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Exploring the profitability of improved storage technologies and their potential impacts on food security and income of smallholder farm households in Tanzania

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A B S T R A C T

This study assesses the profitability of selected improved grain storage technologies and the potential impact of their adoption on food security and income of smallholder maize producers in Tanzania. We used on-farm experiment data, time series maize price data, and household survey data to address the objectives. For the improved technologies, we considered Purdue Improved Crop Storage (PICS) bags, metallic silos of different sizes, and polypropylene (PP) bags treated with Actellic Super®. We compared them with PP bags without insecticide treatment as the control. Results show that PICS bags and PP bags plus Actellic Super are profitable in all locations and not significantly different. While the feasible period varies by location, profit is most likely negative if farmers sell their maize in the first two months after harvest and in the last two months before the next harvest. There are mixed results with regards to the profitability of metallic silos; bigger silos are profitable for farmers who have economies of scale to use them while smaller ones are profitable only within the context of higher grain price and bigger seasonal price gap. The results also show that PICS bags (or PP bags plus Actellic Super) are useful to address food security and income objectives among poor rural households whereas metallic silos with bigger storage capacity can increase the income of those farmers who have bigger surplus grain to sale.

1. Introduction

On-farm storage can play two important roles among smallholder farmers in Africa and perhaps elsewhere in the developing world. First, it can enhance household food security by enabling farmers to have stable supply of own-produced food (Haile-Gabriel and Hundie, 2006; Hodges and Stathers, 2013; Tesfaye and Tirivayi, 2018). Second, it can increase farmers' income by enabling them to engage in temporal arbitrage in the presence of substantial seasonal price fluctuations (Kaminski et al., 2016; Gilbert et al., 2017; Tesfaye and Tirivayi, 2018). These roles are particularly visible in many farming systems of Africa where production occurs once in a year arising from unimodal rainfall pattern and lack of irrigation infrastructure. Farmers use traditional storage structures such as polypropylene bags, jute sacks, granaries made of wood and mud, and plastic containers to store their grains (Nukenine, 2010; Abass et al., 2014). While traditional storage structures are affordable and easily accessible to farmers, not always they are effective in protecting grains from storage pests resulting in high losses (Tefera, 2012; Hodges and Stathers, 2013). On-farm experiments show that grain losses associated with traditional storage structures (without chemical treatment) exceeds 30% if grains are stored for six months or more (De Groote et al., 2013; Chigoverah and Mvumi, 2016; Abass et al., 2018). Such a high degree of loss indicates the necessity of improving existing storage systems.

Improved storage technologies have been tested and found effective in reducing storage losses (De Groote et al., 2013; Baoua et al., 2014; Njoroge et al., 2014; Chigoverah and Mvumi, 2016;

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Williams et al., 2017). For instance, Baoua et al., (2014) found that Purdue Improved Crop Storage (PICS) bags can completely prevent maize from damage by storage insect pests. Similarly, De Groote et al. (2013) and Chigoverah and Mvumi (2016) found that metallic silos and super grain bags are very effective in controlling maize weevils and the larger grain borer. Nevertheless, technical soundness is a necessary but not a sufficient condition for adoption of market goods or technologies among farmers. This is because acquisition of new technologies entails pecuniary investments and farmers will not adopt them unless the financial benefits sufficiently outweigh the costs (Pannell et al., 2006; Kuehne et al., 2017). Therefore, one of the major questions to be answered prior to promoting new storage technologies is whether they are profitable within local contexts. This is particularly important to promote the use of the bags for low-value staple crops like maize.

Moreover, farmers adopt new technologies when they believe that such a decision would make them better off the potential of which depends on the technology's relative advantage over the existing ones in terms addressing basic household objectives such as attaining food security and earning adequate income. Improved storage technologies can enhance household food security or income directly by avoiding grain losses (De Groote et al., 2013; Baoua et al., 2014; Njoroge et al., 2014) or, indirectly, for example, by enhancing the adoption of yield-increasing crop technologies such as improved varieties (Ricker-Gilbert and Jones, 2015). While ex-ante evidence on the contribution of improved storage technologies toward these objectives is necessary to prioritize interventions, many studies have focused on identifying factors that affect adoption decisions or ex-post impacts (Bokusheva et al., 2012; Tesfaye and Tirivayi, 2018).

Many studies consider postharvest grain loss as the reduction of weight alone (De Groote et al., 2013; Njoroge et al., 2014; Williams et al., 2017). However, grain weight loss (GWL) gives a partial measure of grain losses given that most smallholder farmers would evaluate storage technologies not only in terms of GWL but also in terms of price discounts arising from grain quality deterioration (Compton et al., 1998; Mishili et al., 2011; Jones et al., 2014; Kadjo et al., 2016). For instance, Compton et al. (1998) found that consumers demanded a 1% price discount for a 1% damage level in maize grain during the harvest season although more damage was tolerated during the lean season. Similarly, Kadjo et al. (2016) found that a 10% increase in insect damage resulted in a 3% maize price discount while discounts were larger during the harvest season than the lean season. Therefore, evaluation of improved storage technologies should go beyond GWL so that it reflects the wider production objectives of smallholder farmers (Ndegwa et al., 2016; Williams et al., 2017). This entails the estimation of total grain value loss (TGVL) which combines the physical and monetary losses arising from insect pest damage (Jones et al., 2014).

While much is known about the performances of the new storage technologies from the biological side, empirical evidence on their economics is quite limited. This study aims to fill this gap based on diverse data sets and new analytical approaches, which can easily be replicated for different crops, storage technologies, and contexts. We address several issues in this paper. First, based on a time series price data (over 10 years' monthly price data) and on-farm experiment data, we compute the mean profit which farmers may earn if they use selected improved storage technologies (Purdue Improved Crop Storage bags, metallic silos, and polypropylene bags plus Actellic Supper) to store their maize until the lean season. Our data also allowed us to assess the temporal variability of the profit associated with the storage options; this evidence is missing in postharvest literature to the best of our knowledge. Second, it assesses the potential impact of using the improved storage technologies on household food security and income, which will be useful to prioritize interventions among development practitioners. Third, it tests whether storage losses can induce early sale of part of the grain allocated for household consumption. In so doing, our study contributes to the explanation of the “sell-low, buy-high” puzzle observed among smallholder farm households (Stephens and Barrett, 2011).

2. Methodology

2.1. Study areas

The study was conducted in Manyara (Babati and Kiteto districts) and Dodoma (Kongwa District) regions of Tanzania. The locations are characterized by unimodal rainfall pattern. The growing season starts in December/January and ends in June/July. Crops cultivated in the areas include maize, sorghum, millet, and legumes such as beans, groundnuts, cowpea and pigeon pea. Maize is the dominant crop which accounts for 61% and 38% of the total cultivated lands in Manyara and Dodoma regions, respectively (URT, 2016). In terms of production, maize accounts for about 40% in Dodoma and for about 70% in Manyara. Legumes are grown mostly as intercrops with maize and other cereals.

About one-third of the total maize produced in these districts is marketed (URT, 2016). District towns are the major marketing centers for farmers, but farmers also sell products in village markets. There is an international market for maize in Kibaigwa town (Kongwa District) which is accessed by neighboring countries such as Malawi and Kenya. Farmers sell most of their produce immediately after harvest when prices are low. One of the reasons could be fear of grain damage due to lack of good storage facilities. In fact, more than 75% of the farmers in these areas use polypropylene bags for storage while the remaining farmers use other traditional methods such as the granary (Kihenge) and plastic containers/tins which are not effective in protecting stored grains from insect damage (Abass et al., 2014).

