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Smallholder food storage dynamics and resilience

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Abstract

For smallholder farmers in developing countries, agricultural production is seasonal yet food demand is constant throughout the year. One fundamental agricultural decision is how much harvest to sell versus store for subsequent household consumption. Little is known about the temporal dimensions of grain storage, the extent to which storage levels vary over time, and the diversity of food storage patterns across different household types. This paper examines household level maize storage consumption, sales, and purchases using weekly food storage data collected via text message. We demonstrate how high frequency data can be used to measure rates and patterns of food storage decline, identify thresholds of food security, and anticipate future periods of food insecurity at a fine spatial scale.

Keywords Food storage · Resilience · Maize · Africa · Zambia

1 Introduction: Food storage and resilience

Food storage, specifically grain storage, is often used as a buffer against food insecurity for subsistence households. Storage is crucial since grain production is seasonal while food demand is constant (see Fig. 1). Decision making regarding food storage is just as critical as crop and production management when it comes to food security. Smallholders are fundamentally limited by total harvest but most households make highly dynamic decisions that affect their food reserves such as how much to sell at the end of the harvest season, whether to provide food in exchange for labor from another household, and how to acquire additional food if reserves run low.

Explanations for the lack of market participation among smallholders vary, but subsistence farming remains an important mechanism to reduce the vulnerability of households to market price fluctuations (Baiphethi and Jacobs 2009; Omamo 1998a; Omamo 1998b; Key et al. 2000). For example, many authors have found that when farmers do engage with the market, they often sell right after harvest for a low price, and buy back later in the season at higher prices, largely driven by credit constraints (Burke et al. 2017; Stephens and Barrett 2011; Park 2006). These households are then vulnerable to unexpected price spikes later in the season. Thus, storing their own primary grain production for consumption throughout the year may be an optimal response to potential price risk, transactions costs and imperfect credit markets (Saha and Stroud 1994).

Given the heavy reliance of farmers on their own grain production, storage decisions are central to food security. Primary grains occupy the largest area of the farm for many smallholder farmers and comprise the majority of a household's caloric intake (van Ittersum et al. 2016). Little attention is given in the literature to the dynamics and decision-making involved in grain storage and the implications of food storage for household resilience. By examining the entire cycle of food production, we are able to examine the relationship between food storage and sales and the relationship of food storage to household resilience.

The concept of resilience has emerged as a lens through which scholars characterize the dynamics of social–ecological systems, which often follow nonlinear paths and result in multiple stable states and tipping points (Folke 2006). The concept draws on earlier conceptualizations of ecological systems

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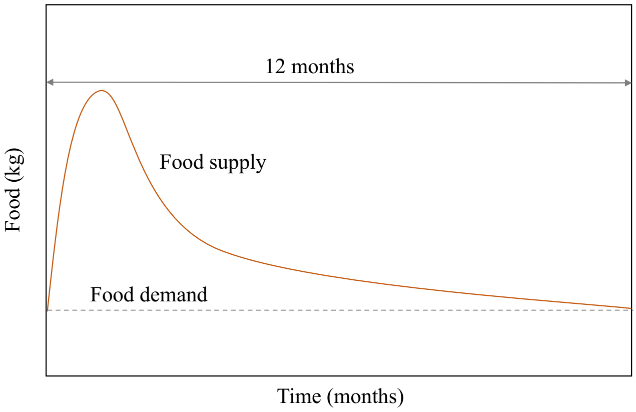


Fig. 1 Conceptual figure illustrating constant food demand and seasonal food supply

and farming systems research, which focus on multiple basins of attraction (such as Fresco 1988). Resilience, in a more contemporary context, can roughly be defined as managing the capacity of a social–ecological system to adapt to and shape change (Smit and Wandel 2006; Janssen and Ostrom 2006). Resilience often focuses on theoretical models of ecological relationships but has more been recently applied to international development (Barrett and Constas 2014), the global food system (Seekell et al. 2017), food security (FAO 2015), and food production and distribution of food. We apply the concept of resilience as a lens to understand the dynamics of food storage, which are often characterized by thresholds, nonlinear dynamics, and uncertainty.

Food storage is a fundamental characteristic of food systems in Sub-Saharan Africa. Resilience requires a household or person to maintain an adequate amount of food in storage or have sufficient cash or a social network to support them if their storage is depleted, especially in the face of various types of external shocks. Some households chronically produce insufficient quantities of maize to feed their households throughout the year, often because of fixed assets, such as small land holdings or insufficient household labor. Other households might find themselves with adequate or inadequate food storage in a given year depending on various types of income and asset shocks, including weather related production shocks (Carter and Barrett 2006). A second type of food storage shock are those that directly impact grain storage including pest and disease or the need of the household to draw down stocks at a more rapid rate than expected. Households that experience food shortage can cope by exchanging food or labor within their social networks. In this sense, the resilience of the overall food system is subject to the distribution of households that have adequate food supplies and the extent to which households that experience food shortages at different stages of the agricultural season can mitigate those shortages through social relationships.

The traditional model of storage supply is built on the behavior of profit maximizing firms as opposed to the more realistic network of smallholder farmers, small traders and processors, found in developing countries (Timmer 2012). Previous work has examined grain loss during harvest activities (Parmar et al. 2018), the effect of geographic and rainfall conditions on post-harvest grain loss (Hengsdijk and De Boer 2017), and modelled grain storage as a way to mitigate price risk. However, little attention has been devoted to changes in intra-annual staple crop storage and food storage as a type of resilience (Park 2006; Saha and Stroud 1994). Further, even fewer papers have tracked detailed grain storage levels throughout the year, and none have used a data approach that captures intra-annual short term decision making such as deploying frequent text message surveys. While recent work highlights inter-annual variation in food security, it is largely thought of in terms of food production and harvest, ignoring the recurring temporal dynamics associated with post-harvest smallholder food storage and sales (see Barrett 2010 for a discussion of food insecurity measurement).

The objective of this paper is to examine food storage from a resilience perspective. We evaluate smallholder resilience by examining food storage dynamics at a high temporal frequency (ie. through weekly surveys rather than annual) and assess the extent to which monitoring food storage dynamics can anticipate future food insecurity. We pay particular attention to changes in food storage over time and examine the amplitude and rates of change of food storage swings. We answer the following research questions: 1) Are food storage dynamics homogenous across households, as is often assumed in food security studies? 2) What is the amplitude of food storage swings inter-annually and are there patterns of food dynamics? 3) How can food storage dynamics be used to target food insecurity? We investigate these questions with smallholder farming households in Zambia, a country that faces frequent weather-related shocks and production shortfalls.

