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Physical quality of maize grain harvested and stored by smallholder farmers in the Northern highlands of Tanzania: Effects of harvesting and pre-storage handling practices in two marginally contrasting agro-locations

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A B S T R A C T

On-farm trials were conducted to investigate the effects of maize harvesting and handling practices of smallholder farmers on the quality of the produce before, and during storage in two contrasting agro-locations. Farmers harvested and prepared the crop according to local practices, and stored it in ordinary woven polypropylene bags for 30 weeks. Grain moisture, insect populations, insect-damage, moldy/diseased/discolored grain, rodent-damage, shriveled grain, broken grains, non-consumable grains, impurities, and overall losses were monitored. Moisture of the pre-stored grain ranged between 11.0 and 23.7% while the overall physical damage was $16.9 \pm 6.2\%$. Late harvesting increased moldy/diseased/discolored grain two-fold while de-husking and drying practices increased the levels in early-harvested grain by factor of 2–3. Insect populations were >10 times higher in the cooler agro-location, and handling practices increased them by factor of 2–10. The interaction of agro-location, harvesting time and drying influenced the amount of grain that was unfit for human consumption. Pre-storage losses of 3.6–11.2% were determined, mainly as grade-outs. With storage, the quality of early-and late-harvested maize did not differ. However, the majority of examined parameters were distinct by agro-location. Moreover, secondary pests and the levels of shriveled and broken grain levels were also distinct by drying method, while moldy/diseased/discolored grain, non-consumable grain, and overall losses were distinct depending on whether the harvested cobs were de-husked or not de-husked before drying. The high levels of grade-outs at the pre-storage stage suggest that sorting should be emphasized for quality improvement at the farm gate not only for the market but also household nutrition. Cultivation of varieties with superior maturing and post-harvest traits would lower the sorting losses. Agro-location and farmer practices influenced grain quality and magnitude of losses during storage. These findings should inform choice of intervention steps right from the pre-storage stage.

1. Introduction

At least 7.4 million farm producers cultivate maize (*Zea mays* L.) for food and income in Tanzania (TNBS, 2019). The annual per capita consumption is estimated at 73 kg, and maize alone is projected to contribute approximately 33–40% of the total daily calorie intake, because of the greater caloric density compared to other crops consumed by households (Minot, 2010). With a national annual production of at least 5.7 million tons (TNBS, 2019), about 250–400 kg of each ton undergoes quality deterioration or is completely lost along the post-production pipeline, and therefore not unavailable to feed families or generate revenue. Improper approaches of harvesting, preliminary processing and handling, diminish the harvest by 20–130 kg per ton, while poor storage further decreases the stocks by 150–250 kg per every ton stored (Abass et al., 2014).

Insects, molds, and manual processing were identified as the

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main causes of grain loss in smallholder maize farming systems in Tanzania (Abass et al., 2014). The generally warm and humid conditions encourage pests and molds to attack the maturing crop in the field, and at the pre-storage stage (Boxall, 2002). During the latter, inappropriate methods of drying, threshing, winnowing, sorting, and grading leave behind broken grain, dirt, impurities, and other contaminants increasing the proneness of the produce to further damage by pests and pathogens in the course of storage. Consequently, post-harvest operations may affect the class of grain produced and consumed or sold, as well as its safety and shelf-life (Mendoza et al., 2017).

Many factors are responsible for the way farmers harvest and handle produce when the crop is mature. In maize-based crop-livestock systems, early harvesting is beneficial as the crop residues can be secured for forage when the quality is still high (Tolera and Sundstøl, 1999). Early harvesting is therefore a desirable practice. Occasionally, farmers strip the leaves and cut off the tops of the maize crop after attaining physiological maturity, leaving behind the cobs to dry in the field. In cooler zones, this practice encourages drying by exposing the ears to the sun (Subedi, 1996). Other farmers harvest early to make room for the next crop (Chegere, 2018). Socio-economic factors such as the size of farms, fear of pilferage, how quickly farmers want to utilize the crop, availability of labor, and availability of post-harvest equipment were also found to be important decision factors (Kaaya et al., 2005). Moreover, agro-climatic conditions are also important. In cooler agro-zones, for example, lower ambient temperatures reduce the drying potential of air hence the produce fails to dry well or stays longer in the field and on drying platforms.

Understanding the impact of post-harvest operations on grain quality within the contexts of farming environments should guide farmers on the choice of better intervention steps, if necessary, to decrease spoilage and post-harvest losses, and ultimately contribute to food security and safety (Mendoza et al., 2017). Maize is cultivated across almost all agro-climatic regions of Tanzania in the lowland, intermediate, and highland zones (Suleiman and Kurt, 2015). These agro-environments are also becoming increasingly variable due to climate change. As a result, the conditions under which maize is harvested, handled, and stored continue to vary widely affecting not only the incidence and severity of loss agents (Khaliq et al., 2014; Magan et al., 2011), but also the way farmers respond to post-harvest challenges (Stathers et al., 2013). Traditionally, most post-harvest losses have been associated with insect pests. However, a significant proportion of the total loss, which is often not quantified, emanates from fungal contamination, rot and diseases, rodent damage, mechanical injury, and other defects. These forms of damage are linked to farming environments, but also to the harvesting and handling practices. For this reason, addressing harvesting and handling practices is critical for safety and wholesomeness of the grain that ultimately becomes available for consumption by households and for the market.

The objectives of the present study were therefore to: (i) evaluate the kinds and levels of defects that constitute post-production loss at harvest stage and during pre-storage handling of maize in contrasting agricultural environments; (ii) examine the effect of harvesting/handling practices on the quality of the harvested produce before storage and (iii) investigate the effect of harvesting/handling practices on grain quality and overall losses during ordinary storage. The objectives were achieved using a losses assessment methodology that evaluates a broad spectrum of grain damage and quality defects. Such knowledge is important for identifying measures that farmers, under different contexts, might need to take in order to derive the intended benefits of improved post-harvest technologies.

2. Materials and methods

2.1. Trial sites, timing, and selection of farmers

On-farm trials were conducted in Babati district, located in Manyara region of Tanzania. Babati is characterized by warm and temperate climate, but is also typified by agro-climatic gradients. The district generally experiences a bimodal rainfall pattern with short rains peaking in November–December while long rains peak in March–April. On average, temperatures are highest in November and lowest in July. Trials were conducted in two agro-locations: Long village (S 4° 13′ 15.62''; E 35° 25′ 31.80''; 2162.8 m.a.s.l) and Seloto village (S 4° 15′ 2.48''; E 35° 31′ 3.70''; 1628 m.a.s.l) that have contrasting weather patterns. Weather data of the two agro-locations were downloaded from agriculture - weather data platform (aWhere). The platform (www.awhere.com) provides global cloud-based data for historic and current observations, and forecasts with daily and 9 km spatial resolutions. This data was generated using aWhere's in-house 3D curvilinear interpolation algorithm that blends multi-source data from ground weather stations, Doppler radar (where available), and satellite observations. Satellite data sources include the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al. 2007), Global Precipitation Measurement (GPM) mission (Hou et al. 2013) and the Agricultural Reanalysis of Precipitation Data (AREA-PD). Global assessment of aWhere data revealed that temperature differ from ground stations data by a mean of less than 0.67 °C and precipitation is within 10 mm up-to 95% of the time. The aWhere datasets were developed to improve agricultural advisories especially in Africa where the density of weather observations network is low. Trials were conducted from July 2016–March 2017, covering a whole post-harvest cycle that usually lasts 7–9 months.

2.2. Experimental details

A preliminary survey was undertaken to inventory harvesting/handling practices of farmers. Seven procedures were identified (see Table 1). Ten willing farmers (5 in each village) who had sufficient produce (>5 acres of crop) were recruited. A section measuring approximately 50 m × 30 m of the farm belonging to each of the participating farmers was demarcated. The farmers, in each of the two locations, were randomly assigned the harvesting/handling practice procedures (Table 1). Each farmer was assigned 2–3 treatments, which they replicated four times each. The farmers harvested and prepared the maize accordingly, and bagged the shelled grain in woven polypropylene (PP) which were then stored in their own stores for 30 weeks. Early harvesting was done at the beginning of July, and late harvesting 6 weeks later. Shelling of cobs was done using a motorized sheller with a throughput of 0.7 tons per hour. Tarpaulins were improved drying mats (Collapsible Drier Cases, CDC™) from Grainpro Philippines Inc. (Subic Bay, Philippines). Storage bags were obtained locally from a dealer in Babati. All farmers were compensated for the maize, but volunteered storage structures in the homestead. The structures were rooms made of brick or mud wall, with earthen or concrete floor and roofed with iron sheets. Village extension officers monitored the trial on regular basis.