2.2. Analyzing profitability of storage technologies

We considered four storage options in our analysis namely: Purdue Improved Crop Storage (PICS) bags (hermetic), metallic silos (hermetic), polypropylene (PP) bags (non-hermetic) plus Actellic Super® (a mix of Pirimiphos-methyl 16 g/kg and Permethrin 3 g/kg locally known as Shumba), and polypropylene (PP) bags. The PICS bags and the PP bags are of 100 kg storage capacity. We considered four storage sizes of metalic silos which are being promoted in Tanzania being 0.5t, 1t, 1.5t, and 2t.

2.2.1. The model

The profit earned from storing grains, Π , is given by Equation (1) which is a modified version of the model proposed by Jones et al. (2014). The modification was made to accommodate fixed costs in our analysis.

$$\Pi = [(1+s)(1-v)(1-w)]p_0q_0 - c_v - r_1\frac{m}{12}(p_0q_0 + c_v) - \mathscr{R}K \tag{1a}$$

$$\mathscr{R} = \frac{r_{2(1+r_2)^t}}{(1+r_2)^t - 1} \tag{1b}$$

where s is seasonal price gap; v is price discount due to grain damage by insect pests; w is dry weight loss of the stored grain; c_v is variable cost of storage; K is initial investment on storage structure; p_0 is price of grain at harvest; q_0 is quantity of grain available for storage at harvest; m is duration of storage in months; $\mathscr{R}$ is the capital recovery factor; t is service life of storage structure in years; and r_1 and r_2 are opportunity costs of capital for short term and long term investments, respectively(OCC).

2.2.2. Estimating model variables

In this section, we describe how the components of the model were estimated and the data used to estimate them.

Grain weight loss (w) and price discount (v): These two variables are combined to estimate the total grain value loss (TGVL) such that TGVL = 1-(1-w)*(1-v) = w + v-w*v (Jones et al., 2014). The dry weight loss was estimated based on on-farm experiment data. The experiment was conducted in Dodoma and Manyara regions between October 2014 and May 2015 involving 20 farmers who were residents of four villages. Each farmer hosted all of the storage treatments listed above. Samples were taken from the center and four peripheral and equidistant points perpendicular to the center of each storage container using compartmentalized sampling probes (i.e. a 1.8m aluminum probe of 12 openings for metallic silos and a brass open-handled probe of six openings for PICS bags and PP bags), thereby making a total of five samples from each container weighing 1 kg. Samples were visually examined for broken and damaged grain using the 1000 grains count. The percentage damaged grain was calculated following the formula described by Boxall (1986). Weight loss (WL) was calculated as shown by Njoroge et al. (2014). The samples were taken for 30 weeks every six weeks (see Abass et al., 2018 for more details on the experiment). We made linear interpolation from the actual data for the remaining period. The interpolated values are very close to the actual values reported elsewhere (Chigoverah and Mvumi, 2016). Price discount was estimated from grain damage data based on Compton et al. (1998). Studies indicate that grain buyers in Africa show some tolerance before they seek price discount from the sellers. However, the tolerance level varies across time and increases as one goes from the harvest season through to the lean season (Jones et al., 2014; Kadjo et al., 2016). We adopted a 7% tolerance level following Jones et al. (2014).

Storage costs (c_v, K) and maize harvest price (p_0): Based on expert opinion and secondary data, the following prices and service lives were assumed for the storage materials: PICS bags = $2, PP bags = $0.45, Actellic Super = $0.62/bag, labor for chemical application = $0.2/bag, 0.5t metallic silo = $124, 1t silo = $160, 1.5t silo = $202, and 2t silo = $242. The service lives of the bags and the silos were assumed to be two years and 15 years, respectively. The price of maize grain during harvest in each district was the average of the recent three years (2014–2016). The average farm gate prices were $0.135/kg in Babati, $0.130/kg in Kongwa, and $0.112/kg in Kiteto for these years.

Opportunity cost of capital (r_1, r_2): We used the lending interest rates as a proxy for opportunity cost of capital (OCC). The assumption is that farmers would borrow money from commercial banks and invest in the storage business given that the seasonal maize price gap is high enough to motivate them to engage in temporal arbitrage. This is appropriate particularly for those farmers who do not have enough cash deposit to cover expenses that may appear after harvest which forces them to sell their maize. The average bank lending rate in Tanzania was 14.2% for short-term loans (up to one year) and 16.1% for long-term loans (longer than one year) in the past three years (2014–2016) (BoT, 2015, 2016, 2017). We used the short-term rate for stored maize and the long-term rate for storage facilities.

2.2.2.1. Seasonal price gap (s).

We used monthly average maize grain price data to estimate seasonal price gaps. These were collected from agriculture offices in the study districts. Our data cover January 2007–June 2017 in Babati, January 2006–May 2017 in Kongwa, and January 2006–June 2017 in Kiteto. All prices were originally measured in Tanzania Shillings (TZS) which were later converted to US dollars (USD) equivalent using the average USD-TZS exchange rates corresponding to each month.

Farm gate prices are more appropriate to analyze the profitability of on-farm storage (Jones et al., 2014) while market prices may cause upward bias on the results since they include transport and market transaction costs. However, we could not find any data set consisting of farm gate prices in the districts. Instead, we estimated farm gate prices from market prices following the suggestion of World Bank (2009) and Brooks et al. (2007). According to World Bank (2009), farm gate prices are on average 63% of market prices in nearby towns in Tanzania. We used this estimation to construct data series for farm gate prices in our study areas. This would not have any impact on the estimation of the seasonal price gaps but it would be useful to mitigate potential overestimations of profits.

The seasonal price gap, which is the difference between the maximum and the minimum prices, can be measured in different ways. One common approach is to estimate it from monthly dummies from a regression on trend adjusted prices of time series data (Gilbert et al., 2017). This can be specified as follows:

$$P_{ym} = K + \gamma t + \sum_{j=1}^{11} \delta_j Z_{mj} + \varepsilon_{ym} \tag{2}$$

where the trend $t = 12*(y-1) + m$ and Z_{mj} is the dummy variable defined by

$$Z_{mj} = \begin{cases} 1, & j = m \\ 0, & j \neq m \end{cases} \tag{3}$$

The seasonal factor is derived from the coefficient of the estimated equation using the following formula:

$$S_m = \delta_m - \frac{1}{12}\sum_{j=1}^{1} \delta_j \,, \ (\mathrm{m} = 1, 2, \ldots, 12) \tag{4}$$

While straight forward, this dummy variable approach usually leads to overestimated seasonal price gaps which will lead to wrong conclusions (Gilbert et al., 2017). The bias would be serious particularly when the sample size is small (5–15 years) and price seasonality is poorly defined. This problem can be mitigated by adopting parsimonious models such as trigonometric methods (Kaminski et al., 2016; Gilbert et al., 2017). Trigonometric approaches can reduce upward bias in the estimated seasonal price gap by allowing larger number of observations to be used per parameter to be estimated.

