0 ± 0.7bB	12.9 ± 1.1aA	0.9 ± 0.3aC	20.1 ± 1.4a
Average losses	4.6 ± 0.2B	10.1 ± 0.5 A	0.5 ± 0.1C	15.5 ± 0.6
Overall average losses[h]	4.7 ± 0.2B	8.6 ± 0.3 A	0.5 ± 0.1C	14.1 ± 0.4

*Mean (± SE) values within a column in each storage form category followed by the same lower case letter are not significantly different at the 5 % probability level;** Mean (± SE) values within a row in each storage form category followed by the same upper case letter are not significantly different at the 5 % probability level

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moisttransitional zone

[f] Moistmid-altitude zone

[g] Total losses refer to the sum of the losses due to insects, rodents and moulds in each agro-ecological zone

[h] Overall average losses refer to the average losses calculated irrespective of maize storage forms and agro-ecological zones

packed in bags, is frequently stored in designated rooms in living houses, and less frequently in granaries and cribs. The predominance of maize storage in the form of shelled maize observed in the present study was also reported by Golob et al. (1999) in their study in Kenya. They also observed in their study that maize storage in the form of cobs was the most common storage practice in the LLT zone which is similar to the findings of the present study. According to Golob et al. (1999), the predominance of the shelled maize form of storage was related to the arrival of the Larger grain borer (*Prostephanus truncatus*). In East Africa the coping strategy adopted by the extensions services focused mainly on the simple recommendation of shelling maize, treating it with Actellic Super Dust (ASD) and storing it in an appropriate container.

Storage periods lasted predominantly 1–4 months for maize in cobs, 1–4 and 5–8 months for shelled maize, and insects and rodents were the main causes of storage losses, whose controls mainly relied on synthetic insecticides, rodenticides and biological control of rodents using cats. Similar observations were reported by Nduku et al. (2013) in a comparative analysis of maize storage structures in Kenya, although 8–9 months was reported to be the average storage period. In a separate study, Bett and Nguyo (2007), however, reported an average maize storage period of 4 months in the Eastern and Central parts of Kenya, which is consistent with the current study's findings. The shorter periods of storage are probably related to the marketing and consumption behavior of many small-scale farmers, who harvest a few bags of maize for subsistence but, additionally, rely on the sale of maize for household income.

Magnitudes of losses

Results of the present study show that rodents are the second most important maize storage pest problems in Kenya, after

Table 8 Regression of the influence of socio-economic, storage and agro-ecological factors on the level of losses due to rodents and the total losses during on-farm maize storage