2.3. Sampling

Samples were taken at the time of storage, and at six weeks intervals. Each bag was opened, and 1 kg of grain was drawn from several random points by pushing a sampler from the top to the bottom of the bag at multiple random points. The sample was analyzed for moisture content (m.c.) using a HE lite moisture tester

Table 1
Harvesting and pre-storage handling practices.

Practice	Abbreviation
Early harvest[a], de-husk cobs, shell, bag	EH
Early harvest, dry cobs with husks on the ground, husk cobs, shell, bag	EDgH
Early harvest, dry cobs with husks on tarpaulin, husk cobs, shell, bag	EDtH
Early harvest, de-husk cobs, heap on the ground to dry, shell, bag	EHDg
Early harvest, de-husk cobs, dry on tarpaulin, shell, bag	EHDt
Late harvest[b], de-husk cobs, shell, bag	LH
Late harvest, de-husk cobs, dry on tarpaulin, shell, bag	LHDt

[a] Early July.
[b] Six weeks after early harvest.

(Pfeuffer GmbH, Kitzingen, Germany), and then sub-divided into two sub-samples using quartering method. One sub-sample was randomly drawn and set aside for analysis. Samples were sealed in zip-lock bags, and preserved in a cold room maintained at 8 °C awaiting analysis within two weeks.

2.4. Determination of insect counts, grain damage and physical loss

The aim was to quantify not only insects and insect damage but also other forms of damage including moldy/diseased/discolored grain, rodent damaged grain, broken grain, shriveled grain, and impurities/foreign matter so as to have a full picture of the physical grain quality and total losses. A sub-sample was weighed and sieved through a 6 mm mesh sieve to separate the impurities comprising insects, insect frass, small broken grains, dust, and other fine debris. From the trash, adult insects were separated by species using forceps, and counted. The broken grains were also separated. Insect counts were reported as number per kg of grain. The large foreign matter remaining on the sieve were hand-picked and combined with the finer impurities and the mass recorded (M_{imp}) as g/kg. From the grains retained on the sieve, 1000 grains were randomly picked and weighed (M_{1000}). These were then each displayed on a sorting board with 1000 slots (one slot for one grain), and then sorted into various categories according to dominant type of damage. Further, the damaged grains were separated into consumable and non-consumable ones based on acceptance - rejection criteria of local maize consumers. Trained technicians were used to collect the following data: Number of insect damaged grains (n_i) and the mass (m_i); number of moldy/diseased/discolored grains (n_{mrd}) and the mass (m_{mrd}); number of rodent damaged grains (n_r) and the mass (m_r); number of broken grains (n_b) and the mass (m_b); number discolored grains (n_d) and the mass (m_d); number of shriveled grains (n_s) and the mass (m_s); total number of damaged grains, $N_{td} = (n_i + n_{mrd} + n_r + n_b + n_d + n_s)$ and the mass, $M_{td} = (m_i + m_{mrd} + m_r + m_b + m_d + m_s)$; total number of sound grains, $N_{ts} = (1000 - N_{td})$ and the mass, $M_{ts} = (M_{1000} - M_{td})$; number of consumable damaged grain (N_{tdc}) the mass (M_{tdc}); number non-consumable damaged grains, $N_{tdnc} = (N_{td} - N_{tdc})$ and the mass, $M_{tdnc} = (M_{td} - M_{tdc})$. The average mass of one damaged grain (a) was estimated as M_{td}/N_{td}. The average mass of one sound grain (b) was estimated as M_{ts}/N_{ts}. The mass of the damaged grains before the damage (c) was estimated as $b \times N_{td}$. Hence, the mass of the 1000 grain sample (T), assuming no damage, was obtained as follows: $T = (c + M_{ts})$. The percent overall damage by mass was calculated as (c/T x 100). The percent loss was calculated as $(c - M_{tdc})/T \times 100$. An assumption was made, that on average, a damaged grain weighed less than a non-damaged one.

2.5. Statistical analysis

Data were analyzed using GLM procedures on IBM® SPSS® Statistics 20 (IBM Corporation, New York, USA). A series of multivariate analyses of variance were performed. Climate data (Five dependent variables: daily temperature - minimum and maximum; atmospheric relative humidity - minimum and maximum; and precipitation) as well as grain quality data (10 dependent variables: insect population, insect damage, rodent damage, shriveled grain, moldy/diseased/discolored grain, broken grain, non-consumable grain, impurities, total damage, overall losses) were first checked for the critical assumptions for multivariate analysis: normality, absence of univariate and multivariate outliers, absence of multicollinearity, linear relationship among variables, and homogeneity of covariance matrices. For the grain quality parameters, data were not normally distributed and therefore, were required, non-parametric Kruskal-Wallis test was used to separate means of treatment groups. Multivariate outliers were checked by running a multiple linear regression with the dependent variables as the independent variables, and computing the Mahalanobis' distance (MD) values for each case. Outlier cases were identified by comparing the derived MD values with the critical maximum value from chi square tables at $P = 0.001$, and df = number of dependent variables). Critical value of 20.52 and 29.59 were applied for the five dependent variables related to climate, and the 10 dependent variables related to grain quality, respectively. All cases with MD values above the critical value were removed. Multicollinearity of dependent variables was tested using collinearity diagnostics on the regression function of SPSS, followed by evaluation of the derived Variance Inflation Factors (VIF). Absence of multicollinearity was satisfied if the derived VIF values for all variables were <4. For the grain quality data, this assumption was met after excluding the parameter 'overall damage'. Thus nine variables (rodent-damaged grains, shriveled grain, moldy/diseased/discolored grain, insect population, broken grains, non-consumable grains, impurities, insect-damaged grains, and losses) were retained. The assumption of linear relationship between pairs of dependent variables was tested using pearson's correlation. For the grain quality data, a threshold was applied; only parameters that had a correlation coefficient of at least 0.2, with at least three other parameters were included in the analysis. On the basis of this criterion, the variable 'impurities' was excluded. Homogeneity of covariance matrices across groups was tested as part of multivariate analysis using Box's M test; covariance matrices were presumed homogenous if the derived p-value was >0.001. This last assumption was not met for the analyses, hence Pillai's Trace statistic has been reported as it is considered to be more robust where the assumptions of multivariate analysis have been violated.

Analyses to assess effects of harvesting/handling practices on quality of grain before storage were performed on the baseline data. A preliminary multivariate analysis of covariance (MANCOVA) with grain moisture as covariate evaluated whether the various practices identified in Table 1 (combinations of harvesting time, de-husking and drying) differed significantly. At this level, practice was the independent variable, while the eight quality parameters (as a group) were the dependent variables. After identifying a significant effect, an expanded MANCOVA was then performed to test the effects of the specific practice aspects. For this we considered an experimental matrix consisting of 4 independent variables and their categories: climate or agro-location (Long, Seloto); harvesting time (early-harvesting, late harvesting); De-husking (de-husk before drying, de-husk after drying); Drying (on the ground, on tarpaulin, none).

Analyses to evaluate effects of storage duration was achieved using one-way repeated measures ANOVA (RM-ANOVA) with Greehouse-Geisser correction. Individual quality parameters were the subjects. Time was the 'within-subject' factor, in which 0, 6, 12, 18, 24, and 30 week sampling points were the factor levels. Agro-location, harvesting time, de-husking, and drying were incorporated as 'between-subject' factors. From the output, 'within-subject' effects revealed whether storage time influenced significantly the quality parameter in question, whereas 'between-subjects' effects revealed whether the outcomes of the different levels of agro-location, harvesting time, de-husking or drying differed significantly during the storage span. All graphs were plotted using SigmaPlot® for Windows Version 11.0 (Systat Software GMBH Erkrath, Germany).

3. Results

3.1. Weather patterns of trial sites

From multivariate analysis, the trial sites were significantly different in terms of the prevailing conditions (Pillais Trace = .653, $F_{5,\ 716} = 270.053$, $P < 0.001$, $\eta_p^2 = 0.653$). The significance was on temperature and atmospheric r.h. (minimum temperature: $P < 0.001$; maximum temperature: $P < 0.001$; minimum r.h.: $P < 0.001$; maximum r.h.: $P = 0.003$), but not on precipitation ($P = 0.560$). Paired t-tests showed than Long village was cooler and less humid than Seloto (see Fig. 1). The maximum as well as the minimum temperature profiles were significantly different (maximum: $t = 19.815$, $df = 728$, $P < 0.001$; minimum: $t = -30.70$, $df = 728$, $P < 0.001$). The maximum and minimum temperatures in Seloto averaged 27.74 ± 0.10 and 15.92 ± 0.08 °C, respectively compared to 24.99 ± 0.09 and 12.43 ± 0.08 in Long. The relative humidity (r.h.) profiles were also significantly different (Maximum r.h: $t = 3.080$, $df = 728$, $P = 0.002$; Minimum r.h: $t = 5.932$, $df = 728$, $P < 0.001$). The maximum r.h. averaged 89.34 ± 0.36% in Seloto and 87.44 ± 0.50% in Long, whereas minimum r.h. averaged 43.50 ± 0.54 and 38.74 ± 0.59, respectively.