If we assume a non-trending time series data, the trigonometric seasonality can be specified as the following two parameter sinusoidal equation.

$$S_m = \alpha\Delta \cos\left(\frac{m\pi}{6}\right) + \beta\Delta \sin\left(\frac{m\pi}{6}\right) \tag{5}$$

However, the absence of trend in food prices cannot be justified due to the fact that prices are non-stationary mainly due to inflation. Therefore, a model that takes into account non-stationarity of price time series would be more appropriate. The model with trending data is specified as follows:

$$\Delta P_{ym} = \gamma + \alpha\Delta \cos\left(\frac{m\pi}{6}\right) + \beta\Delta \sin\left(\frac{m\pi}{6}\right) + u_{ym} \tag{6}$$

Seasonal factors can be computed from a pure cosine function as follows:

$$S_m = \lambda \cos\left(\frac{m\pi}{6} - \omega\right) \tag{7}$$

where $\lambda = \sqrt{\alpha^2 + \beta^2}$ and $\omega = \tan^{-1}\left(\frac{\alpha}{\beta}\right)$

The least square estimation of Equation (6) yields unbiased and consistent estimates. We use this equation to estimate seasonal price gaps. We juxtapose the results of the trigonometric model and the dummy variable model in Annex C for the sake of comparison.

2.2.3. Sensitivity analysis

We conducted sensitivity analysis with respect to four selected variables (OCC, harvest price, cost of the storage facilities, and service life of the storage facilities). We varied (up and down) the base values of OCC, harvest price, and costs of storage facilities by 20%, the service life of the bags by one year, and the service life of metallic silos by five years. Moreover, we estimated the breakeven values for two selected variables (seasonal maize price gap and maize price level) and showed the potential tradeoffs between them.

2.3. Measuring potential impacts at household level

Potential impact of using the improved storage practices were estimated based on data on the on-farm experiment and Tanzania Africa RISING baseline survey (TARBES). Details on the sampling procedure can be found in Charles (2015) while the data is available at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=%3ca%20href=title = "https://dataverse.harvard.edu/dataset.xhtml?persistentId = doi:10.7910/DVN/PPUL2W">https://dataverse.harvard.edu/dataset.xhtml?persistentId = doi:10.7910/DVN/PPUL2W. Impacts were assessed from two angles: from the food-security angle and from the income angle. We considered maize grain availability at household level for consumption to address the first angle and maize marketable surplus to address the second. Households were classified into two categories (surplus-producers and non-surplus-producers) based on households' level of maize production when compared to the average maize consumption in Tanzania. The average maize consumption was computed based on FAO food supply data for the years 1990–2013 (http://www.fao.org/faostat/en/#data/FBS), Lukmanji et al. (2008), NBS and MFP (2016), and TARBES data. The result shows an average per capita maize consumption of about 0.27 kg/day. This means that a kilogram of maize can be used for about 4 days for a person. Surplus producing (SP) households were defined as those households which were self-sufficient in maize production all the time in a year while also producing some surplus for sale. Households in this category were considered as having two main objectives to achieve i.e. optimizing household consumption from own maize stock (food security objective) and maximizing income from grain sale (income objective). Non-surplus producing (NSP) households were defined as those households whose maize outputs were less than or equal to their consumption requirements. It was assumed that households in this category would have a single objective of optimizing household maize consumption (i.e. food security objective). About 79% of the sample households were surplus producers while the remaining households were non-surplus-producers. The mean amount of marketable surplus among the SP households ranged from about 1.8t in Kongwa to about 2.5t in Kiteto with the mean figure of about 2t. The NSP households produced, on average, 67% of their consumption requirements in Babati, 52% of their consumption requirements in Kongwa, and 72% of their consumption requirements in Kiteto.

We estimated the potential impact on food security based on the loss abated whereas we estimated the impact on income based on the net returns obtained when farmers shift grain sales from the harvest season to the lean season. We also assumed that households would store grain for consumption and for sale in the same facility. This is particularly relevant for those households who would decide to use metallic silos due to its high fixed cost and that it may not be feasible for some households to buy separate facilities for consumable and marketable grains.

2.3.1. Impact on household food security

We assume that farm households use part or all of their maize produces for consumption. Let Y be the amount of maize a household allocates for consumption. This amount has to be stored and released in installments for consumption as consumption spreads over time. Let K be the consumption requirement of the household in one period. The amount of stored grain would decline by K amount in each period such that $f(t_0) > f(t_1) > ..f(t_{n-1}) > f(t_n)$, and $f(t_n) \cong 0$ (where "n" implies the end of the year for surplus producing households). The series of household grain balance is $f(t_1) = Y - K$, $f(t_t) = Y - 2K$, $\ldots f(t_n) = Y - nK$. This can be generalized as $f(t) = Y - tK$, where t = 1, 2, …, n.

Suppose that the stored grain is subject to loss due to insect pests and $g(t)$ represents the marginal percentage of grain weight loss during the tth period. The amount of loss at household level at the end of each period will be given by the pattern $h(t_1) = (Y-K)g(t)$, $h(t_2) = (Y-2K)g(t_2), \ldots, h(t_n) = (Y-nK)g(t_n)$.

Let $k(t)$ be the cumulative distribution of the amount of grain loss at household level over time. If discrete distribution is assumed

$$k(t) = \sum_{t=1}^{n} f(t)h(t), \tag{8a}$$

and for the continuous time case,

$$k(t) = \int_{t=1}^{n} f(t)h(t)dt = f(t)\int_{t=1}^{n} h(t)dt - \int_{t=1}^{n} f'(t)\left[\int_{t=1}^{n} h(t)dt\right]dt \tag{8b}$$

where $f'(t)$ refers to the first derivative function of $f(t)$.

$f(t)$and $h(t)$ can be estimated from empirical data. We use ARBES data to estimate $f(t)$ and the on-farm experiment data to estimate $h(t)$.

Equation (8a) (or Equation (8b)) shows the loss abatement effect of the improved storage. However, this effect is not without costs. Rather, it involves costs of the improved storage facilities which would affect food security negatively. The latter effect is visible particularly among the NSP households as the additional costs of the improved storage facilities would reduce their entitlement to food by reducing their purchasing power. Therefore, the net effect of the improved storage on food security will be the difference between its positive effect on food availability (loss abatement effect) and its adverse effect on food access. This can be presented as:

$$F = k(t) - \frac{1}{p_0}(C_I - C_T) \tag{9}$$

F is households' net food reserve; k(t) is the amount of grain saved from loss at the specified storage time (t), C_I is annualized cost of improved storage structure, C_T is annualized cost of traditional storage structure, and p_0 is grain price at harvest.

Equation (9) shows the direct effect of improved storage on food security. In addition, improved storage can affect household food security indirectly by avoiding the “sell low, buy high” situation in which farmers sell their maize during the harvest season at low prices due to fear of storage losses and buy the grain during the lean season at high prices as their stocks run out of grain (Stephens and Barrett, 2011). However, one has to check whether the “sell low, buy high” situation (if exists) is attributable to storage losses before considering this indirect effect of improved storage. We use Equation (10) to test whether the “sell low, buy high” puzzle can be explained by storage losses (see Annex A for the derivation of Equation (10)).

$$\frac{Y_l}{Y_s} \geq \frac{s+1-(1+r)^t+\delta(1+r)^t+\gamma(s+1)}{s+1} \tag{10}$$

where Y_l is the expected amount of grain loss due to insect pest damage; Y_s is the amount of grain allocated for sale; s is seasonal price gap; δ and ϒ are coefficients associated with costs of selling and buying of maize grain, respectively; r is monthly discount factor; t is the number of months between the month of selling the grain and the month of buying it.

If the strict inequality in the equation holds true, the “sell low, buy high” puzzle can be justified by the presence of storage losses. In that case, the indirect effect of improved storage on food security can be computed by using the following equation. One of the assumptions behind this equation is that farmers will sell one-half of their consumption grain immediately after harvest and store the remaining one-half for consumption until the lean season.

$$F' = \left(\frac{1}{2}\omega_T - \omega_I\right)Y - \frac{1}{p_0}(C_I - C_T) - \frac{1}{2}Y\Big[(1-\delta)(1+r)^t - (1-\gamma)(1+s)\Big] \tag{11}$$

where ω_T is the GWL under traditional storage, ω_I is the GWL under improved storage while the other symbols are as defined earlier.