Variable	Rodents losses		Total losses	
	Coefficient (SE)	*p*-value	Coefficient (SE)	*p*-value
Constant	8.94 (2.22)	<0.0001***	0.99 (5.45)	0.855
Socio-economic characteristics				
Gender (dummy =0 if male; dummy =1 if female)	0.48 (0.45)	0.289	-0.75 (0.80)	0.352
Age (dummy =0 if age < 41 years; dummy =1 if age ≥ 41 years)	0.38 (0.51)	0.454	0.86 (0.95)	0.368
Education level (dummy =0 if no formal education was received or did not complete primary education; dummy =1 if completed primary or secondary school)	-0.63 (0.53)	0.238	-1.75 (1.23)	0.154
Experience in maize farming (dummy =0 if experience in maize farming is <16 years; dummy =1 if experience in maize farming ≥16 years)	-0.88 (0.52)	0.093*	-1.28 (1.00)	0.200
Storage practices and management				
Storage as shelled grain (dummy =0 if stored maize as cobs; dummy =1 if stored maize as shelled grain)	0.67 (1.36)	0.620	4.45 (4.18)	0.287
Practice of both cobs and shelled grain storage (dummy =0 if stored maize as cobs; dummy =1 if practice of both cobs and shelled grain storage was done)	-0.30 (1.41)	0.827	0.98 (3.84)	0.798
Use of improved cribs with iron sheet roof (dummy =0 if no; dummy =1 if yes)	1.63 (0.92)	0.079*	0.16 (1.78)	0.926
Use of improved cribs with grass thatch roof (dummy =0 if no; dummy =1 if yes)	1.63 (0.79)	0.040**	2.91 (1.87)	0.121
Use of traditional granaries (dummy =0 if no; dummy =1 if yes)	1.34 (2.03)	0.508	5.33 (4.23)	0.208
Storage duration (dummy =0 if maize was stored for >9 months; dummy =1 if maize was stored for <9 months)	-0.38 (0.60)	0.530	0.45 (1.19)	0.704
Storage of short rain season harvest only in a year (dummy =0 if no; dummy =1 if yes)	-0.09 (0.89)	0.912	1.35 (0.61)	0.617
Storage of harvests of both short and long rain seasons in a year (dummy =0 if no; dummy =1 if yes)	0.26 (0.75)	0.720	3.29 (1.95)	0.092*
Use of insecticides (dummy =0 if no; dummy =1 if yes)	-0.20 (0.66)	0.761	-2.12 (1.24)	0.088*
Use of rodenticides (dummy =0 if no; dummy =1 if yes)	2.26 (0.86)	0.009***	-1.11 (1.41)	0.432
Cat (dummy =0 if no; dummy =1 if yes)	-0.40 (0.58)	0.491	-5.76 (1.22)	<0.0001***
Trap (dummy =0 if no; dummy =1 if yes)	-5.38 (1.67)	0.001***	-4.27 (1.36)	0.001***
Received training in grain storage protection (dummy =0 if no; dummy =1 if yes)	0.88 (0.75)	0.239	1.22 (1.21)	0.313
Presence of rodents in storage (dummy =0 if no; dummy =1 if yes)			14.05 (2.75)	<0.0001***
Agro-ecological zones (LLT[a] = base category)				
DMA[b]	-8.73 (1.36)	< 0.0001***	1.64 (2.37)	0.488
DT[c]	-9.33 (1.43)	< 0.0001***	-3.91 (2.27)	0.086*
HLT[d]	-4.28 (1.61)	0.008***	0.98 (2.78)	0.724
MT[e]	-9.17 (3.68)	< 0.0001***	5.03 (2.95)	0.089*
MMA[f]	-5.56 (1.57)	0.004***	7.12 (2.56)	0.005***
Pseudo R^2	0.198		0.189	
Final sample size	544		588	

Significance of P-value: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$

[a] Lowland tropical zone

[b] Dry mid-altitude zone

[c] Dry transitional zone

[d] Highland tropical zone

[e] Moist transitional zone

[f] Moist mid-altitude zone

insects. The Larger grain borer and the Maize weevil (*Sitophilus zeamais*) are the main storage insect pest in farm storage in Kenya (Bett and Nguyo 2007; De Groote et al. 2013; Ng'ang'a et al. 2016). This observation is supported by the results of the regression model which showed that the presence of rodents in storage contributed significantly to total postharvest losses incurred. Farmer estimates of losses due to rodents varied between 1.3 and 9.7 % depending on the agro-ecological zone, and on average contributed 43 % of the total losses (11.2 ± 0.7 %) when maize was stored as cobs and 30 % of the total losses (15.5 ± 0.6 %) when maize was stored as grain. In Mozambique, Belmain et al. (2003) conducted a field trial on stored maize cobs and measured cumulative weight losses of 54.7 ± 5.1 % (attributed to rodents and insects) during 8 months of storage in the absence of rodent control methods. However, in the presence of mechanical traps, the losses decreased to 18.9 ± 4.2 %. The huge difference from losses reported in this study could be attributed to the fact that in making their estimates, farmers were likely to have considered their withdrawal of the stored maize for consumption, sale or other uses, unlike in the study of Belmain et al. (2003) where withdrawals were neither allowed nor corrected for. Additionally, the losses reported in the present study are attributed to a 1–4 months storage period. According to Henkes (1992), on-farm storage losses depend on storage duration, but more importantly, on the rate at which withdrawal for consumption or other uses is done. However, the losses reported in this study are perceived losses which could be different from measured losses as the possibility of underestimation or overestimation of the actual losses by farmers exists. In spite of this potential limitation, surveys are a preferred losses estimation approach as large sample of the population can be studied. Furthermore Hodges et al. (2014) suggested that the survey approach should complement the actual measurement of losses as it is essential to put the loss data obtained into the contexts of both farming and household.