3.2. Harvesting and pre-storage handling practices of farmers

From the preliminary survey undertaken to inventory farmer harvesting/handling practices, about two thirds of farmers (62%; n = 129) harvested early, when the maize showed signs of maturity. Harvesting was done by opening the husks and removing the cobs from the plant. The cobs were then transported to the homestead for drying, shelling, and bagging for storage. Drying was done either directly on the ground or on tarpaulins. A significant 16% of farmers cut the entire plant and piled the crop in the field for 2–3 weeks to dry, and then de-husked the cobs which they dropped in the field (on the ground or tarpaulin) for a few days to dry further, before transporting to the homestead for shelling and bagging. Some farmers also shelled the maize on the farm and bagged or sold right away. Another 8% of farmers left the crop in the field to dry (late harvesting), removed the cobs from the plant and then transported to homestead for shelling and bagging. About a quarter (24%) of farmers did not dry the maize further after field drying. Prior to shelling the cobs were sorted (85% of farmers) on the basis of mold damage (71.7%), cob rot (46.2%), insect damage (21%), rodent damage (12.3%), maturity (11.2%), color (2.8%), cob size (2.8%), sprout damage (1.9%), grain size (1.0%), and damage by birds (0.9%). Half of farmers (52.8%) used mechanical threshers for shelling, while the rest applied manual methods. The foreign matter (chaff, soil, dust, broken cobs) in shelled grain was removed by winnowing (88%) and hand picking (10.1%). A few farmers (5.8%) relied on the thresher to blow away foreign matter, and therefore did not carry out further cleaning or winnowing.

3.3. Grain quality prior to storage

An overview of the levels of the various quality defects on shelled grain as measured before storage is presented in Fig. 2. The levels were generally spread across a wide range (grain moisture: 11–23.7%; moldy/diseased/discolored grain: 1.7–21%; total insect

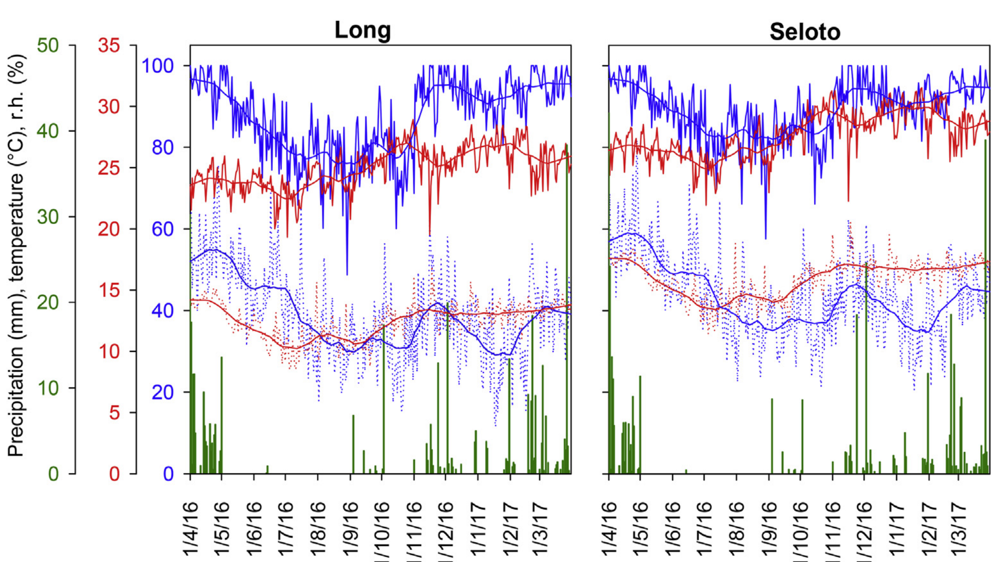

Fig. 1. Profiles of precipitation (Green), temperature (red) and relative humidity (blue) in Long and Seloto during the trial period. Minimum and maximum temperature and r.h. profiles are represented by the lower- and upper-line plots, respectively. Data are daily measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

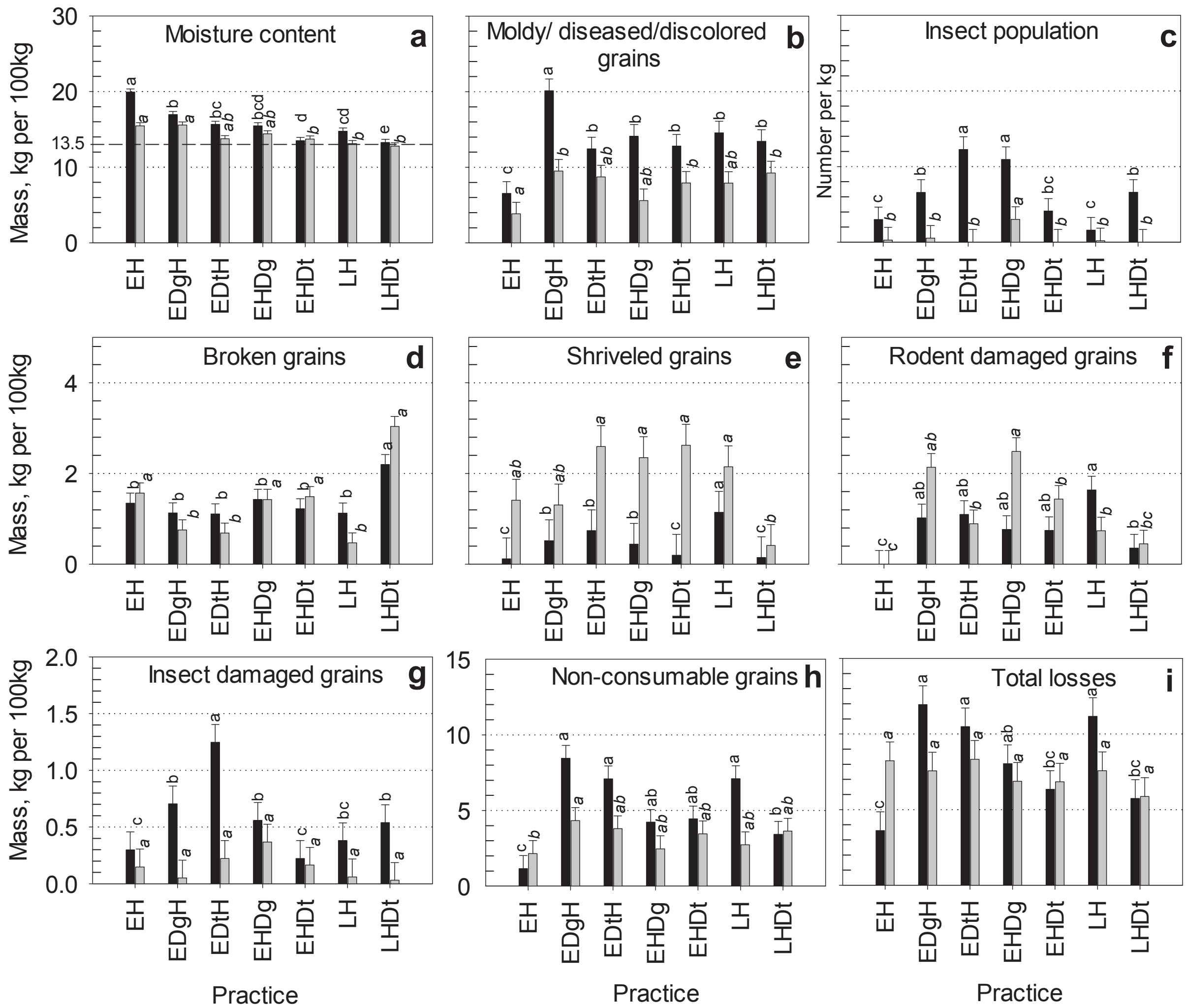

Fig. 2. Quality defects on shelled maize grain in Long (black) and Seloto (grey). EH: cobs harvested early, de-husked, shelled, grain bagged; EDgH: cobs harvested early, dried on bare ground, de-husked, shelled, grain bagged; EDtH: cobs harvested early, dried on tarpaulin, de-husked, shelled, grain bagged; EHDg: cobs harvested early, de-husked, dried on bare ground, shelled, grain bagged; EHDt: cobs harvested early, de-husked, dried on tarpaulin, shelled, grain bagged; LH: cobs harvested late, de-husked, shelled, grain bagged; LHDt: cobs harvested late, de-husked, dried on tarpaulin, shelled, grain bagged. Regular letters compare means within practices in Long; italic letters compare means within practices in Seloto.

population: 0–22.4 counts/kg; broken grains: 0.0–3.7%; shriveled grain: 0.0–4.2%; rodent damaged grain: 0.0–4.0%; insect damaged grain: 0.0–1.3%; non-consumable grain: 0.2–9.7%; overall losses 1.4–14.8%.