Finally, the total potential effect of using improved storage on household food security can be estimated by adding the outputs of Equation (9) and Equation (11).

2.3.2. Impact on household income

The impact of improved storage on income has to do with households who have some surplus to sale. The effect on income arises from two sources. The first one is associated with the fact that improved storages will enable households to engage in temporal arbitrage of maize who otherwise would sell their grain immediately after harvest at low prices. We call this the *temporal arbitrage effect*. The second one is associated with their effect on the amount of marketable grain by avoiding loss due to insect pest damage which is dubbed here as the *loss abatement effect*. Let S be the amount of maize which a household allocates for sale such that S and Y (as defined above) add up to the household's total maize production. Suppose that a household allocates S_1 amount of grain for sale in the absence of the improved storage facilities and S_2 in the presence of the improved storage facilities. Further, assume that consumption gets priority to selling among households i.e. selling occurs when households' consumption needs are met. In the absence of improved storage, households are expected to allocate more self-produced grain for consumption than they would do in the presence of improved storages due to expected grain loss in the former case. Thus, S_1 is greater than S_2. This implies also that the difference between S_1 and S_2 can be equated to $k(t)$ (as defined above). Then, the potential impact on household income (I) can be computed as:

$$I = \varphi p_0[S_1 + k(t)] - c_v - r_1\frac{m}{12}[p_0(S_1 + k(t)) + c_v] - \Re K \tag{12}$$

where $\psi = (1+s)(1-v)(1-w)$, for brevity.

By rearranging terms, Equation (12) can be put as:

$$I = \underbrace{\left[\varphi p_0 S_1 - c_v - r_1\left(\tfrac{m}{12}p_0 S_1 + c_v\right) - \Re K\right]}_{\text{Temporal arbitrage effect}} + \underbrace{\left[\varphi p_0 k(t) - r_1\tfrac{m}{12}p_0 k(t)\right]}_{\text{Loss abatement effect}} \tag{13}$$

3. Results

3.1. Storage loss and price seasonality

Fig. 1 shows grain weight loss (GWL) and total grain value loss (TGVL) under the polypropylene bags. The GWL and TGVL associated with PICS bags, PP bags plus Actellic Super, and metallic silos are not included in the figure since they are negligible. The grain weight loss goes up to 70% at the end of the 52nd week. This would translate to 100% grain damage. The TGVL is about 96% at the end of the period. The difference between the GWL and TGVL shows the percent of revenue loss associated with price discounts on damaged grains. The difference is small in the first few weeks while it gets bigger in the course of time arising from bigger price discounts associated with bigger grain damages.

We tested for non-stationarity (unit roots) of the price data series based on the Augmented Dickey-Fuller procedure (Greene, 2008). The results show that the series associated with all locations are non-stationary and are the result of I(1) process which means that taking the first difference of the original series would produce a stationary (non-trending) process. Thus, we used the trigonometric model with trending data to estimate seasonal price gaps. The results are displayed in Fig. 2. The model identified July as the lowest price month in all locations. This is consonant with the data we collected through key informant interviews. Seasonality is significant at 1% alpha level. It means that one cannot ignore the seasonal nature of maize grain supply in explaining price movements. The seasonal price gap varies between 32% and 55% depending on location. Kongwa takes the highest position in terms of seasonal price gap and Babati takes the lowest. Kiteto lies in between but it is located closer to Kongwa than to Babati.

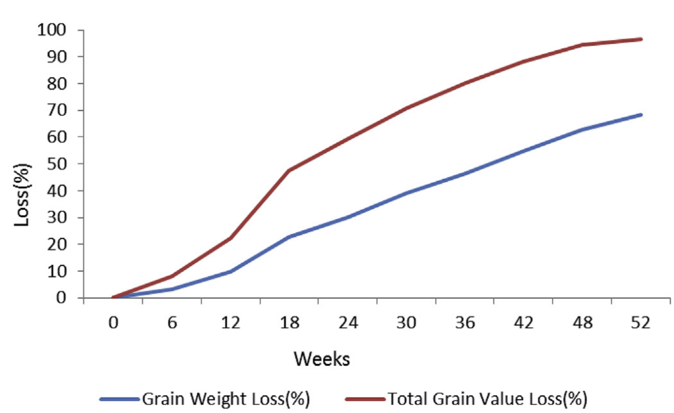

Fig. 1. Maize storage losses under polypropylene bags.

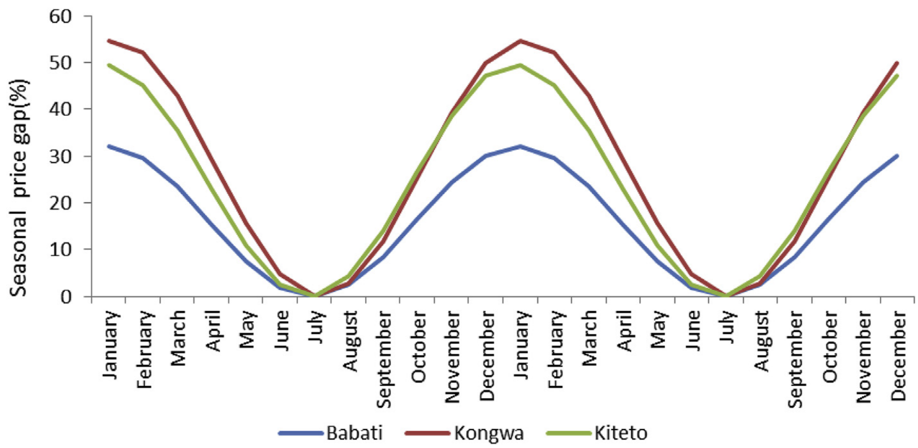

Fig. 2. Estimated seasonal maize price gaps in the study areas.

3.2. *Profitability of the storage technologies*

The results on profitability of PICS bags, PP bags plus Actellic Super, and PP bags are shown in Fig. 3. The curves associated with PICS bags and PP bags plus Actellic Super overlap which shows that the application of the two storage options result in similar financial returns. Thus, we report the results from the two technologies in a combined manner referring to as PICS (Actellic Super). Profits vary by months in which grain sales are expected to occur. They are negative if farmers sell their maize in the first two months after harvest (August and September) and in the last two months before the next harvest (May and June). This holds true for all locations and storage types. October to March is the profitable period for temporal arbitrage in all locations when PICS (Actellic Super) is used for storage. The highest profit is earned when the produce is sold in January. The length of the feasible period (i.e. when profit is greater than zero) for PICS (Actellic Super) is longer by one month in Kongwa and Kiteto than in Babati. This is because of the weak price seasonality observed in Babati. Polypropylene bags without chemical treatment is not feasible in any month and location while the loss associated with this storage facility monotonically increases as the duration of storage increases.

Metallic silos have shorter feasible periods than PICS (Actellic Super) (Fig. 4). This is due to the high cost of metallic silos as compared to PICS (Actellic Super). The length of the feasible period of metallic silos varies by location and their storage capacity. The longest feasible period is associated with the 2t silo (Silo20) and the 1.5t silo (Silo15) in Kongwa and Kiteto (October–March) while the shortest one is associated with the 1t silo (Silo10) in Babati (December and January). Metallic silo of sizes 0.5t (Silo5) is not profitable in Babati and Kiteto in any month.