The LLT zone was identified as the main hotspot region for losses due to rodents during maize storage. In this zone, the majority of farmers (74.3 %) ranked rodents as the number one storage problem, and the levels of losses caused by rodents were higher than those caused by insects. A higher proportion of farmers using rat traps as compared to the other AEZs, was also observed. The significance of rodents in the LLT zone is probably related to factors that affect the distribution of commensal rodents. *R. rattus* is more often abundant in coastal areas (Gillespie and Myers 2004), and is largely confined to warmer climates (Timm et al. 2011). However, the effects of altitude on the distribution of rodent species are more important because factors such as wet or dry conditions which relate to annual cycles of rainfall affect their diversity, reproduction and survival rates. Higher diversities and populations are found in the wet low altitude regions (Stanley et al. 1998; Kasangaki et al. 2003; Venturi et al. 2004; Makundi et al. 2007), and under the warm conditions that prevail in the LLT zone.

Factors affecting losses

From regression analysis, maize storage forms were not significant as far as rodent storage losses were concerned. The same observation was also made for total losses implying different forms of storage exposed maize to pest attack in the same way. However, maize storage structures such as improved cribs with iron sheet or thatch roof contributed significantly to the increase of losses due to rodents. This is explained by the fact that these storage structures, as constructed, were not rodent proof and are likely to provide harborage points for rodents. During the surveys, we observed that apart from the metal silo used by a few farmers, all the other storage structures were not rodent-proof. Moreover none of the farmers interviewed had rat guards installed on their storage structures. Fixing rat guards on the pole of granaries is recognized as an effective method for preventing rodents from gaining access to grain storage structures provided they are fixed at a height of at least 1 m above ground, and there are no trees and other leverage objects close to the granary (Mejia 2003). The structural nature of the majority of the granaries and cribs probably made it difficult to fix rat guards on the foot poles, which could be related to possible lack of knowledge on this method of rodent control. When the total losses were considered, none of the storage structures were significant in the regression model suggesting that the level of protection of the stored maize was dependent on other factors. From the regression models, it was expected that losses would be lower with shorter storage duration. However, storage period even though having a negative sign was not a significant determinant of the level of losses. This was probably because, the number of farmers storing for ≥9 months was small, and did not influence significantly the model when the storage duration variable was transformed into a dummy variable (taking a value of 1 when storage duration was <9 months; and 0 when the storage duration was ≥9 months). Storage season, when taken individually (harvest of the short rain season or long rain season) was also not significant in influencing the losses caused by rodents or total losses, suggesting that there is no specific seasonality for pest infestation during maize storage in on-farm stores. According to Bonnefoy et al. (2008) rodent multiplication can occur throughout the year, implying a fairly constant presence of rodents around unprotected produce although seasonal population peaks may occur depending on availability of food among other factors (Ballenger 1999). However, storage season influenced the total losses incurred by farmers when the harvests were from both short and long rainy seasons was done. This is probably related to the build up of infestation levels from one season to the next without a break in the pest cycle.

Among the methods used for control of rodents, rodenticides and traps were significant in the regression model for the losses caused by rodents. It was of interest, however, that the model result implied rodenticides use was associated with higher losses as opposed to lower losses. The reasons for this result are unclear as the active ingredients (zinc phosphide, brodifacoum and difethialone (second generation anti-coagulants)) of the rodenticides reported by the farmers are known to provide good control of rodents even where some rodents evolve resistance (Lodal 2001; Staples et al. 2003; Eason et al. 2013; Buckle 2013). However, factors such as inappropriate use in terms of dosage or frequency of application by farmers can also elicit neophobic (avoidance) behaviour in some rodent species (MacDonald et al. 1999;Quy 2001). Moreover adulterated or expired products may significantly compromise the effectiveness. According to Buckle (1999), acute rodenticides such as zinc phosphide are favoured by smallholder farmers because of their low cost but are also prone to adulteration during manufacture and distribution, which results in low quality baits. Buckle (1999) also reported that even when they are properly made, acute rodenticides baits have the disadvantage of eliciting 'bait shyness' because rodents are able to relate to the symptoms of poisoning when sub-lethal doses are administered.