Preliminary MANCOVA was performed to examine whether the various practices as described in Table 1 influenced grain quality as a whole, i.e. with the various quality parameters analyzed together as a group. Grain moisture was the covariate. The effect of practice was statistically significant (Pillai's Trace = 1.469; $F_{48,\,492} = 3.324$; $P = 0.005$; $n_p^2 = 0.239$). The covariate was also significant (Pillai's Trace = 0.357; $F_{8,\,77} = 5.355$; $P < 0.001$; $n_p^2 = 0.357$), meaning that grain moisture influenced the observations on some of the parameters. Specifically, grain moisture was significant on insect population ($P < 0.001$, n_p^2 0.206), insect damage ($P < 0.001$, n_p^2 0.178), moldy/diseased/discolored grain ($P < 0.001$; n_p^2 0.125), non-consumable grain ($P < 0.001$, n_p^2 0.169), and losses ($P = 0.003$, $n_p^2 = 0.097$). The significance of practice was on all parameters except insect damage (broken grain: $P < 0.001$, $n_p^2 = 0.463$; rodent damage: $P < 0.001$, n_p^2.290; moldy/diseased/discolored grain: $P < 0.017$; n_p^2 0.267; shriveled grain: $P = 0.025$, $n_p^2 = 0.154$; non-consumable grain: $P < 0.001$; $n_p^2 = 0.413$; insect population ($P = 0.015$; $n_p^2 = 0.168$; losses: $P < 0.001$; $n_p^2 = 0.278$). The separation of means on the basis of practice is given in Fig. 2. A separate preliminary MANCOVA examined the effect of agro-location. The covariate (grain moisture) was not significant (Pillai's Trace = 0.166; $F_{8,\,82} = 2.042$; $P < 0.051$; $n_p^2 = 0.166$), whereas agro-location was significant (Pillai's Trace = 0.593; $F_{8,\,82} = 14.96$; $P < 0.001$; $n_p^2 = 0.593$) on insect population ($P < 0.001$, $n_p^2 = 0.262$), insect damaged grain ($P < 0.001$, $n_p^2 = 0.137$), shriveled grain ($P < 0.001$, $n_p^2 = 0.243$), moldy/diseased/discolored grain ($P < 0.001$, $n_p^2 = 0.254$) and non-consumable grain ($P = 0.003$, $n_p^2 = 0.092$). Thus agro-location influenced all the examined quality parameters except rodent damage, amount of broken grain, and the overall losses.

An expanded was MANCOVA further explored the effects of the individual operations or practice aspects. Agro-location was incorporated in the analysis to examine the potential interaction of specific operational actions with climatic conditions. The results are presented in Table 2. The covariate (grain moisture) was significant, and explained 34% of the variability. Similarly, agro-location, harvesting time, and drying were significant, whereas de-husking was not, although it accounted for 16% of the observed variability in

Table 2
MANCOVA output for quality of maize prior to storage.

Effect	Pillai's Trace	$F_{\text{hypothesis df, error df}}$	*P*-value	Effect size (η_p^2)
Intercept	0.234	$2.676_{8,70}$	0.013	0.234
Grain moisture content (covariate)	0.343	$4.569_{8,70}$	0.000	0.343
Agro-location	0.510	$9.106_{8,70}$	0.000	0.510
Harvesting time	0.355	$4.824_{8,70}$	0.000	0.355
De-husking	0.161	$1.682_{8,70}$	0.118 (NS)	0.161
Drying	0.652	$4.296_{16,142}$	0.000	0.326
Agro-location * harvesting time	0.256	$3.009_{8,70}$	0.006	0.256
Agro-location *De-husking	0.254	$2.985_{8,70}$	0.006	0.254
Agro-location * Drying	0.486	$2.848_{16,142}$	0.000	0.243
Harvesting time * Drying	0.548	$10.596_{8,70}$	0.000	0.548
De-husking *Drying	0.178	$1.896_{8,70}$	0.074 (NS)	0.178
Agro-location * Harvesting time * Drying	0.302	$3.793_{8,70}$	0.001	0.302

grain quality. Agro-location was the most significant main effect accounting for 51% of the variability. Harvesting time, and drying explained 36 and 33% of the variability, respectively. Several interaction effects were significant and these are also presented in Table 2. Harvesting time * drying was the most significant two-way effect; the interaction explained 55% of observed variability. A three-way effect: agro-location * harvesting time * drying was also significant and explained 30% of observed variability. The actual effects on specific quality parameters are summarized in Table 3.

Insect population was explained by grain moisture and the interactions agro-location * de-husking and agro-location * drying. The insect damage levels were also explained by grain moisture and agro location * de-husking, as well as drying. Insect counts were >10 times higher in Long village (6.4 ± 0.9 adults/kg) compared to Seloto (0.6 ± 0.2 adults/kg). Drying the maize cobs with the husks whether on the ground or on tarpaulin (practices EDtH, EDgH) resulted in higher insect infestation. The insect damage levels were also higher by factors of 1.8 and 2.2, respectively, when cobs were dried with the husks compared to when the cobs were de-husked and then dried (practices EHDt, EHDg, LHDt). This effect was observed in Long and not in Seloto where insect populations were rather low.

The levels of moldy/diseased/discolored grain were explained by agro-location, and harvesting time * drying. The levels were two times higher in Long (13.4 ± 0.8%) than Seloto (7.5 ± 0.5%). Also, in both agro-locations, late-harvested maize (Long: 14.5%, Seloto: 7.9%) had twice the amount of moldy/diseased/discolored grain than early-harvested maize (Long: 6.5%, Seloto: 3.8%). However, the levels increased two-to three-fold when the early-harvest maize was dried. Drying on the ground (practices EDgH, EHDg) resulted in higher levels of moldy/diseased/discolored grain by factor of 1.2 compared to drying on tarpaulin (practice EHDt). Moreover, drying the sheathed cobs on ground (practice EDgH) resulted in the highest amounts of moldy/diseased/discolored grain (Long 20.1%, Seloto 9.5%).

The amount of broken grain was dependent mainly on harvesting time * drying. This interaction explained 23% of the variability in levels of broken grain. Late-harvested maize dried on tarpaulin (practice LHDt), and early-harvested maize that was not dried at all (practice EH) had higher amounts of broken grains. For shriveled grain, harvesting time * drying was the most significant effect (15% of the variability) although other interactions (agro-location * harvesting time; agro-location * de-husking) were also significant, accounting for 10% and 5% of the variability, respectively. The levels of shriveled maize were 4 times higher in Seloto than Long, and the early-harvested maize in Seloto had significantly

Table 3
Significance of main effects and interaction effects on quality parameters of harvested grain prior to storage.