Fig. 5 shows the mean profit that farmers may make when they sell their maize during the lean season (November–March). The mean profit varies across locations arising from differences in seasonal price gaps and harvest price levels. In the case of PICS (Actellic Super), profits are all positive ranging from \$16/t (in Babati) to \$41/t (in Kongwa). Metallic silos are associated with both positive and negative profit depending on size and location. Profit increases monotonically with silo size where bigger size silos show positive profit in some locations. In Kongwa and Kiteto, silos having one ton or bigger storage capacity are profitable generating profit of \$5 to \$28 per ton of grain stored. In addition, Silo5 is profitable in Kongwa. In Babati, Silo20 is marginally profitable while Silo15 would breakeven. As expected, polypropylene (PP) bag without

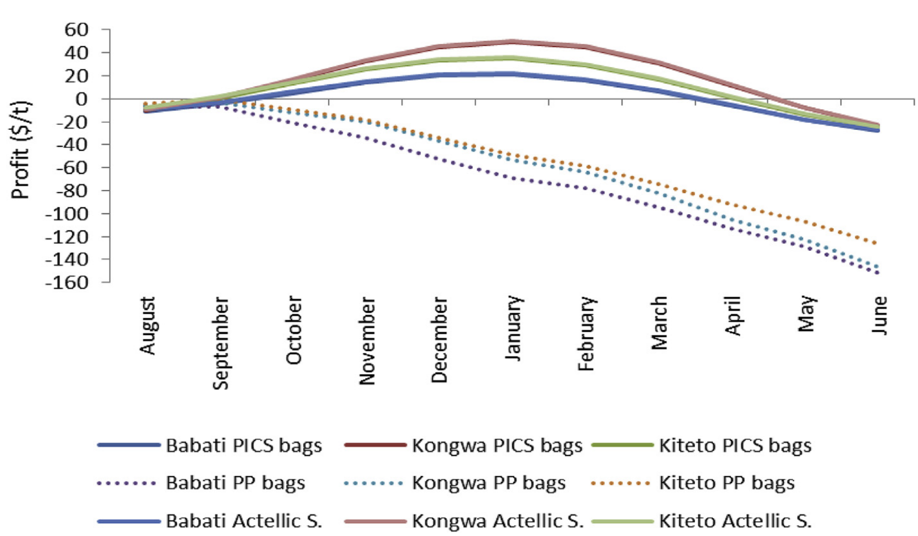

Fig. 3. Profitability of using PICS bags, PP bags plus Actellic Super, and PP bags for maize storage.

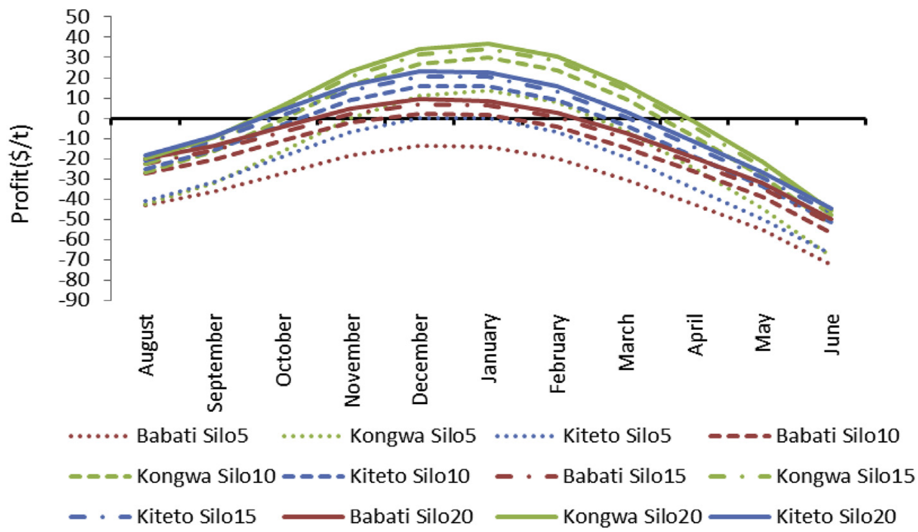

Fig. 4. Profitability of using various sizes of metallic silos for maize storage.

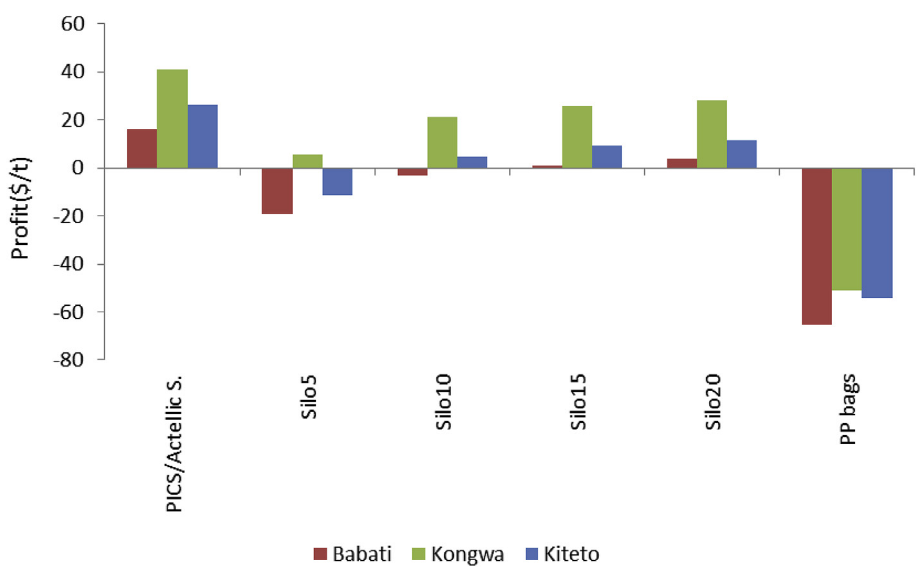

Fig. 5. Mean profits associated with storage technologies, lean season sale.

chemical treatment is associated with big losses in all locations as shown in the figure by the elongated downward facing bars.

The results of sensitivity analysis show that changes in OCC, price of maize, price of storage structure, and service life of storage structure will affect profitability substantially although most of the storage options remain in the feasible set. The core feasible set (cases which are consistently associated with positive profit given that the changes in the above four factors would occur) constitutes PICS bags (Actellic Super) in all locations, S10, S15, and S20 in Kongwa and Kiteto while the remaining cases are either not feasible within the range of the scenarios we considered or they change positions between the scenarios. If OCC increases, Silo5 in Kongwa, Silo15 in Babati, and Silo20 in Babati will be excluded from the feasible set of the base scenario; if it decreases, Silo5 in Kiteto and Silo10 in Babati will be added to the feasible set. The average profit of the core feasible set is about $20 per ton of stored grain for the base scenario. The increase (decrease) in OCC will result in a decrease (an increase) of the average profit of the core feasible set by 14% (28%). Two cases will be added to the feasible set of storage structures if the price of maize increases namely: Silo5 in Kongwa and Silo10 in Babati. In this case, the mean profit will increase by 49%. If maize price decreases, Silo5 in Kongwa, Silo15 in Babati and Silo20 in Babati will be excluded from the feasible set while the mean profit will decrease by 34%. The reduction of prices of the storage facilities will make profitable Silo5 in Kongwa and Silo10 in Babati while the increment of the prices will exclude Silo5 in Kongwa, Silo 15 in Babati, and Silo 20 in Babati from the feasible set. The increment of the service life of the storage structures will not affect the composition of the feasible set but it will increase the average profit by 18%. However, the reduction of the service life of the storages structures will exclude Silo5 in Kongwa and Silo15 in Babati from the feasible set and will reduce the average profit by 22%.