2 Background: Maize storage and dynamics of storage

Maize is one of the most important food security crops worldwide, providing about 20% of global calories (Brown et al. 1988), and is particularly important to the food and livelihood security of farmers in southern Africa, providing as much as 60% of an individuals caloric intake (Shiferaw et al. 2011). In the region, maize is largely grown without irrigation in a single growing season and is particularly susceptible to dry spells during flowering, rainfall variability, and growing season length. Climate change will create warmer, drier growing conditions in Sub-Saharan Africa (SSA) (Cairns et al. 2013). These changes and the resulting rise in abiotic and biotic stresses on maize particularly confound the problem of food security in Sub-Saharan Africa (SSA).. With the levels of warming that are predicted, the majority of currently cropped maize area is projected to experience negative impacts, with reductions in harvest ranging from 12% to 40% (Ramirez-Villegas and Thornton 2015). The increasing demand for maize and reliance on maize by a growing African population compounds the impact of climate change on food security. Without appropriate adaptation measures and given the challenges and projected growth in maize yields, food insecurity could afflict an even larger share of farmers in SSA (Shiferaw et al. 2011).

Production and storage of maize grain is the backbone of food security for many smallholder farmers, derived exclusively from their own farm production and steadily consumed throughout the year. Storage decisions can be the critical difference between survival and starvation. Maize and other traditional grains such as millet and sorghum serve as a form of savings for smallholder farmers and thus grain storage also has implications for household investments in education and future food security (Smale et al. 2016).

Food sales and monetization of small amounts of maize from storage post-harvest or during the lean season is common among smallholders. Non-poor households generally produce enough maize each season to feed the household, sell maize to purchase other household assets, and pay expenses such as school fees, medical costs, transportation expenses, and additional food (Dillon 2016). Many African farmers remain autarkic despite attempts to draw farmers into market participation through liberalization and large scale farm support programs (Jayne 1994). Explanations for lack of market participation among smallholders include high transaction costs (Omamo 1998a) and missing markets (de Janvry et al. 1991). Without adequate storage infrastructure and capacity, improving production will have little effect on farmer well-being (Abate et al. 2015).

Households in sub-Saharan Africa cultivate an assortment of agricultural systems (Tittonell et al. 2010), and often maize is the staple crop in both subsistence and cash crop systems (Byerlee and Eicher 1997). Maize as a regional staple crop makes up approximately 60% of the caloric consumption of the average household in Southern Africa (Denning et al. 2009), and, on average, is consumed at a rate of over 100 kg per person annually (Smale et al. 2011). During times of low grain storage, households may rely on wild fruits and vegetables and livestock to buffer against food shortages (Mavengahama et al. 2013; Thornton et al. 2007), but maize remains the dominant crop of importance regardless of the dietary situation in the households. As such, maize is the primary focus of most farm households and thus a valuable indicator of both future income flow and food insecurity.

A major hurdle to food security in sub-Saharan Africa is post-harvest losses of cereal grains during storage (Adams 1977; Tefera 2012). Grain storage takes place at multiple scales from the household level to community stores and co-operatives to large warehouses such as strategic grain reserves. Since most maize production is intended for consumption, smallholders store maize grains in makeshift granaries or in plastic sacks in their homes. These granaries can take on a range of various quality structures from seasonal to semi-permanent and permanent and are constructed of various materials such as mud, straw, wood, earth and brick. Post-harvest losses result from a variety of factors that occur during the harvesting process such as breakage, leakage, pests, and grain rot. (Tefera 2012). These issues may lead to maize losses in excess of 30% in various countries (Savary et al. 2019; Tefera 2012; World Bank 2011). Despite the majority of agricultural research having focused on increasing productivity, understanding how to better protect harvested grains is gaining importance around the globe (Savary et al. 2012). Much of the literature on grain storage focuses on crop losses and maize storage quality, particularly related to mycotoxins (Wagacha and Muthomi 2008).

3 Data and methods

3.1 High frequency data collection

This data comes from a sample of 750 farmers, each representing a single household, reporting maize storage by text message or short message service (SMS). Of the 750 households originally enrolled, 570 began responding to weekly survey questions related to food storage, creating a high frequency, spatially diverse sample of households, responding from October 2015 until present. Zambia has a unimodal rainfall pattern with the growing season and rainy season generally starting in November and lasting until April.

To select households, we contacted camp officers (similar to agriculture extension agents) and asked them to contact a community chairperson who invited an equal number of male and female farmers to a group meeting at a central location. If a farmer did not personally have a phone or was not literate or able to read English we asked if they had access to a phone or someone who could help them respond. All of these farmers were invited to participate and we collected their cellphone number and basic demographic data. Household locations of participating households are displayed in the inset in Fig. 2. Note that a larger sample of households across Zambia exists but we are only reporting on the 570 farmers located in Southern Province to highlight the microclimatic differences at a finer scale.

The weekly SMS surveys involved asking farmers very concise questions that required simple responses. They received the text messages at the same time every week. As they responded to the questions they were sent additional questions in succession. The maximum number of questions they could receive in a given week was eight and response rates begin to decline after receiving two questions. Data presented in this