Effect	Insect population	Insect damage	Moldy/diseased/discolored grain	Broken grain	Shriveled grain	Rodent damage	Non- consumable grain	Loss
Moisture	0.011 (0.063)[1]	0.041 (0.053)	NS	NS	0.070 (0.040)	NS	0.000 (0.179)	0.000 (0.243)
Agro-location	0.000 (0.163)	0.001 (0.130)	0.001 (0.130)	NS	0.000 (0.206)	NS	NS	0.060 (0.045)
Harvesting time	NS[2]		0.006 (0.094)	NS	NS	NS	0.000 (0.251)	0.000 (0.246)
De-husking	NS	NS	NS	0.006 (0.093)	NS	NS	NS	NS
Drying	NS	0.009 (0.114)	0.007 (0.122)	0.006 (0.125)	NS	0.000 (0.236)	0.001 (0.161)	0.014 (0.105)
Agro-location * harvesting time	NS	NS	NS	0.044 (0.052)	0.006 (0.095)	NS	0.001 (0.146)	0.001 (0.124)
Agro-location * de-husking	0.032 (0.056)	0.005 (0.093)	NS	0.031 (0.057)	0.037 (0.053)	0.003 (0.105)	NS	NS
Agro-location *drying	0.048 (0.076)	NS	NS	NS	NS	0.000 (.206)	NS	0.040 (0.080)
Harvesting time *drying	NS	NS	0.024 (0.065)	0.000 (0.230)	0.000 (.151)	0.000 (.212)	0.000 (0.405)	0.000 (0.301)
De-husking *drying	NS	NS	NS	NS	.024 (.064)	NS	NS	0.024 (0.065)
Agro-location * harvesting time *drying	NS	NS	NS	NS	NS	NS	0.000 (0.240)	0.000 (0.157)

[1]*P* -value (Effect size).
[2]NS = not significant.

higher amounts, an indication of poor filling. Drying increased the levels further particularly when the maize was dried on tarpaulin, probably due to grain shrinkage. Rodent damage was explained by agro-location * de-husking (effect size: 11%), agro-location * drying (effect size: 21%), and harvesting time *drying (effect size: 21%). There was higher rodent damage in Seloto, and the magnitude was higher by factor of 1.5 when harvested cobs were dried on the ground. Furthermore, the maize dried with the husks had higher rodent damage levels in Long. Late-harvested maize (practice LH) had higher rodent damage compared to early-harvested maize (practice EH) but drying also increased rodent damage levels in the early-harvested cobs probably because of longer exposure periods that were need to achieve sufficient drying, alongside other factors such as better camouflage of rodents within the sheathed cobs.

Agro-location * harvesting time * drying was significant for the amount of grains that were unfit for human consumption. In addition, de-husking was significant as a main effect, accounting for 16% of the variability, compared to 24% accounted for by the three-way effect. Analogously, these effects were significant for losses, which averaged 7.48 ± 3.28%. The loss levels did not differ across agro-locations for the early-harvested maize but were higher in Long (8.4%) than Seloto (6.4%) for the late-harvested maize, which was probably because of the higher insect and mold incidence levels in Long. Also, the early-harvested cobs that were de-husked and then dried on tarpaulins (practice EHDt) exhibited lower loss levels by up to 5 percentage points in Long compared to the other practices. In Seloto, the loss levels did not vary with the various practices.

3.4. *Changes in grain quality during storage*

A preliminary repeated measures ANOVA (RM-ANOVA) with practice as the between-subject factor tested whether practice (see Table 1) had significant effect on selected parameters. After confirming a significant effect, a further expanded RM-ANOVA tested the effects of the individual aspects of practice (harvesting time, de-husking, drying) and agro-location, as well as the interactions of these with time. The statistical outputs are summarized in Table 4. Generally there was no difference between early-and late-harvest maize on all the quality parameters examined. Strikingly, however, the levels of all parameters except grain moisture, rodent damage, and *Tribolium* spp counts (secondary insect pest) remained distinct by agro-location. The levels of moldy/diseased/discolored grain, non-consumable grain and overall losses were distinct depending on whether cobs were de-husked or not during drying, whereas grain moisture, *Tribolium* counts, shriveled grain, and broken grain levels were distinct based on the drying approach applied (drying on the ground, drying on tarpauling or not drying at all). Profile plots showing estimated marginal means of some of the parameters as a function of time are presented in Fig. 3, Fig. 4, and Fig. 5.

3.4.1. *Grain moisture*

Grain moisture declined steadily. From the preliminary RM-ANOVA, effect of practice was significant as well as the interaction of time and practice ($F_{19.88,\ 141.97} = 4.104$; $P = < .000$; $n_p^2 = 0.334$). The expanded RM-ANOVA showed that the significant effect of practice was on drying (Table 4). The maize dried on tarpaulin maintained significantly lower moisture levels for nearly 18 weeks (Fig. 3c). Early- and late-harvested maize lots were not different in terms of the moisture level during storage. Similarly, moisture contents of grain shelled from maize cobs that were dried with and without the husks did not differ. However, the interaction effects of the three practice aspects with time were significant (see Fig. 3a−c) suggesting differences in the in-situ drying dynamics of stored grain depending on the initial moisture levels, as a result of the different harvesting and handling practices. Compared to the drier grain, the wet grain continued to lose moisture, apprentlly at a faster rate evenutally attaining a a lower moisture level. Moreover, moisture contents of grain stored in the two agro-locations were not distinct ($P = 0.697$), and significant interaction effect between time and agro-location was observed (see Fig. 3d). The higher grain moisture in Seloto after 12 weeks of storage may be explained by the higher atmospheric r.h., which might have resulted in lower rate of in-situ drying of the stored maize.

3.4.2. *Moldy, diseased, discolored grain*

The effect of time was not significant for the levels of moldy/diseased/discolored grain. Also, preliminary RM-ANOVA showed that practice (Table 1) was not significant ($P = 0.406$; $n_p^2 = 0.125$). The expanded test, however, showed that de-husking was significant (Table 4); grain from the maize cobs dried with the husks retained higher levels of moldy/diseased/discolored grain throughout (see Fig. 3f). Indeed, early harvested-cobs that were dried on tarpaulin after de-husking (practice EHDT) had the lowest levels of moldy, discolored, and diseased grain); the levels were 1.7 times lower compared to the early-harvested maize cobs dried on the ground with the husks (practice EDgH). The levels of moldy/diseased/discolored grain in the cooler location were consistently higher by factor of 1.6. The interaction of agro-location with time was also significant ($P = 0.022$; Fig. 3h).

3.4.3. *Insect population and damage*

Sitophilus and *Tribolium* spp were identified during storage. The effect of practice on *Sitophilus* counts was not significant ($P = 0.883$) and follow-up tests showed that the population were not different as a result of harvesting time, de-husking, or drying (Fig. 4a−c). The effect of agro-location was, however, significant; *Sitophilus* spp counts were consistently higher in Long village through the entire

Table 4
Grain quality during storage as influenced by harvesting time, de-husking, drying, and agro-location.

	Effect of time		Between-factor effects (*P*-value (n_p^2))			
	$F_{\text{hypothesis df, error df}}$	*P*-value (n_p^2)	Harvesting time	De-husking	Drying	Agro-location
Grain moisture	$95.06_{\ 2.92,\ 122.44}$	0.000 (0.694)	NS	NS	0.012 (0.189)	NS
Moldy/diseased/discolored grain	$1.93_{\ 3.12,\ 122.20}$	NS	NS	0.033 (.117)	NS	0.000 (0.317)
Sitophillus spp	$61.11_{\ 3.058,\ 128.43}$	0.000 (0.593)	NS	NS	NS	0.015 (0.133)
Tribolium spp	$16.37_{\ 1.85,\ 77.80}$	0.000 (0.280)	NS	NS	0.012 (0.190)	NS
Insect damaged grain	$112.80_{\ 2.92,\ 122.72}$	0.000 (0.729)	NS	NS	NS	0.000 (0.729)
Rodent damage grain	$1.81_{\ 2.37,\ 99.43}$	NS	NS	NS	NS	NS
Shriveled grain	$11.70_{\ 2.15,\ 96.74}$	0.000 (0.226)	NS	NS	0.034 (0.156)	0.000 (0.436)
Broken grain	$30.67_{\ 3.85,\ 157.66}$	0.000 (0.428)	NS	NS	0.001 (0.302)	0.010 (0.151)
Non-consumable grain	$20.08_{\ 2.82,\ 118.62}$	0.000 (0.323)	0.088 (0.079)	0.036 (0.116)	NS	0.000 (0.302)
Losses	$91.71_{\ 2.80,\ 86.92}$	0.000 (0.750)	NS	0.030 (0.156)	0.054 (0.171)	0.002 (0.356)

(n_p^2): Effect size; NS: not significant.