Fig. 6 shows breakeven-level iso-profit curves with respect to

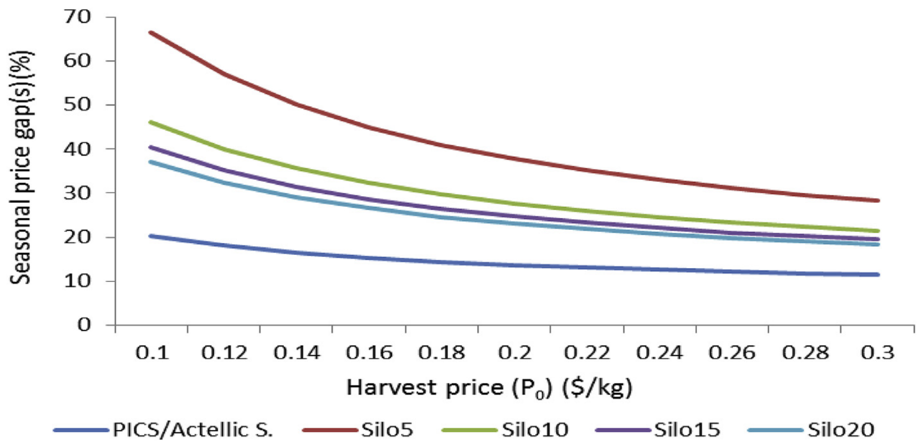

Fig. 6. Breakeven values of maize price at harvest and seasonal maize price gaps.

two selected variables in our model namely: maize price at harvest and seasonal maize price gap. It shows that the higher becomes the maize price at harvest the lower would be the minimum seasonal price gap required to achieve breakeven in the storage business, and vice versa. Moreover, it shows that PICS bags (Actellic Super) are associated with the smallest threshold values of both variables indicating that they have the widest feasibility horizon. Silo5 takes the other extreme while the remaining silos are found in between. The pattern of the iso-profit curves also show that feasibility horizon of metallic silos increases with their storage capacity.

3.3. *Potential impact the storage technologies on household food security*

We estimated the impacts of using the improved storage technologies on household food security based on Equation (9) as our test for the "sell-low, buy high" puzzle did not justify early selling because of storage loss. (The result of the analysis of the "sell-low, buy-high" practice is found in Annex B.) Results show that PICS (Actellic Super) has a positive potential impact on household food security with some variation among household categories and locations (Fig. 7). The impact among the NSP households is about 40 kg of grain which can sustain an average household of having six members for more than three weeks. The impact among the SP households is about 157 kg equivalent to 14 more food secure weeks. Actually, the net gain of SP households is equivalent to the quantity of maize to be added to marketable surplus grain when SP farmers use PICS bags (Actellic Super) instead of polypropylene bags without chemical treatment. The net benefit of the NSP households from the improved storage technology is substantially low as compared to the benefit of the SP households. This is because of the fact that households in the NSP category produce small amount of maize which would be consumed before storage pests cause substantial damage to the grain. There is a slight difference among the three locations in terms of impact figures which is visible particularly when we consider NSP households; Babati takes the highest position and Kongwa takes the lowest.

Metallic silos can save from loss 13–32% of the total grain allocated for consumption among the farm households. The mean net positive effect is about 50 kg for SP households. However, the net effect is negative among NSP households as the big investment associated with this technology outweighs its loss abatement effect. Actually, the maize available for household consumption will decrease by about 90 kg if NSP households finance the silos from their maize production; this amount can sustain the household for about seven weeks (Fig. 7).

3.4. *Potential impact of the storage technologies on household income*

Fig. 8 displays the potential financial benefit of the sample households (surplus producers) if they would participate in

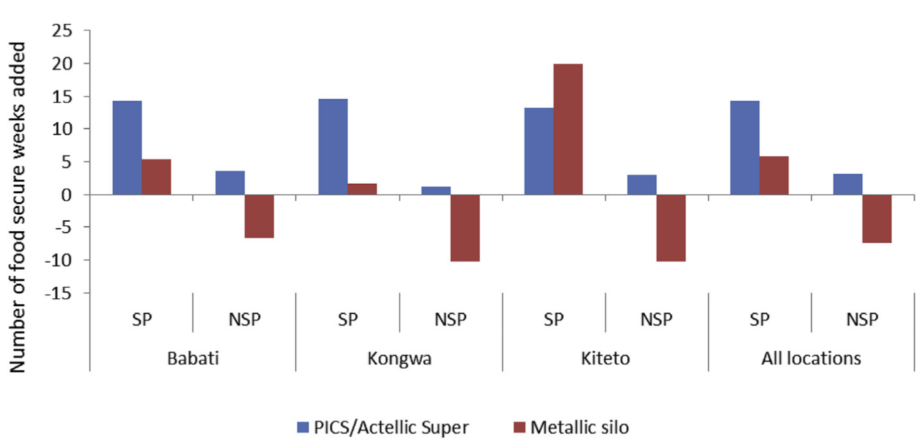

Fig. 7. Potential impact of improved storage technologies on household food security.

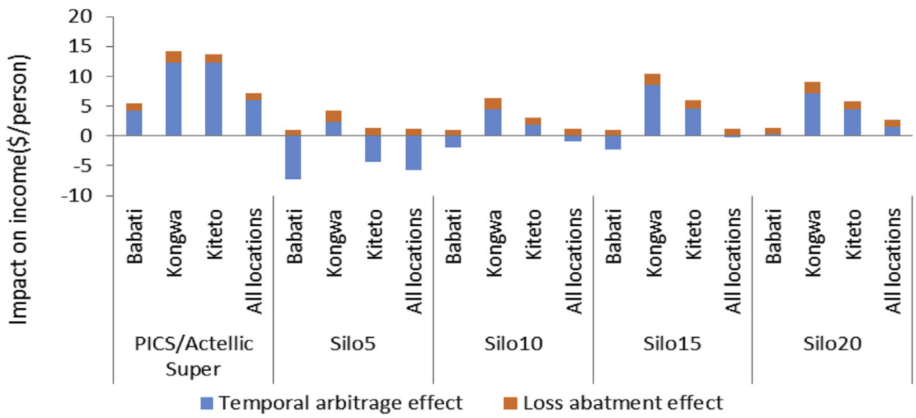

Fig. 8. Potential impact of using improved storage technologies on income (USD/person).

temporal arbitrage of maize by making use of the improved storage options. We assumed that, in the process of storage, farmers would combine different types and sizes of storage facilities to minimize diseconomies of scale. The potential benefits vary by storage types and locations. Using PICS (Actellic Super) for maize storage can have positive potential impact on income in all locations. The mean impact ranges from $5 per person (in Babati) to $14 per person (in Kongwa). Most of the impact is attributable to the temporal arbitrage effect of the storage (82%). Metallic silos have mixed effects on income depending on their size and the location where they are used. Silo20 is associated with positive potential impact in all locations with the impact varying from $1 per person (in Babati) to $9 per person (in Kongwa). Silo10 and Silo15 can also have positive impact on income in Kongwa and Kiteto while they are associated with negative impacts in Babati. Silo5 has positive potential impact only in Kongwa.