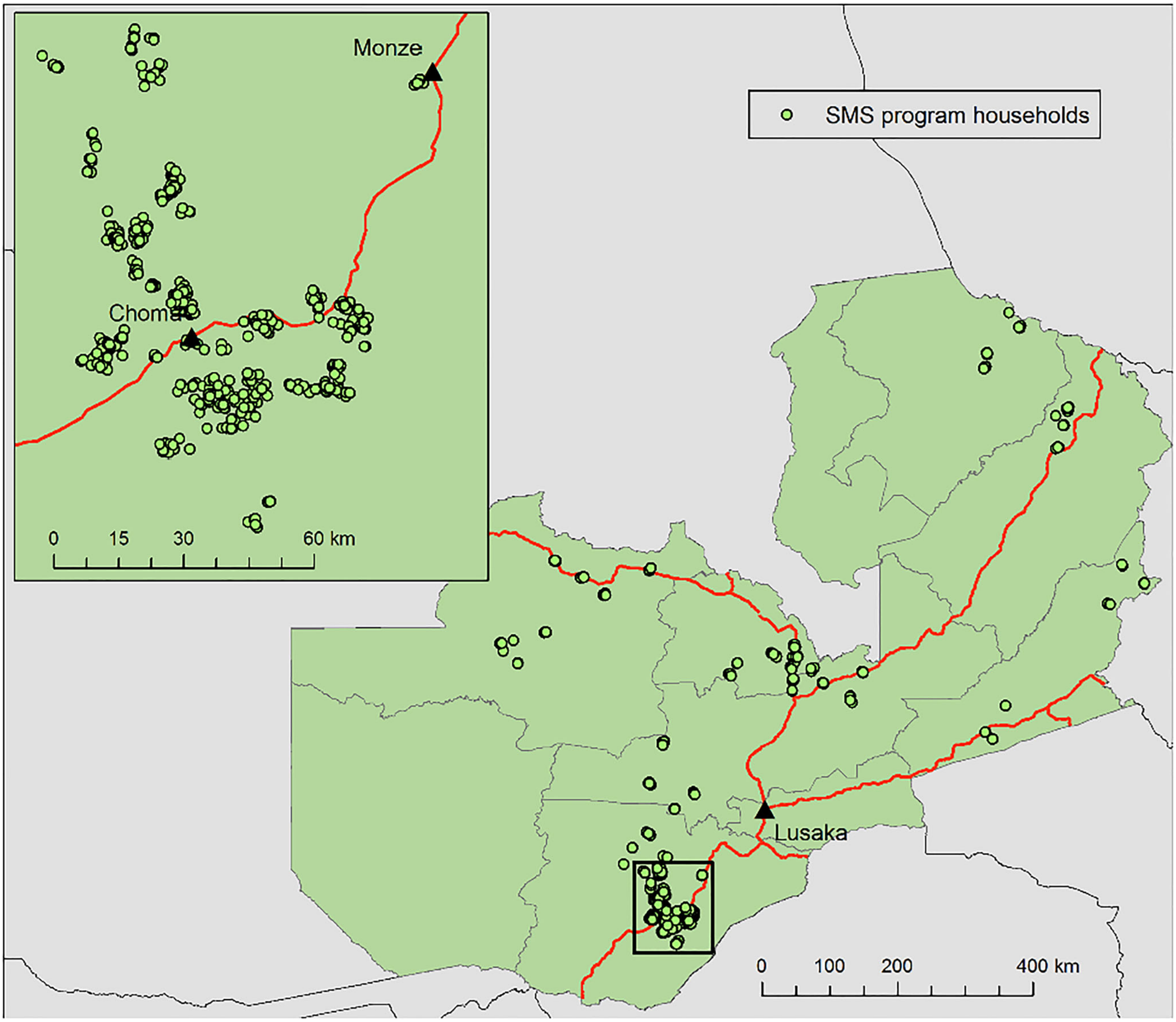


Fig. 2 Location of households participating in SMS data collection within southern Province

paper include responses to two questions: a) Did it rain on your fields in the last week (yes/no)? and b) And how many 50 kg bags of maize do you currently have in storage?

3.2 SMS methodology

SMS data present numerous challenges in cleaning and processing (Giroux et al. 2019). Text messages were sent to farmers using TextIt, a low-cost messaging platform developed by a Rwandan software company that allows users to create SMS or voice applications for data collection. We build the survey question sets, referred to as "flows," directly in TextIt, and these can be constructed to include skip logic or branching depending on the response to a prior question. Flows can also be designed so that respondents can be shifted from one set of questions to another based on their responses. An Android smartphone based in Lusaka runs the TextIt application that is used to remotely send and receive the survey questions and answers. As compensation for participating, farmers receive an amount of phone company credit each week directly to their phone, that covers all of their potential text message responses.

The survey questions distributed via text are constrained to be relatively simple due to the challenges involved in transmitting messages over text and the inability of farmers to have information at their fingertips. Binary responses are the most reliable and lead to the least amount of error, while multiple words are the most challenging to interpret. For example, it is challenging to ask farmers which seed varieties they planted due to problems interpreting the spelling of the variety name. There is much less error introduced when farmers are asked binary questions (ex. Did it rain on your field this week?) or numerical questions (ex. How many bags of maize do you have in storage now?), since the range of responses is more limited and can be interpreted more easily with misspelling.

Figure 3 displays the number of households who responded to SMS messages about the quantity of food in storage over the study period. As many as 300 out of the total 570 participating farmers responded in any given week, or just over 50% of the sample, while the average response rate is approximately 40%. There is a declining trend of the number of respondents in the data, showing farmer attrition either due to changes in phone numbers or lack of interest in responding. There are also numerous weeks with low response rates due technical issues in transmitting or receiving texts and periods where some farmers were receiving question flows that did not contain a question about storage.

To verify the accuracy of the SMS method we overlay rainfall data collected from a local meteorological station (labeled "met") with the percentage of farmers reporting rainfall in a given 7-day period (labeled "SMS"). Figure 4 shows that the SMS data roughly match the incidence of rain events across the study period. There are weeks at the tails of the rainy season where some farmers report rainfall (< 20% of farmers), yet the meteorological station does not record rainfall. The major advantage of collecting rainfall data via SMS is it provides a fine spatial resolution of rainfall events that is not captured by the sparse meteorological stations found across Africa.

We examine food storage dynamics by plotting SMS reported responses about rainfall occurrence and the quantity of food in storage over time. We assess storage patterns and measure the amplitude of both peaks and shortages of food storage. Rates of storage decline based on food consumption and previous consumption rates are estimated and used to predict food insecurity incidence.

4 Results and discussion

4.1 Maize storage and sales

As a result of the unimodal rainy season in southern Africa, farmers have one chance to produce a maize crop to feed them throughout the year. Food supply or maize in storage is thus generally the lowest towards the end of the growing season, while farmers wait for their new harvest to mature. The period from February to March is often referred to as the lean season and is known for having high rates of food insecurity (Lentz et al. 2019). Numerous factors influence the amount of storage a household maintains and thus there is wide heterogeneity among households' maize storage throughout the year. In as much as a household's food storage level represents a form of food savings and insurance against shortages or price hikes, the storage level can also be an important predictor of vulnerability and food security.

Although maize is the primary land use in much of East and Southern Africa, it is of course true that most households produce a variety of crops and food security is not solely a product of maize storage. Pulses, sweet potatoes and vegetables are important components of dietary diversity. However, a majority of caloric intake by households in East and Southern Africa is from maize (Denning et al. 2009) and small-scale farmers allocate a majority of land in production to maize cultivation in part due to the cultural preference for maize as a dietary staple. If necessary, households will switch to less preferred foods to maintain food security but yields of non-maize crops are equally sensitive to seasonal rainfall patterns as maize production. It is unlikely that a household will have a sufficient supply of non-maize food sources to support household food security for several months when maize supplies are depleted.