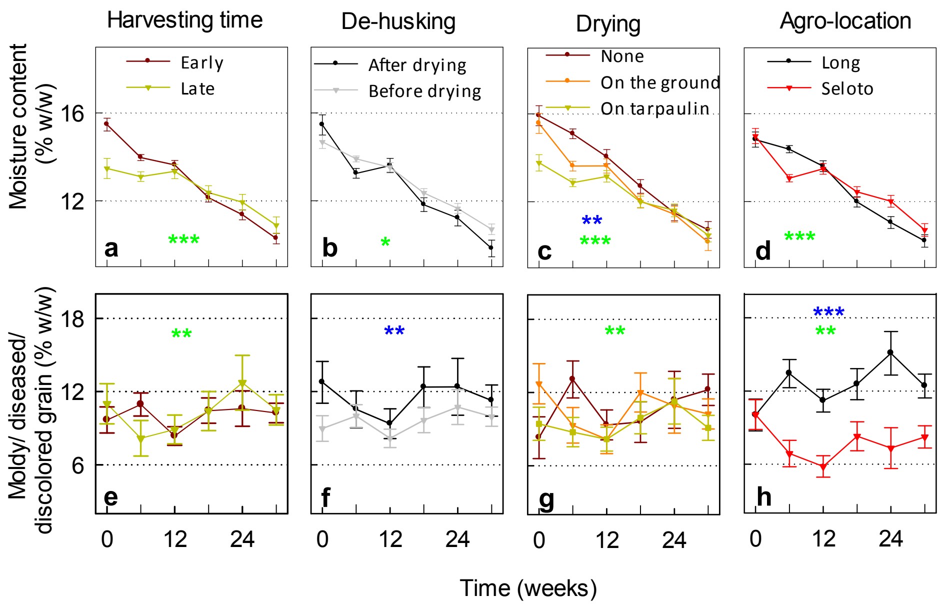

Fig. 3. Profile plots for marginal means of grain moisture, and moldy/diseased/discolored grain by harvesting time, de-husking, drying, and agro-location as categorical variables. Blue asterisk: depicted categories of the particular variable are significantly different; Green asterisk: there is significant interaction with time. ***$P < 0.001$; **$P < 0.05$; *$P < 0.1$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

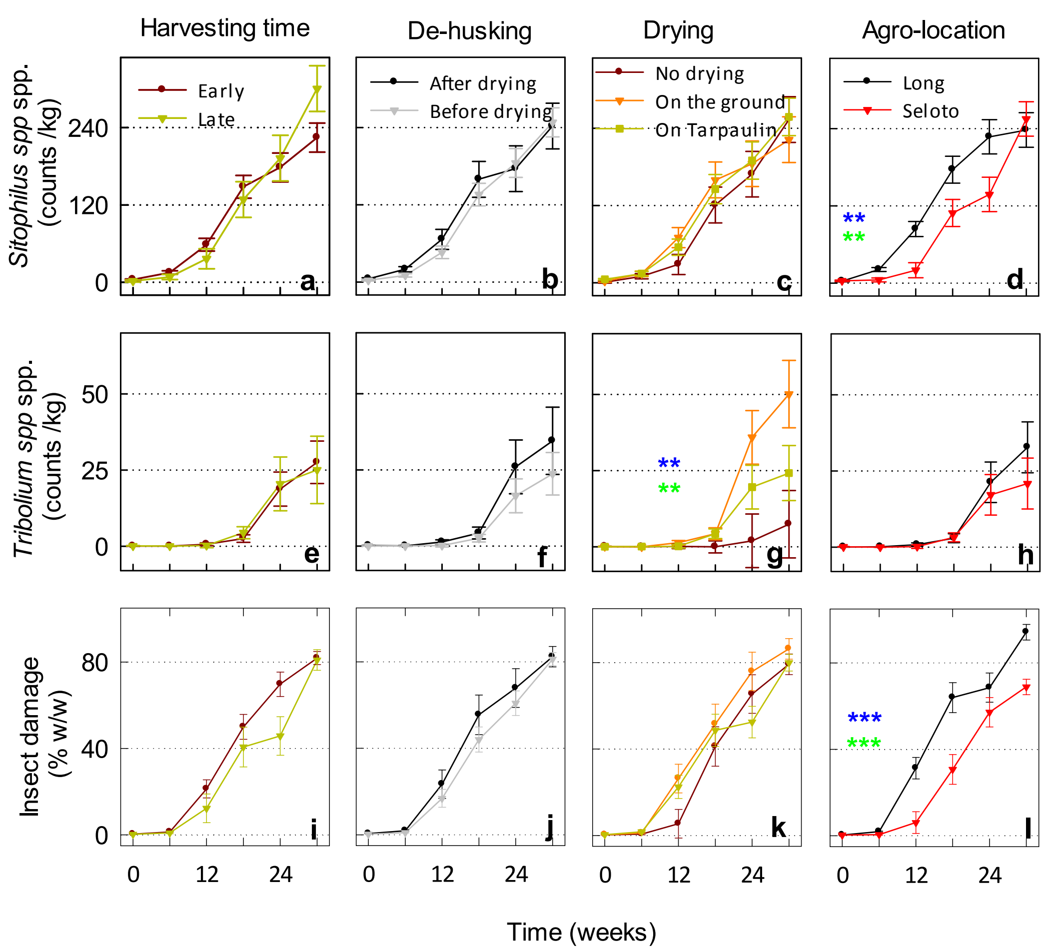

Fig. 4. Profile plots for marginal means of insect counts and insect damage by harvesting time, de-husking, drying and agro-location as categorical variables. Blue asterisk: depicted categories of the particular variable are significantly different; Green asterisk: there is significant interaction with time. ***$P < 0.001$; **$P < 0.05$; *$P < 0.1$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

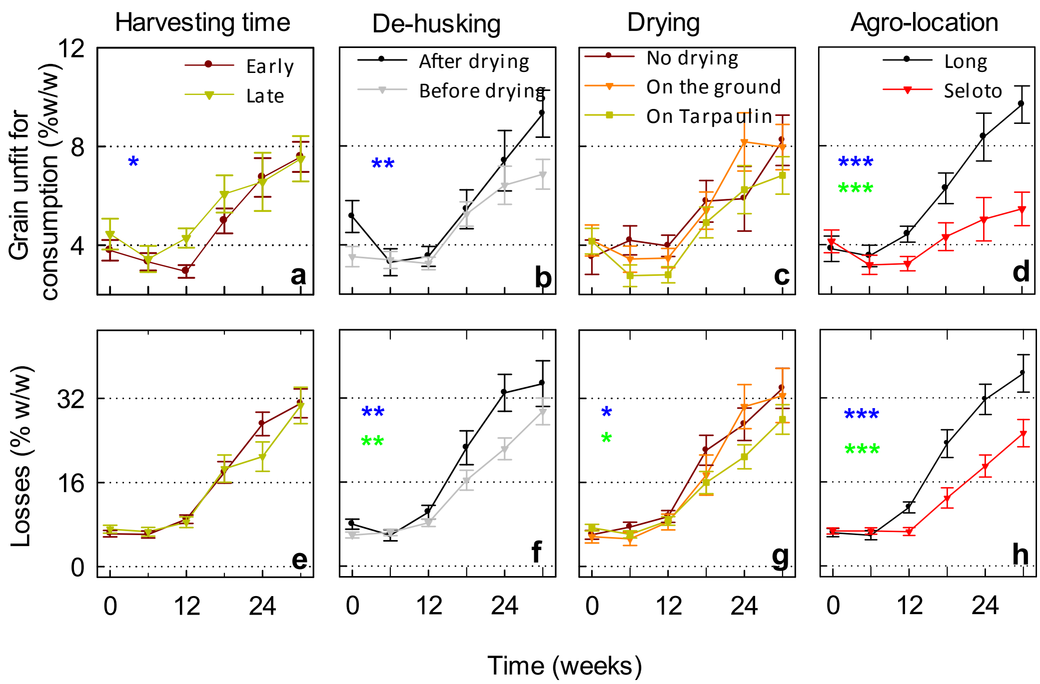

Fig. 5. Profile plots of marginal means for proportion of grain unfit for consumption and overall losses by harvesting time, de-husking, drying, and agro-location as categorical variables. Blue asterisk: depicted categories are significantly different; Green asterisk: there is significant interaction with time. ***$P < 0.001$; **$P < 0.05$; *$P < 0.1$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

storage period (Fig. 4d). For *Tribolium* spp, practice was significant ($P = 0.029$) and follow-up analysis showed that the significance was on drying (Fig. 4g). The interaction of drying method with time was also significant (Fig. 4g); the maize dried on the ground (practices: EDgH and EHDg) had significantly higher *Tribolium* spp. counts from 18 weeks onwards suggesting that infestations were picked from the soil. Furthermore, the maize dried with the husks had comparatively higher *Tribolium* counts (Fig. 4f) although the effect was not significant. Unlike *Sitophilus,* the *Tribolium* counts did not differ with agro-location ($P = 0.247$; Fig. 4h).