4. Discussion

Our results show that the total value loss of stored maize grain is substantially high particularly when polypropylene bags are used (without chemical treatment) for three months or more while the losses associated with the improved storages techniques are negligible. This is in agreement with some other studies elsewhere in Africa (De Groote et al., 2013; Baoua et al., 2014; Chigoverah and Mvumi, 2016). However, storage loss under the traditional system is too low during the first two months and, hence, investment in improved storage facilities is not economically feasible for such a short duration of grain storage.

The profitability of the improved storage structures depends, among others, on seasonal grain price gap which we considered in our analysis. Seasonal price gap for maize grain varies between 32% and 55% depending on location; Babati and Kongwa are on the lowest and highest sides, respectively. These are sizeable gaps which imply the existence of high potential for those farmers who would like to engage in temporal grain arbitrage. Previous studies on temporal maize prices variations in Africa also show the existence of high seasonal price gaps (Sahn and Delgado, 1989; Kaminski et al., 2016; Gilbert et al., 2017). For instance, Kaminski, et al. (2016) estimated the average seasonal maize price gap at 27% for 20 markets in Tanzania whereas Gilbert et al. (2017) found an average maize seasonal price gap of about 33% among several African countries. Our estimates are a bit higher than the findings of these studies perhaps because, in both studies, samples included markets characterized by two harvest seasons where price seasonality is low.

PICS bags are profitable given the existing maize price seasonality and maize price level. While the profits vary by location arising from spatial differences in seasonal price gap, the figures are sufficiently greater than zero in all locations. Profit will remain positive even if the seasonal maize price gap becomes less than 20% at farm gate harvest price of $130/t (i.e. average of 2014–2016) while a better performance can be realized when the price is higher. Moreover, PICS bags have a feasibility period of at least six months (October to March), which is wide enough to accommodate the marketing schedules of most of the farmers. These results show the cost effectiveness of PICS bags strengthening the conclusions of some other studies in Africa (Jones et al., 2014; Ndegwa et al., 2016). However, PICS bags are not profitable if farmers sell their maize during the first two months due to low grain prices and low grain loss and if farmers sell their maize during the last two months before the next harvest due to low grain prices and high opportunity cost of capital. Similarly, Ndegwa et al. (2016) reported a negative marginal rate of return (marginal cost greater than marginal revenue) associated with PICS bags in the context of early sales of maize. PP bags plus Actellic Super performs as good as PICS bags and hence, on economic ground, the two storage technologies are good substitutes to each other. However, for public health reasons, using insecticides on staple food is not recommended particularly in places where farmers do not have trainings on the codes of application (Abass et al., 2018).

Metallic silos are the other improved storage facility which are effective in protecting grains from insect pest damage (De Groote et al., 2013; Chigoverah and Mvumi, 2016; Abass et al., 2018). Our results show that metallic silos of one ton or bigger storage capacity are profitable in Kongwa and Kiteto while the financial benefit of using smaller silos is not justified. Previous studies also show that size would matter for economic feasibility of metallic silos i.e. the bigger the size the more profitable they would be (Kimenju and De Groote, 2010; CIMMYT, 2011). The implication is that farmers having bigger marketable surplus maize are more likely to benefit from the adoption of metallic silos than their counterparts. However, most of the options of metallic silos we considered are not profitable in Babati due to the weak price seasonality observed in this location suggesting that some level of subsidy would be required to realize adoption. The results also imply that metallic silos are more feasible as maize storage when grain price is high, seasonal price gap is not too low and/or market transaction cost is not too high to offset the price premium, and farmers have economies of scale to use large capacity silos.

The potential impacts of the storage options on food security and income are mixed depending on the storage method. Using

PICS bags or PP bags plus Actellic Super instead of PP bags without chemical treatment can increase the availability of maize grain for household consumption. Moreover, the income of farm households is expected to increase by 30–84 US dollars per year if these technologies are applied. While the increment of grain availability for household consumption is due to the loss abatement effect of the improved technologies (De Groote et al., 2013; Abass et al., 2018), the income gain arises from temporal grain arbitrage which would enable farmers to benefit from higher grain prices during the lean season (Bokusheva et al., 2012; Jones et al., 2014). The potential impact of metallic silos on household food security is marginal or negative although silos can save 13–32 percent of households' stored grain from insect damage. The net effect is negative or marginally positive because of the high costs associated with metallic silos. Nevertheless, the potential impacts of bigger metallic silos on household income are positive. Positive impacts on income can be realized particularly in areas where seasonal price gaps are sufficiently high to offset the high investment costs. Contrary to our results, a study in Central American countries shows that metallic silos could improve food security and well-being among adopters (Bokusheva et al., 2012). In fact, this happened in the presence of subsidies and free donations of metallic silos to farmers by governments and NGOs.

The results imply that PICS bags or PP bags plus Actellic Super have higher probability of adoption than metallic silos among farmers having diverse amounts of marketable surplus. Indeed, targeting bigger maize farmers may lead to a better adoption of metallic silos while a non-targeted dissemination strategy may yield better results for PICS bags and Actellic Super. Moreover, PICS bags and Actellic Super are more suitable to single-season as well as double-season farming systems as compared to metallic silos due to the lower costs of the former. In fact, metallic silos are less likely to be profitable in double-season farming systems where seasonal price gaps are low (Kaminski et al., 2016; Gilbert et al., 2017). However, metallic silos can be preferable in terms of some other merits. One of the merits of metallic silos is that they are much more durable than PICS bags, which may be useful to reduce the transaction costs of accessing storage facilities and to minimize the risks associated with price inflation. Our results also show that profitability substantially improves when service lives of the storage facilities increase and/or when prices of the facilities decrease. Therefore, training on proper handling of the storage structures can increase their service lives thereby improving their profitability. Moreover, efforts should be made to reduce the cost of production of the storage structures (particularly that of metallic silos) so that the current price will come down to make the facilities more attractive to smallholder farmers. Furthermore, alternative hermetic storage technologies such as plastic silos, which are much cheaper than metallic silos and with similar efficacy against storage pests, need to be tested (Ndegwa et al., 2016; Abass et al., 2018).

Finally, an important caveat applies to our findings. We considered insect pests as the only cause of storage grain loss in our analysis. The addition of other factors (such as rodents and fungi) into analysis may change our conclusion as the storage options may have different levels of efficacy against different agents of grain loss. For instance, metallic silos are more effective than hermetic bags to protect grains from rodents while both technologies are equally effective against insect pests (Abass et al., 2018). Therefore, the outcomes of this study will be applicable to locations where insect pests are the most important cause of grain loss in maize.

Declaration of statement of interest

The authors declare that there is no conflict of interest in this manuscript.