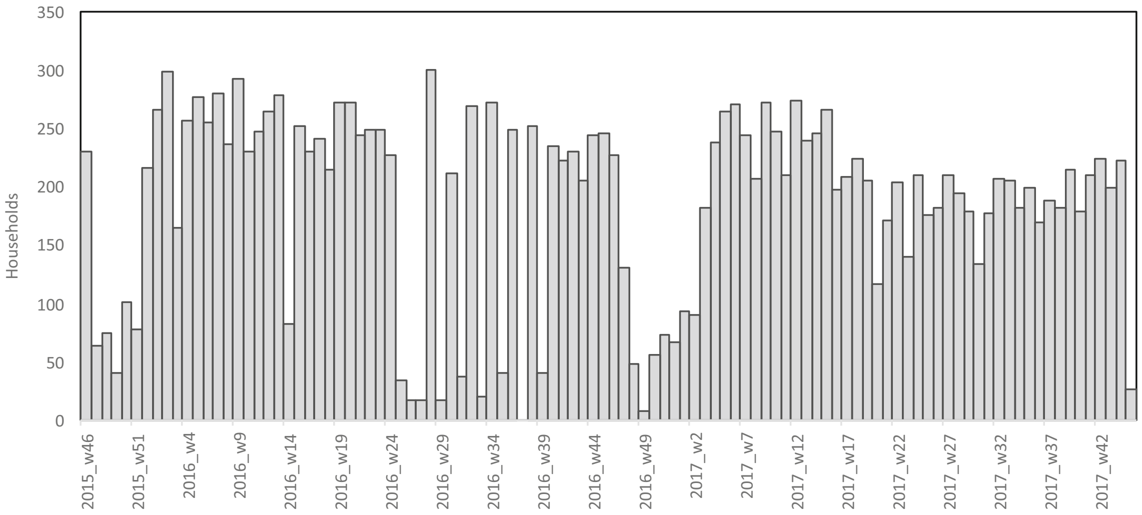


Fig. 3 Number of households reporting on food storage via SMS on a weekly basis from October 2015 to November 2017

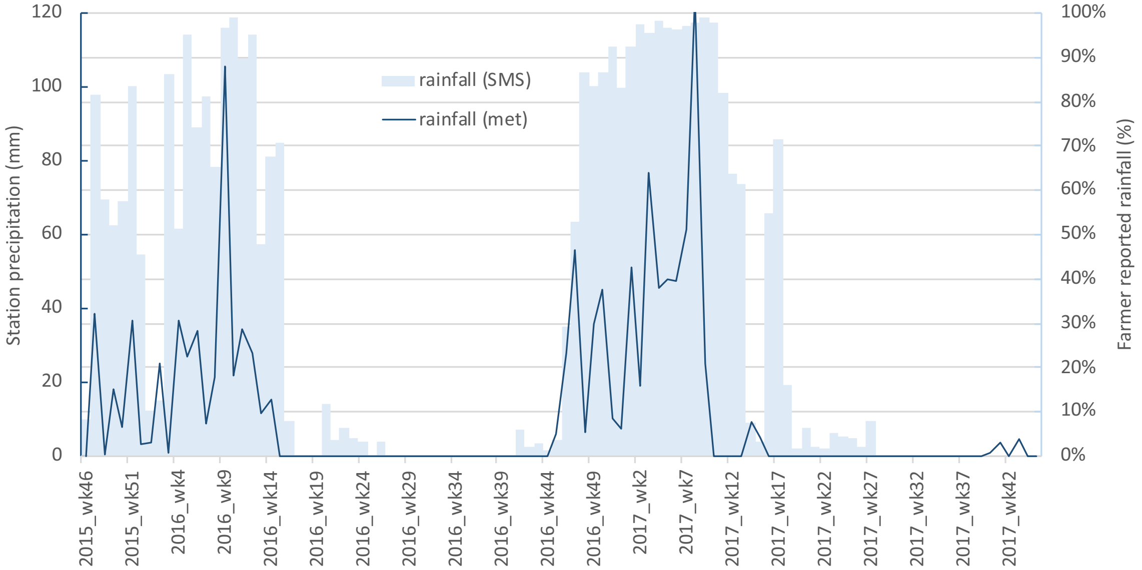


Fig. 4 SMS and meteorological station measured rainfall over 2 years starting in week 46 of 2015

Figure 5 displays the frequency distribution for maize harvest, storage, and sales in October 2015 from the household survey distributed before the SMS survey was administered. The distribution of maize harvested is relatively normally distributed (although right-skewed and positively bound) with a mean distribution of 1500 kg. The vast majority (about 85%) of households have 100 kg or less per person in storage. More than half of households sell no maize while 5% of households sell more than 250 kg of maize per person.

In a good year, most households harvest a sufficient quantity to provide food reserves for each household member until the next harvest. Assuming an average consumption rate of 100 kg of maize per person per year (De Groote et al. 2015), approximately 75% of households in this sample fall into that category for the 2015-2016 growing season. Households with lower harvests and limited market access have little choice but to hold all or nearly all of their maize in storage. Households with larger harvests are faced with the challenge of deciding how much harvest to sell and when to sell it. Selling too much maize to pay for non-food expenses can place households in a low food storage state early in the season, where they are forced to repurchase maize at a later date, likely at a higher price.

Post-harvest maize sales in Zambia tend to be transactions with private “briefcase buyers” and the Food Reserve Agency (FRA) as part of the national grain reserve program. Briefcase buyers enter the market earlier in the harvest period than the FRA, sometimes prior to the actual harvest and offer farmers lower farm gate prices for their maize. When offers are made pre-harvest they often involve advance payments. Briefcase generally provide farm gate purchasing meaning that they incur the transportation costs for the farmer, which is part of why they offer lower purchase prices. Many of these buyers will then transport the maize across borders for sale at higher prices in other countries. If a farmer can wait until after the harvest period to sell, the FRA starts buying maize from farmers in a subset of regions at pan-territorial prices that are often significantly higher than the price paid by briefcase buyers and other private buyers (such as the local mills). The FRA is designed to store maize with lower losses and