Insect damage increased steadily reaching 69% and 94% at 30 weeks in Seloto and Long, respectively, and the effect of practice was not significant ($P = 0.588$). Interaction of practice and time was also not significant ($P = 0.834$). Moreover, harvesting time, de-husking and drying approaches did not result in distinct insect damage levels (Fig. 4i–k). The effect of agro-location was significant (Fig. 4l). Interaction of agro-location and time was also significant (Fig. 4h). The upsurge in insect damage commenced earlier in Long (6 weeks after storage), than Seloto (12 weeks) following the same trends observed for *Sitophilus* spp. populations.

3.4.4. Rodent damaged, shriveled and broken grains

The amounts of rodent damaged, shriveled and broken grains remained generally low (<2%). There was no significant effect of time, and the effects of agro-location, harvesting time, de-husking and drying were not significant. For shriveled and broken grain, however, effect of time was significant; the amounts decreased steadily to <0.5%. Practice was significant on broken ($P < 0.000$) but not on shriveled grain ($P = 0.171$). The follow-up RM-ANOVA showed that drying was the significant aspect of practice (Table 4); the maize dried on tarpaulin, consistently retained had higher levels of broken and shriveled grains. The effect of agro-location was significant as well. The amounts of shriveled and broken grain decreased significantly (to <0.4%) but the levels remained consistently higher in Seloto than Long (shriveled grain: $P < 0.000$; broken grain: $P = 0.010$).

3.4.5. Non-consumable grain, and overall losses

Part of the damaged grain was unfit for human consumption. A marked increase in this fraction occurred from 12 weeks onwards (Fig. 5). The preliminary RM-ANOVA showed that practice was not significant on non-consumable grain ($P = 0.299$). However, the expanded analysis revealed that de-husking was significant ($P = 0.025$); the maize dried with husks had higher amounts of non-consumable grain in the early and advanced stages of storage (Fig. 5b). Harvesting time was also significant at $P < 0.1$ ($P = 0.088$); the early-harvested maize contained lower amounts on non-consumable grains in the earlier stages of storage (Fig. 5a) but not in the later stages probably because of advanced insect damage. Effect of agro-location was significant and the interaction of agro-location with time was also significant (Fig. 5d); higher amounts of non-consumable grain were determined in Long and the levels increased at an increasing rate while they increased at a decreasing rate in Seloto.

The effect of time on losses was likewise significant, and the effect of de-husking as well (Table 4). Interaction of de-husking with time was also significant ($P = 0.044$; Fig. 5f). The maize dried without the husks had significantly lower loss levels as storage progressed, which coincided well with lower insect damage levels (though not significant), and lower levels of moldy/diseased/discolored grain. The effect of drying was also significant at $P < 0.1$ ($P = 0.054$) whereby maize dried on tarpaulin exhibited lower loss levels from 12 weeks onwards (Fig. 5g). Effect of agro-location was significant on level of losses, and the interaction with time was highly significant (Fig. 5f). On average, the losses increased five-fold (from 7.7% to 36.3%) in Long, and three-fold (from 7.5% to 25.3%) in Seloto, over the storage period. Thus the rate of accumulation of losses was higher in Long. Furthermore the build-up of losses also commenced 6 weeks earlier compared to Seloto.

4. Discussion

4.1. Effect of agro-location and harvesting/handling on quality of the pre-stored grain

The results of the present study show that there were significant differences in the quality of maize grain stored in the two agro-locations. The differences emanated from the interaction between climatic conditions and the harvesting and grain handling practices applied by farmers, and reflected on almost all quality parameters. A key quality parameter of harvested grain is moisture. There were conspicuous differences in the m.c of early- and late-harvest maize in the two agro-locations. Moisture content of 22–25% is considered ideal for efficient harvesting (Nielsen, 2018) although field drying to ~18% m.c. is sometimes considered sensible to reduce drying costs. Early harvesting was done within the proper timing in the cooler agro-location, but was somewhat late in the warmer agro-location because of rapid dry-down. Maize kernels are considered physiologically mature when the m.c. is 30–35% (Brooking, 1990). At this stage, grain filling ceases, and so maturity is noticeable with the apparent blackening of the kernel's placental region. Depending on atmospheric conditions, and the ear and husk characteristics of the maize variety (e.g. number and thickness of husk leaves, husk coverage of the ear, tightness of husk leaves, ear angle, and properties of the kernel pericarp), the crop would require a post-maturity dry-down period of 2–4 weeks to reach the right moisture for harvesting (Cross and Kabir, 1989; Nielsen, 2018). An ideal waiting period of 3–4 weeks was suggested for humid zones in East Africa (Kaaya et al., 2005; Alakonya et al., 2008) and West Africa (Borgemeister et al., 1998). Ordinarily, however, farmers may recognize the ideal harvest stage when the husks turn brown and the cobs droop, or when the kernels are hard, glassy, and resistant to scratching with the thumbnail (De Lucia and Assennato, 1994).

Despite allowing the crop to wait longer for late harvest (6 weeks after early harvest), grain moisture did not reach the recommended level for safe storage in the cooler location (average atmospheric temperature 18.7 °C; r.h. 63%). Similar findings were reported in Uganda (Kaaya et al., 2005). Thus, in some regions, maize could potentially enter storage with higher than the recommended moisture if keenness to ensure effective post-harvest drying is not observed. The practice of drying the de-husked cobs on the improved tarpaulin was able to lower grain moisture to the safe level for both early and late harvest maize in both locations. This indicates that the practice of de-husking followed by improved drying would contribute to more uniform grain lots with regard to moisture content at the time of storage, which is desirable. Other dying practices applied on early-harvested maize, specifically, drying the sheathed cobs (practices EDgH, EDtH), or drying the maize cobs on the ground (practice EHDg, EDgH) did not perform well. Drying with the husks prevents moisture migration off the surface of the grain, while drying on the ground may allow the produce to absorb moisture from the soil.

The present results also show that there was significant difference in the quality of pre-stored grain with regard to insect populations, the amounts of insect damaged grain, moldy/diseased/discolored grain, shriveled grain, and non-consumable grain in the two agro-locations. Form the weather data, the two agro-locations differed in terms of atmospheric temperature and r.h. by 2–3 °C and 3–5%, respectively. Temperature and r.h. differences within this range can affect incidence and multiplication of insects (Khaliq et al., 2014), molds (Magan et al., 2011) and rodents (Edoh-Ognakossan et al., 2016). The higher *Sitophilus* spp counts observed on the pre-stored grain in the cooler location could be related to the effect of interaction of temperature and r.h. on intrinsic growth rates and population development. The maize harvested in cooler location had >10 times higher insect counts. Throne (1994) reported the optimal temperature and r.h. for growth of maize weevil to be 30 °C and 75%, respectively. But Okelana and Osuji (1985) also observed that the development of *Sitophilus* spp. from egg to adult was best at 25 °C, with variations at different r.h. levels; low r.h. (e. g. 30–50% at 30 °C) could retard progeny development and survival. At the time of harvesting (July–August), the average conditions in the warmer location (20 °C; r.h. 60%) would have favored insect multiplication compared to the average conditions (17 °C; r.h. 55%) in the cooler location. Thus other factors such as the cultivated varieties (Haines, 1991) and farm practices may have contributed to the difference observed on insect populations in the two localities. Drying and de-husking practices contributed to higher levels of insect infestation. In particular, insect counts and insect damage increased during drying especially when harvested cobs were dried with the husks. Drying on bare ground increased insect counts by factor of 3–4 especially in the cooler location, indicating that new infestations were picked from the soil.

The levels of visibly moldy, diseased and discolored grains were two times higher in the late-harvested maize, and drying practices applied on the early-harvested maize in the cooler location increased the levels by factor of 2–3. These findings show that proliferations of fungi and bacteria were encouraged by allowing the crop to stand longer than necessary in the field, and by the drying actions applied. Delayed harvesting encourages ear rot disease and molds (Alakonya et al. (2008). In fact, Kaaya et al. (2005) reported increased levels of *Aspergillus*, *Fusarium*, *Penicillium* and other mold species on maize when harvesting was delayed. The increase was more pronounced for *Aspergillus* spp, reaching ~20 times higher on maize harvested 4 weeks after physiological maturity. Consequently, late harvesting and some post-harvest handling practices, could also compromise the nutritional quality and safety of the produce even before storage (Smith and Di Menna, 2007).