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Annexes

A) Testing the "sell low, buy high" puzzle

Consider that the "sell low, buy high" phenomena arises when a farm household makes decisions to smoothen its intra-annual maize grain consumption. Let us assume that a household has decided to sell Y_s amount of its total maize grain allocated for consumption (Y) in fear of potential storage loss, denoted by Y_l. Suppose the household made this decision with the expectation that it would buy the same amount of grain from the market when the need arises. Suppose the household also knows, from past experiences, that it would pay higher prices to get the same amount of grain during the lean season. Under the assumption of rational choice, the following relationship will prevail:

$$Y_s p_1 - Y_s p_0 (1+r)^t + C_s + C_b \le Y_l p_1 \tag{A1}$$

where p_0 and p_1 are maize grain prices prevailing immediately after harvest and during the lean season, respectively; C_s and C_b are costs of selling and re-buying the grain, respectively;

Let $p_1 = p_0(1+s)$, where s refers to the price seasonality factor, r is monthly discount factor and t is the number of months between the month of selling the grain and the month of buying it. Assuming that the cost of selling (buying) the grain is proportional to the value of the grain at the time of selling (buying) and letting δ and γ be coefficients associated with selling and buying transactions respectively, the following equation can be derived from Equation (A1).

$$\begin{aligned} & Y_s p_1 - Y_s p_0 (1+r)^t + \delta Y_s p_0 (1+r)^t + \gamma Y_s p_1 \\ & \le Y_l p_1, \ 0<\delta<1, \ 0<\gamma<1. \end{aligned} \tag{A2}$$

After a few algebraic processes, we will arrive at the following relationship:

$$\frac{Y_l}{Y_s} \ge \frac{s+1-(1+r)^t + \delta(1+r)^t + \gamma(s+1)}{s+1} \tag{A3}$$

If we assume the coefficients of marketing are the same for selling and buying transactions, Equation (A3) will be reduced to the following equation:

$$\frac{Y_l}{Y_s} \ge 1 - \left[\frac{(1-\delta)(1+r)^t - \delta(s+1)}{s+1}\right] \tag{A4}$$

B) Results of "sell-low, buy-high" analysis

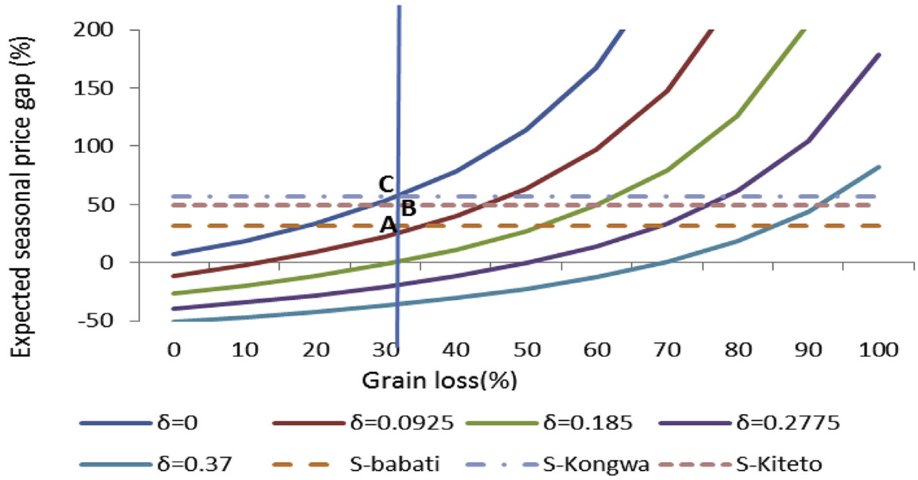

Fig. B1. Interplay of factors for early grain sales.
Note: The broken lines are the price gap lines for the three districts while the vertical line shows the grain loss under PP bags without chemical treatment. Points A, B, and C show the minimum thresholds to justify the association of the "sell-low, buy-high" practice with storage losses as demonstrated in Equation (A4). Since these points are above the curve which displays the average marketing cost (i.e. the green curve), we can conclude that the "sell-low, buy-high" practice is not induced by storage losses.

C) Trigonometric model vs linear model results of seasonal price gaps

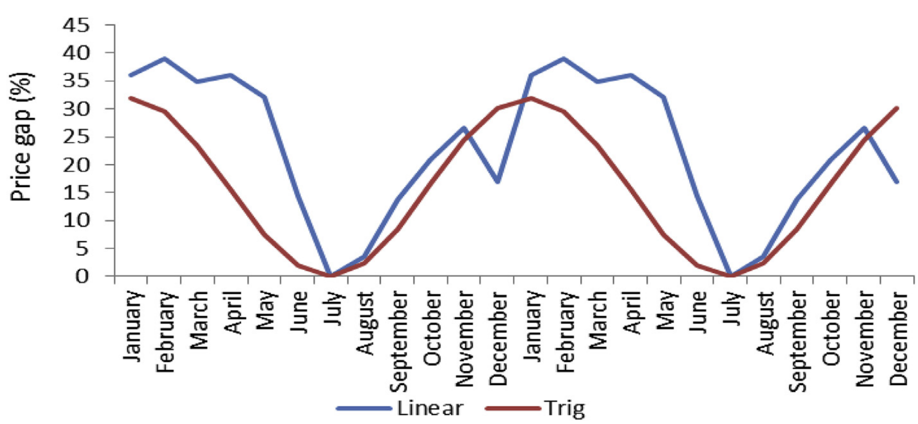

Fig. C1. Estimated seasonal price gaps in Babati using the trigonometric & the linear models3

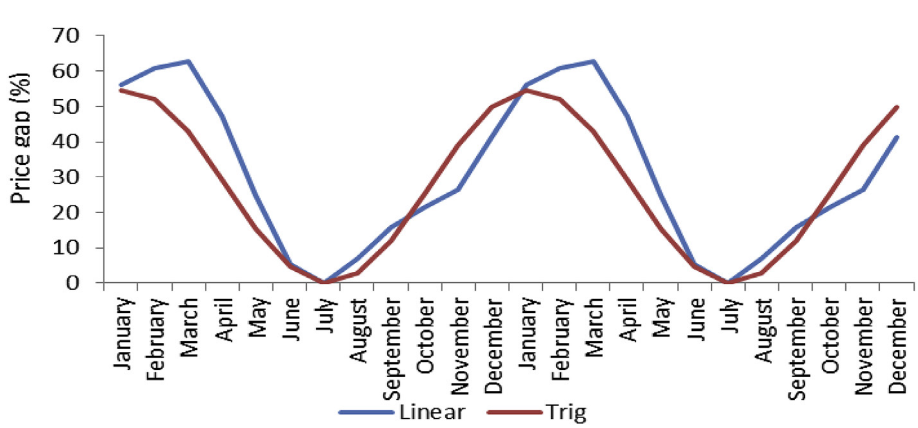

Fig. C2. Estimated seasonal price gaps in Kongwa using the trigonometric & the linear models4

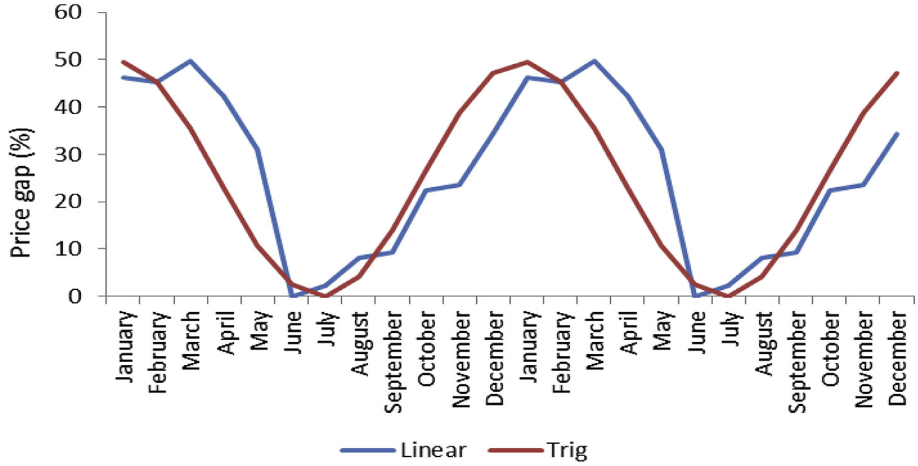

Fig. C3. Estimated seasonal price gaps in Kiteto using the trigonometric & the linear models

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