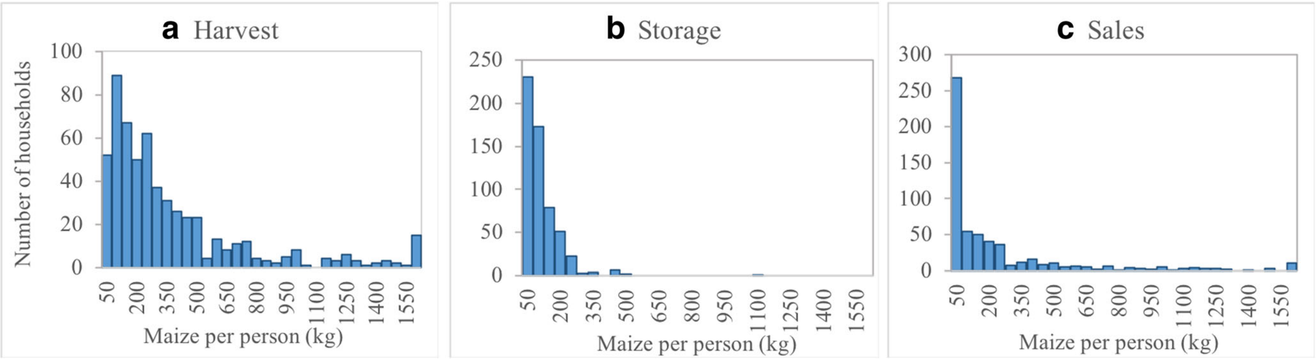


Fig. 5 Frequency distribution of maize harvest (**a**), storage (**b**), and sales (**c**) among 570 farmers in Southern Province Zambia in October 2015 (normalized per person)

transport maize to areas where food shortages occur. In practice, this means that maize is largely resold later in the season to millers in urban areas. Many farmers are unable to wait to sell maize until the FRA starts procuring it and miss out on the higher prices. In addition, FRA is notorious for making late payments and so farmers are concern about the uncertainty of when they will receive FRA payments prevents farmers from selling to FRA.

Storing maize can be extremely advantageous for households since it can buffer them from price spikes and the high transaction costs involved in buying and selling maize. Farmers who are able to sell maize early or who can hold maize in storage until market prices rise or the FRA starts buying at higher prices can benefit immensely compared to those who are forced to sell maize in advance of harvest or who must purchase or borrow maize during the lean season. Households that are unable to sell maize are also unlikely to be able to invest in inputs which can impact future food security. Given how depleted soils are in many parts of SSA, not applying fertilizer in a subsequent year will likely decrease maize yield and the ability to store maize, perpetuating a chronic state of food insecurity.

4.2 Maize storage clusters and descriptive statistics

We grouped farmers given their maize status at the time of the household visit (see Table 1). These groups are based on inflows (mean harvested), storage (mean storage), and outflows (mean sold) of maize from the previous harvest (2014-2015 season). Inflows include how many bags they harvested in the previous season, storage refers to how many they currently have in storage, and outflows are the number of bags they sold in the previous season. Rather than simply divide the sample of farmers into terciles, we clustered across the four variables to identify natural breakpoints that occur across the groups.

Maize harvest, storage and sales are normalized by household size and the mean amounts are reported on a per person basis.

The majority of households are clustered into group A, which has the lowest harvest level, the least amount of maize in storage and sold the least maize. Mean harvested us less than 150 kg per month, mean storage is less than 75 kg per month and mean sold is less than 100 kg. Group A has to hold a larger percentage of their maize harvest in storage and they are unable to sell a large percentage of their harvest. Group B is comprised of households that harvested between 150 and 500 kg per person, store between 75 and 125 kg maize per person and had more than 500 kg in sales per person the previous season. Group C harvested more than 500 kg, has more than 125 kg person in storage and sold more than 500 kg in the previous season. The number of households in each group resembles the frequency distribution of the mean amount of maize in storage—the largest group is comprised of farmers with the least amount of maize in storage. From here on, groups A, B, and C are referred to as low, medium and high storage households respectively.

Table 2 displays the descriptive statistics for the sample of households in each storage group. Higher maize storage households have more people in their household, more of the people have non-farm occupations, and they are less likely to be single-headed households. Higher maize storage households are also less likely to have done piecework in the last six months, indicating more stable employment or more significant farm income or production. Households with higher storage have more cultivated land, more area planted to maize, and more cattle, and do not have to travel as far to collect firewood. Overall higher storage households appear to have more agricultural assets (including land and labor), more secure income (occupations over reliance on piecework) and more access to resources than lower storage households.

Estimates are displayed in percentages for binary variables and indicate the percent of respondents who replied affirmatively. **F test indicates that the mean of the dependent variable differs significantly among the three food storage groups (using ANOVA).

4.3 Weekly rainfall and maize storage dynamics

Figure 6 displays the percentage of households reporting rainfall each week over the study period (bars) and the average amount of maize in storage among the sampled households. The figure depicts the cycle of rainfall and food storage. During most weeks of the rainy season, 90% to 100% of farmers reported receiving some rainfall on their fields in the last 7 days, highlighting the clear unimodal rainy season. Food storage dynamics rise and fall following the rainy season, with

Table 1 Clusters of farmers by mean maize harvested, in storage and sold

	n	% obs	Mean Harvested (kg/person)	Mean in Storage (kg/person)	% of harvest in storage	Mean Sold (kg/person)	% of harvest sold
Group A (low)	333	58%	133.0	50.6	38%	28.6	22%
Group B (medium)	141	25%	346.7	94.1	27%	174.2	50%
Group C (high)	96	17%	1839.7	166.5	14%	1649.5	83%
Total	570	Avg.	1200	129		1030	

Table 2 Descriptive statistics of high, medium, and low storage clusters

Variable	High	Medium	Low	Prob>F**
Household Size	9.88	8.88	7.35	0.00
Have Occupation	19%	17%	14%	0.40
Single headed household	3%	5%	10%	0.02
Piecework (in last 6 months)	23%	26%	39%	0.01
Cultivated Area (Ha)	11.04	8.60	5.75	0.01
Maize Area (Ha)	5.40	3.57	2.15	0.00
Cattle	15.64	9.03	4.18	0.00
Charcoal fuel use	4%	3%	6%	0.32
Firewood distance (minutes)	22.64	24.10	34.05	0.34
n	**97**	**143**	**331**	

most households reporting harvesting maize within weeks of the end of the rainy period. The average harvest is substantially lower in the 2015-2016 season, which can be attributed to the gap in rainfall in late 2015 into the early weeks of 2016. This dry period impacted most farmers and occurred during the critical tasseling stage of maize plant growth.

Figure 7 examines the food storage dynamics more closely by plotting the average maize in storage by the high medium and low clusters described above. A 3-week moving average is calculated to smooth the truncated nature of the responses. Since different farmers are responding in any given week there is fluctuation in food storage levels, which is partially smoothed by taking a moving average.

The high, medium and low food storage categorizations taken from the October 2015 survey persist throughout the weekly reported maize storage over time. There are very small differences in the actual maize in storage at that time but since we clustered households based on storage, harvest and sales we are able to accurately discern high, medium, and low storage groups. The three groups all converge just before harvest and the timing of the convergence depends on how good the harvest was overall.