With respect to rodent damage, the interaction of harvesting time and drying, as well as the interaction of agro-location and de-husking/drying were significant. Delayed harvesting is associated with crop exposure to damage by pests including rodents (Abass et al., 2014). Some rodent species attack maize in the field, and then migrate to granaries at the end of the harvest season when food in the field becomes scarce (Edoh-Ognakossan et al., 2016). However, in the warmer agro-location, drying of the early-harvest maize on bare ground as opposed to drying on tarpaulin increased rodent damage two-fold compared to delayed-harvest maize. Higher diversities and populations of rodents are found in warmer environments (Edoh-Ognakossan et al., 2016). Thus while early harvesting is recommended for better harvest quality, increased crop loss due to rodent damage may occur if subsequent drying steps do not protect the produce against rodent attack.

The amount of broken grains averaged 0.5–3%. Large amounts of broken grain encourage insects and micro-organisms, and are therefore not desirable on grain lots intended for long-term storage. Results of this study showed that the levels of broken grain were dependent on the interaction of harvesting and drying actions, as well as the interaction of agro-location and de-husking/drying. Proper drying of maize before shelling is recommended for easy and complete stripping of cobs (Srison et al., 2016), and a direct relationship between grain moisture (range: 14–28%) and mechanical damage was reported (Nalbant, 1990; Srison et al., 2016). In the present case, interaction of harvesting time and drying was the most significant effect explaining the amount of broken grains. Drying of the late harvest maize on improved tarpaulin increased the levels by factor of 2–6, especially in the warmer location. The late-harvest maize dried on the improved tarpaulin had m.c < 12% which possibly made the grains brittle and easy to break when placed on the motorized sheller. Other factors such as physical and morphological characteristics of the cobs, as well as sheller design (Akubuo, 2002; Nalbant, 1990; Petkevičius et al., 2008; Srison et al., 2016) may contribute to grain breakage. The former connote how strongly grains are attached to the cob, kernels ability to deform, kernel size, shape, hardness, and the size and strength of cobs (Akubuo, 2002). Regarding shriveled grain, higher levels were determined in the warmer location. This was probably related to heat stress during maturation, leading to poorer filling of the endosperm (Begcy and Walia, 2015). High levels of shriveled grain are undesirable because of poor processing quality; they have low flour yield, are difficult to de-hull, and the nutritional value is inferior (Gaines et al., 1997). However, just like the broken grains, our findings show that multiple interactions were responsible for the levels of shriveled grain measured on the grain at the pre-storage stage.

The levels of non-consumable grain and the overall losses were a function of the interaction of agro-location with harvesting time and drying. Early harvesting followed by drying the sheathed cobs on the ground or on tarpaulin, as well as late harvesting, were characterized by higher levels of grain that were unfit for human consumption. These were largely the moldy and diseased grains. Consumers often discard grains that are visibly moldy but such grain are also fed to poultry and livestock, and are likely to pass undetected in processed products when unscrupulous processors blend them with good grain. Hence, these could present a public health risk if effective separation is not achieved on the farm. The overall losses were significant; they exceeded 5% (6.9 ± 3.0%). In the cooler location, however, early harvesting followed by de-husking and drying the cobs on improved tarpaulin before shelling could reduce the pre-storage losses by up to 5 percentage points.

4.2. Effects of agro-location and harvesting/handling practices on quality during storage

Understanding how the grain quality parameters change during storage is useful because it provides knowledge of when destructive damage levels are likely to occur, and can therefore help farmers to plan better for effective and economical deployment of interventions. It is also useful for better extension and advisory on successful use of improved storage technologies. On the overall, the levels of rodent-damaged, and moldy/diseased/discolored grain did not change with time, suggesting that these were not very critical parameters deserving stringent monitoring in the trial locations, under ordinary storage. However, the consistently higher levels of moldy/diseased/discolored grain observed on the maize grain threshed from cobs that were dried with the husks point to the importance of good practice. Similarly, the higher levels of moldy/diseased/discolored grain determined in the cooler agro-location throughout the storage period suggest that right interventions would be to address the factors responsible for this defect at the time of harvesting and preparation of the grain for storage, or even earlier. Specifically, the interaction between harvesting time and drying was significant. Early harvesting potentially decreased the amount of moldy/diseased/discolored grain. However, de-husking and drying the early-harvested cobs on improved tarpaulin (best practice) doubled the defect even though it achieved better results compared to drying the sheathed cobs on bare-ground. This observation suggests that, in zones similar to the cooler agro-location, attention should also be given to better drying techniques. Moldy/diseased/discolored grains are indicators of inferior food quality and inadequate safety. The proliferation of molds during storage is associated with mycotoxin production, and environments that encourage other pests such as mites, as well as cause loss of nutrients, reduced germination, and unpleasant taste of food (Gwinner et al., 1996).

As expected, insect population and grain damage levels increased with storage time. The amounts of broken and shriveled grain in turn decreased due to attack by insects. While *Sitophilus* populations remained distinct by agro-location (also at the onset of storage) the *Tribolium* populations were not. The cooler agro-location thus continued to favor multiplication of *Sitophilus* spp. and the attendant insect damage levels, which were equally distinct by agro-location but not distinct by harvesting, de-husking and drying approaches. Significant *Tribolium* spp populations were noticed after about 12 weeks of storage, which coincided well with noticeable insect damage of the grain. Another notable observation was that higher *Tribolium* counts occurred in the maize that was dried on the ground. *Tribolium* spp. prefer environments that are littered with fine debris, and grain that has not been screened of fine materials and broken kernels is particularly susceptible to attack by the pest, that can also survive extremely dry conditions (Gwinner et al., 1996).

Insect damage levels were high despite the fact that *Sitophilus* spp. was the sole primary pest identified (others are *Prostephanus truncatus* (Horn) and *Rhyzopertha dominica* (Fabricius)). Similar to findings of other recent studies in East Africa (Abass et al., 2018; Ng'ang'a et al., 2016), we did not encounter *P. truncatus*. Traditionally, *Sitophilus* spp. is understood to cause lower damage and weight loss than *P. truncatus* as the feeding habit is less ferocious. Other researchers also reported enormous grain damage by *S. zeamais* in semi-arid agro ecologies in Kenya (Ng'ang'a et al., 2016) and Tanzania (Abass et al., 2018). The high damage levels could be attributed to a number of factors, among them susceptible maize varieties (Khakata et al., 2018) and other conditions favoring rapid multiplication of grain weevils. Generally, however, harvesting, de-husking and drying operations did not result in statistically different insect damage levels.

The levels of non-consumable grain as well as the overall losses increased with time. The effects of post-harvest practices were apparent as higher levels of non-consumable grain were associated with late harvesting and drying cobs with the husks, and higher losses occurred on the maize that was dried with the husks, or on the ground. Moreover the non-consumable grain and overall losses were >2 times higher in the cooler location. Non-consumable grain connote grade-outs that are separated through sorting during preparation for consumption or sale. In central Benin, Borgemeister et al. (1998) reported that losses by insects were more severe during the storage of late-harvested maize, while early-harvested maize had a high levels of mold damage. Moreover, the authors reported higher economic value when the stored maize had been harvested 3 weeks after physiological maturity. Our results corroborate these findings, and confirm that proper practice of pre-storage operations can significantly improve storage. The observation that higher and conspicuous losses occurred six weeks earlier in the cooler agro-location was significant. The pattern is also seen on the build-up of insect populations and insect damage. Other studies in East Africa showed that dramatic increase in insect damage levels occurred after 3–4 months of storage, when no interventions are applied (Ng'ang'a et al., 2016). From the present findings, farmers would need to implement preventive strategies much earlier in some agro-locations. Nonetheless, it would be helpful to confirm these findings by sampling from farmer granaries as well.

In the context of market access, our results have implications for grain trade in the region. The baseline condition of grain prior to storage was characterized by 4.7–31.8% defective grain. Such is the quality of maize that farmer would be selling to the market early in postharvest season, and would require buyers including traders, processors and consumers to apply quality improvement actions (e.g. cleaning, sorting and grading). According to East African maize standards, total defective grain should not exceed 3.2, 7.0 and 8.5% for grades I, II, III, respectively after adjusting the total damage to a tolerance factor of 0.7 (EAC, 2013). The high levels of quality defects potentially deprive farmers of the opportunity to access markets and better prices. With best practice of early harvesting and drying the husked cobs on improved tarpaulins, sorting losses would be minimized to 6–7%. Since sorting is part of quality improvement, and encouraging farmers to undertake the practice is often part of the education and training given by extension workers, integrating pre-harvest approaches to lower these sorting losses would be judicious. Such approaches include selection of varieties with superior maturing and postharvest traits (such as ear rot resistance, closed ear tips, drooping ears, hard-to-lodge stems), and better matching of varieties to their optimal agro-ecologic conditions.

Conflict of interest and authorship conformation form

None.

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Appendix A. Supplementary data

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