One main limitation associated with use of rodenticides relates to safety when the poisonous baits have to be used around households where food is stored, as some rodent species may inadvertently move poison baits away from granaries to areas where children play or food is prepared or stored (Belmain et al. 2015). There is also the risk of unwanted poisoning as rodenticides or baits are toxic to non-target animals. Considering this, mechanical traps and biological control are to be recommended. The result of the regression model showed that farmers who set traps would incur significantly lower storage losses due to rodents. Similar results were reported in Bangladesh, Myanmar and Mozambique (Belmain et al. 2003, 2015), and in Laos (Brown and Khamphoukeo 2010). In Laos for instance, 54.5 % of the farmers considered trapping as the most effective method of controlling rodents followed by rodenticides (12.5 %) and cats (9.5 %). Trapping is, however, perceived to be labor intensive, and the effectiveness is influenced by the migratory behavior of rodents (Palis et al. 2007). To overcome these limitations, community coordinated trapping was suggested (Belmain et al. 2015). The use of cats as an approach to reducing losses had the hypothesized effect in the rodent losses model, as well as the total losses model, although the coefficient was only significant in the total losses model probably due to sample size effects on the model. However, it is also possible that introducing cats for rodent control may not be effective because predation only influences the behavior of rodents without necessarily having a significant effect on the population density (Calhoun 1962; MacDonald et al. 1999). Furthermore, other factors such as the presence of domestic waste, poor hygiene, poor housing structures and improper handling of leftover food may provide an environment favorable to habitation and proliferation of rodents (Panti-May et al. 2012) and can compromise rodent control efforts.

Among the socio-economic characteristics (gender, age, education level and experience in maize farming), experience in maize farming was significant and contributed to lower postharvest losses due to rodents. However when the total losses were considered, none of the socio-economic variables was significant in the regression model which suggests that the magnitude of the total postharvest losses was not influenced by these factors. Socio-economic characteristics have been reported to influence postharvest losses differently in different regions. Similar to the findings in this study, Martins et al. (2014) in their study on the managerial factors affecting postharvest losses in Mato Grosso Brazil observed that education level did not influence the magnitude of losses although it was hypothesized that higher education level should lead to lower losses. In a study of postharvest loss perceptions from nationwide living standards surveys in Malawi, Uganda and Tanzania, Kaminski and Christiaensen (2014), reported perceived lower magnitudes of postharvest losses in households where the household head had a post primary education. Additionally, households headed by females experienced lower losses.

The lack of awareness or poor knowledge of good postharvest practices and technologies by farmers has been pointed out as one of the challenges to be overcome if a meaningful reduction of postharvest losses is to be achieved (Kitinoja et al. 2011; Abass et al. 2014; Affognon et al. 2015). Findings of the present study, however, showed that training on grain storage and protection technologies did not necessarily result in lower storage losses either arising from rodents or other loss agents as farmers who received training incurred similar magnitudes of postharvest losses as those farmers who did not receive the training. This observation suggests that farmers probably did not apply the knowledge transferred during the training, a behavior that could be related to the non-availability of the technologies proposed, lack of economic incentives to store and better protect food, non-cost effectiveness of technologies or the training and other interventions being too narrow or short-lived to pay off (Kaminski and Christiaensen 2014).

Conclusion

The objective of the present study was to generate nationally representative data on the level of postharvest losses, and to evaluate the contribution of rodents to the losses in on-farm stores in Kenya. Other objectives were to characterize on-farm maize storage systems, and to identify the factors in on-farm maize storage that are responsible for the losses. This study reveals that maize storage practices including storage structures, storage form, duration of storage, and stored maize protection methods varied across maize growing AEZs. Also perception of storage pest problems by farmers differed from one AEZ to another. There are, however, some similarities in the storage practices such as the popularity of bags for shelled grain storage and the application of chemicals (insecticides or rodenticides) as main storage protectants. The total perceived storage losses incurred range between 6 and 20 % depending on AEZ and form of storage. Of these losses, rodents contributed 30–43 % country wide, and are perceived as the second most important storage problem for farmers meaning that the impact of rodents in grain stores in Kenya should not be under-estimated. The LLT zone is the main hotspot region for postharvest losses caused by rodents. Since these findings are self-reported by farmers themselves they should, on the one hand, help to incentivize farmers to invest more in developing rodent-proof storage technologies. On the other hand, the findings should enable policy makers to understand the impact that rodents may have on national food security, nutrition and health. This way, they can identify where to invest in awareness creation and training for appropriate intervention. Further research should target actual quantification of the losses in the LLT zone and the determination of the rodent species, diversity and distribution. In addition, there is a need to look at the economics of postharvest loss control by investigating the minimal thresholds for losses below which it is not financially viable to employ different types of control measures. Furthermore, food safety issues related to contamination emanating from rodent infestations in stores need to be investigated.

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Compliance with ethical standards

Conflict of interest statement The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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