4.4 Spatial distribution of maize in storage

In addition to achieving a high temporal frequency with the SMS food storage data we are also able to achieve a fine spatial granularity using the geolocations of households. The microclimatic weather variation evident in the variation in households reporting rainfall in a given week has important implications for food storage shortfalls. Through the fine spatial scale of responses, we can detect clusters of households that are experiencing food storage shortfalls before food in storage reaches critically low levels.

Figure 8 demonstrates the spatial variation in household food storage over time. In week 33 of 2016 (panel 8A), immediately after the peak storage period, numerous households have more than 1500 kgs of maize in storage and few households have less than 250 kgs in storage. Over time (panels 8B and 8C) the high storage households quickly deplete and or sell their storage, leaving clusters of households all with less than 1500 kg in storage. By the 14th week of 2017 nearly all houses have less than 250 kgs with some clusters containing no medium or high storage households at all.

4.5 Maize storage amplitude and rates of decline

The weekly data gathered via SMS gives us the ability to trace the dynamics of food storage over time and to study those patterns to better understand when a given group, particularly the chronically low storage group, may be approaching critically low food storage levels. Calculating the amplitude of

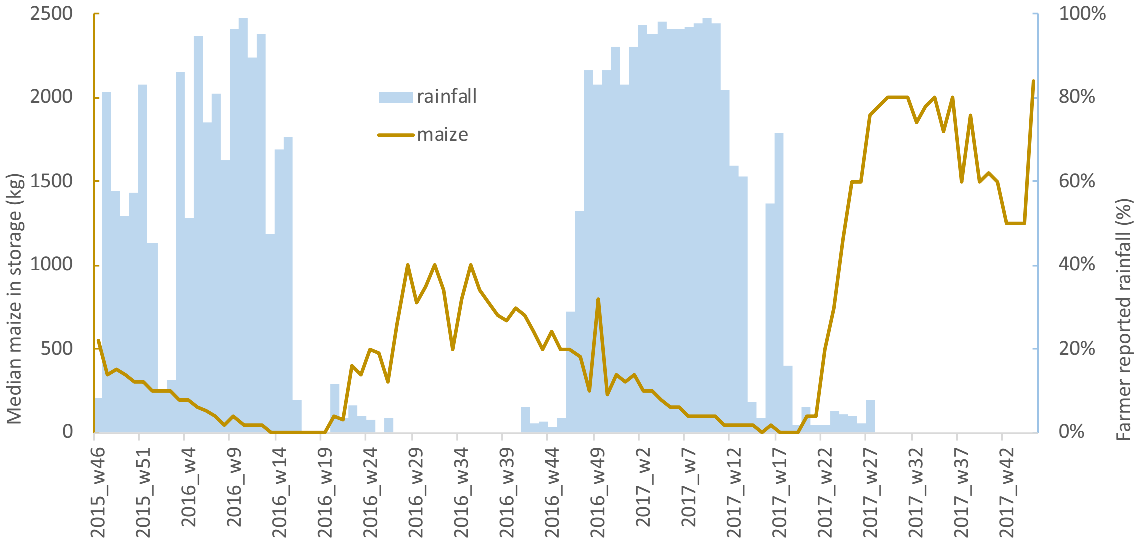


Fig. 6 Percentage of households reporting rainfall and the average amount of maize in storage

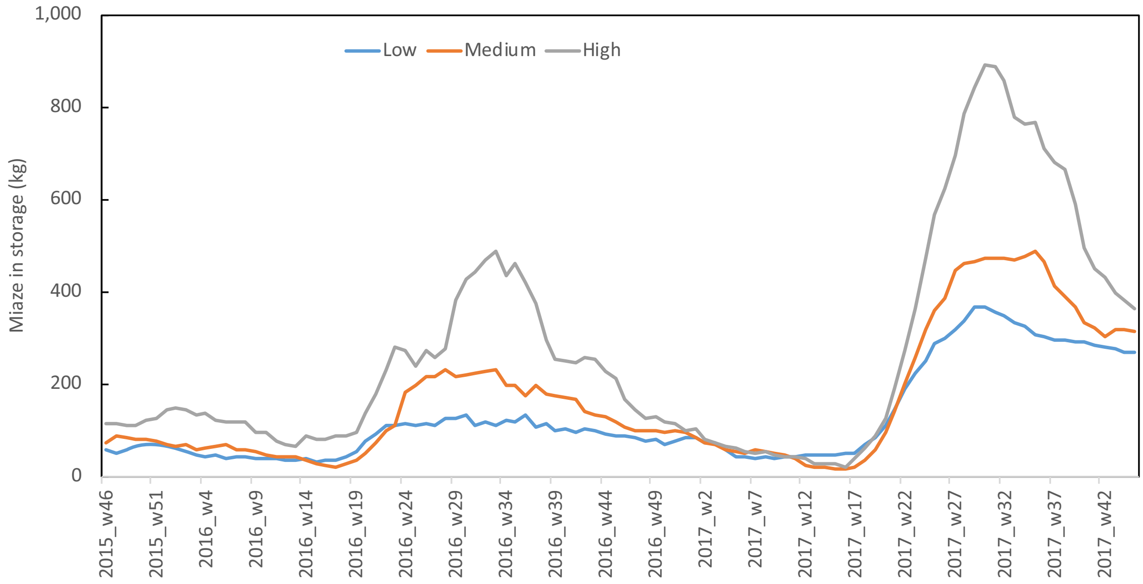


Fig. 7 Maize storage pattern for low (**a**), medium (**b**), and high (**c**) household clusters

food storage dynamics involves measuring the peaks and troughs of food storage. From this we can predict average rates of food storage decline and pinpoint when storage will approach a critical level and for which households. Figure 9 displays the average peak and trough height during the two-year period for the total sample of farmers in the study. The average household had 948 kg of maize in storage at the peak, just after harvest in August, 2016 and almost 3 times this amount, 2709 kg, at peak in August 2017. At the bottom of the trough, also known as the lean season, households had 268 kg less than the base consumption rate. The 'base consumption' represents the average amount of maize consumed per household per week which is roughly 10 kg per person per month or 120 kg per person per year. The dashed red arrow indicates the extent to which maize in storage can fall below the average household consumption rate. Calculating the depletion rate involves estimation of the peak-to-peak amplitude or the change between peak or highest amplitude value and the trough or lowest amplitude value over the total number of weeks between the two points. Getting a sense of patterns of oscillation will allow us to temporally predict swings in food storage.

One important determinant of food storage is the spatial heterogeneity in rainfall which leads to variation in harvest quantity, with implications for potential grain storage and resilience. The location of food insecurity thus can shift from year to year. Households who are chronically food insecure have the lowest quantity of food in storage, while the medium food storage households shift in and out of food insecurity depending largely on how their harvest is impacted by rainfall. These are generally the households that are the most difficult to target when a production shock occurs. Some of these households have safety nets where they can access food and are net receivers of maize on a regular basis, while others do not have access to sharing networks and must resort to coping strategies until the following season.

The rate of storage decline (Δm) can be calculated from the peak period of food storage (the average of storage values over the 2 weeks before and after the highest storage week) to the trough period (including two weeks before and after the lowest storage week). The rate of decline tells us how quickly food reserves are depleted and can be used to pinpoint the week at which food reserves will be completely depleted.

Figure 10 displays the rate of storage decline for high, medium, and low storage groups and the percentage of farmers who fall into the various rates of decline over the 8-week period from peak to trough. In the 2015-2016 season approximately one-third of farmers, experienced a complete harvest decline (100% of maize in storage), the majority of these from the lowest food storage cluster. By clustering the groups in terms of total storage, harvest, and sales at the beginning of the season we can identify the most vulnerable groups of farmers and then pinpoint their expected depletion date. This categorization does not however perfectly predict early depletion as we can see that households in the lowest food storage category fall into various degrees of food storage decline over the 8-week harvest period, from 0% to 100%, and households in the high food storage group also experience 100% decline over the same period. While the categories are not perfect predictors of food storage depletion, the high, medium, and low storage groups are useful as a way to simplify the heterogeneity of maize storage dynamics that exist among the households and track the most vulnerable households.

Selling a larger share of one's' maize harvest could indicate either chronic food insecurity or a more market-oriented agricultural production strategy. Some households sell maize

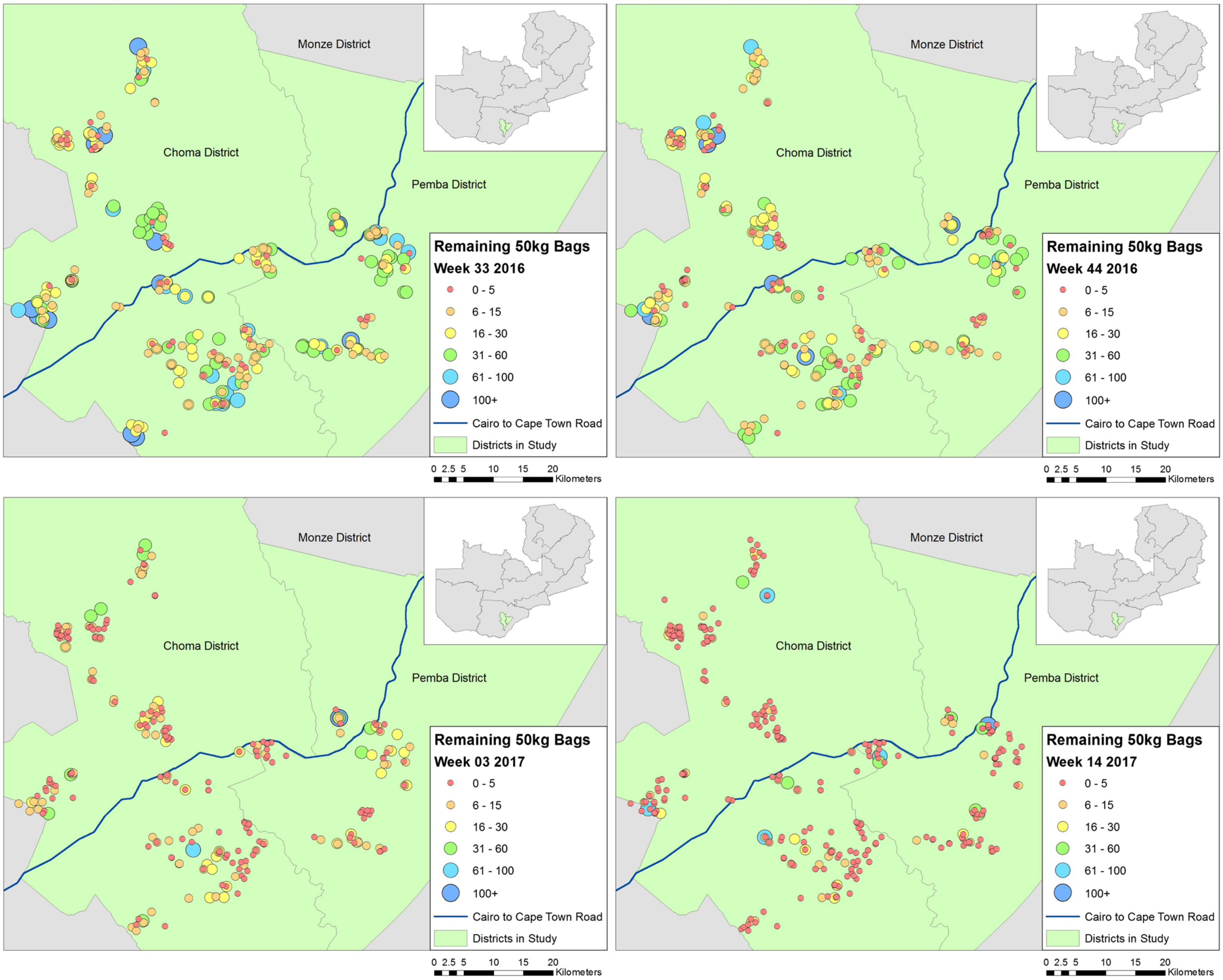
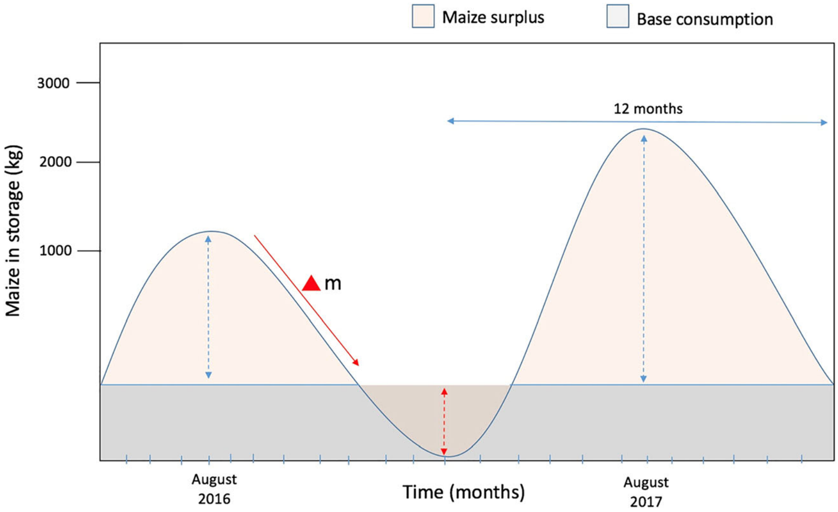


Fig. 8 Maize in storage in Week 33, 2016 (8**a**); Week 3, 2017 (8**b**), Week14, 2017 (8**c**); Week 14, 2017 (8**d**)

Fig. 9 Conceptual figure of maize storage amplitude. *Note: ∆ m refers to the rate of storage decline or depletion of food in storage following the harvest peak; Base consumption refers to the average quantity of maize consumed on a monthly basis. The dashed red arrow indicates the quantity of food storage deficit or the difference between food in storage and the average weekly household consumption rate



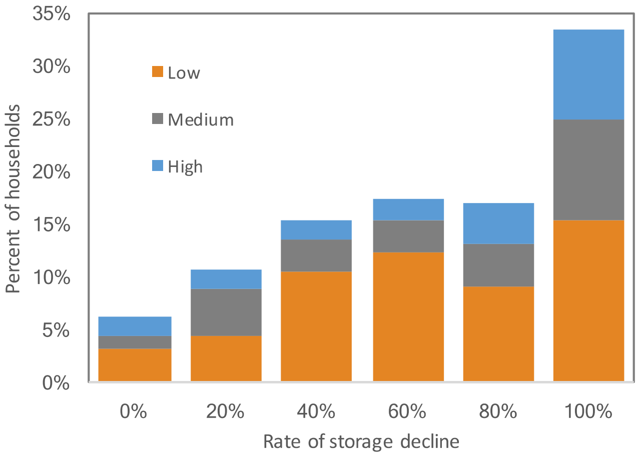


Fig. 10 Rates of maize storage decline by high, medium, and low storage household groups

immediately following harvest while others store maize until the lean period and either sell at a higher price or share maize with neighbors and family who experience food insecurity. Other farmers might need to sell maize as a distress sale, in order to purchased inputs such as seed and fertilizer for the coming season. One limitation of the SMS data is that given the incomplete time series we don't know exactly when, post-harvest, people sold maize. However, by dividing households into low, medium and high storage clusters based on harvest, storage and sales along with monitoring the temporal dynamics and estimated rates of decline, we can predict food insecurity from a single variable monitored over time, cheaply and efficiently through SMS, before it becomes a problem.

While climate change is predicted to reduce maize production in developing countries over the coming decades by 10%, there is enormous variability in the extent of the associated shocks (Jones and Thornton 2003). Identifying which households are resilient to climate related shocks requires spatially explicit rainfall estimates along with yield and food storage data in real time (Giroux et al. 2019). The ability to withstand climate and other types of shocks is central to building household resilience. A combination of understanding about current vulnerability and resilience, captured in household survey data needs to be complemented with the temporal breadth of how shocks impact harvest, storage and sales. Understand future resilience to climate change must be rooted in an understanding of the present structures and causes of vulnerability and resilience (Bohle et al. 1994). Interventions that do not consider the nuances of resilience and ignore environmental changes and or cultural factors such as behavior under uncertainty, can reinforce poverty.

5 Conclusions

Relatively little attention has been devoted to the dynamics of intra-annual staple crop storage and food storage, given the critical role management of food reserves plays in smallholder livelihoods. We characterize various types of households with respect to food storage dynamics using cluster analysis and find evidence that it is difficult for households to change their food storage trajectories. A majority of households have insufficient production to store enough food to sustain their household throughout the year (58%). These households lack the assets to achieve a resilient level of production and must rely on alternative food sources or seek (usually low paying) labor opportunities to enable them to purchase food. Storage dynamics of households in this category appear to be path dependent and these households could be considered chronically food insecure.

Only a small minority of households have production assets sufficient to provide adequate harvest to sustain their household food demand during low rainfall years (about 17%). These households harvest sufficient maize to be food secure throughout the year, are able to sell excess grain to pay for expenses such as school fees, and put away enough maize for storage throughout the year. These households can theoretically support food insecure households nearby when shocks occur.

The middle range of households (25%), move in and out of food security depending on rainfall and respective harvest amounts and are the most difficult to predict and target in any given year. Food storage for these households relies on their ability to strategically choose how much harvest to sell, taking into account the risk of needing to purchase food later in the season at higher prices. Households may be faced with short term financial needs due to illness or other shocks and the food security status of these farmers depends on what can be a complex set of decisions fraught with risk and uncertainty. Some of these marginally food secure households are resilient to production shortfalls while others are not, highlighting the importance of identifying which households lack resilience.

There are limits to using traditional household data to monitor food insecurity. In Zambia and other countries food security is often measured by large cross-sectional surveys of households at harvest time and in the middle of the season. These household surveys are extremely costly, time intensive, and are often conducted when it is too late for emergency food aid to reach vulnerable households. Initiatives such as the World Food Program's Mobile Vulnerability Analysis and Mapping program have begun to rely on information and communication technology (ICT) approaches to monitoring food security, but at this point largely conduct phone calls to households to administer various food security indicator questionnaires orally (Mock et al. 2016). While this type of approach can be quicker and cheaper than an in-person household surveys, this does not capture intra-annual trajectories and patterns of food reserves and food security. Food security can change quickly throughout the season and the relationship of intra seasonal events to expectations of food security and perceptions of vulnerability can effectively be monitored using technological advances afforded by ICTs.

The rapid monitoring approach to food storage using SMS described here can anticipate food insecurity before it is a problem and more accurately target food insecure households cheaply and quickly using a single indicator. This method can be used to pinpoint maize storage the rate of depletion for farmers spread across various microclimates in different states of food reserves. This micro scale data can then be scaled up using estimated threshold values of food availability from land use and production data across a larger landscape (Frelat et al. 2016). There are clear implications for monitoring food storage dynamics at a higher frequency—detecting early food depletion can be a proxy for future insecurity and can help build community food security and food storage resilience. Measuring the amplitude of food swings between peak harvest and periods of food scarcity enables us to identify patterns of food storage and the relationship of harvest quantity to food deficit. Estimation of LLpeak-to-peak food storage amplitude can improve food security planning both temporally and spatially.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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