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PRAGMATIC SOLUTIONS TO REAL WORLD PROBLEMS

Agrarian Frontiers

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Grain Storage Systems for Smallholder Farmers

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ABSTRACT: A growing global population and an increasing demand for food have threatened worldwide food security. Grains, such as wheat, rice, and corn, are the most globally abundant and important crops due to their nutritional benefits and widespread consumption. However, approximately one-third of the food produced for human consumption is wasted. A significant portion of that waste occurs due to pest infestation and bacteria growth in grain crops during storage. Traditional, open-air storage systems utilized by smallholder farmers in the developing world offer no means of protection against these contaminants. This lack of infrastructure also forces farmers to sell their crops immediately after harvest, when demand is low and supply is high, instead of waiting for more profitable timing. Since the mid-twentieth century, several types of improved and affordable storage mechanisms have become available. The most useful of these provide a hermetic seal that prevents both bacterial growth and pest infestation. However, farmers' adoption of these systems is hampered by the vicious cycle of a lack of education, lack of organization, and lack of investible income. This article details the barriers restricting smallholder farmers in the developing world from improving their food storage systems. It also reviews the benefits and drawbacks of current storage mechanisms, including the use of fumigants and insecticides. Recent developments and innovations in smallholder grain storage as well as obstacles to their implementation are also discussed. This synthesis of current knowledge on smallholder storage systems can inform the design of domestic food storage solutions to improve food security in the developing world.

[**smallholder, grain storage, food security, review**]

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Introduction

A growing population and the subsequent increasing demand for food have threatened global food security. At the same time, approximately one-third of the 1.3 billion tons of food produced for human consumptions is wasted (Godfray et al. 2010). This waste occurs at every stage of the Food Value Chains (FVCs), which includes agricultural production, processing, storage, marketing, distribution, and consumption. Several agricultural technologies, such as solar-powered dryers and treadle pumps, have helped decrease waste at various stages within the FVC. In developing countries, harvest and post-harvest processes are the largest contributors to food waste. Premature harvesting, unsafe handling, and inadequate storage account for nearly 40% of food losses. According the Food and Agriculture Organization (FAO), 13 million tons of stored grains are wasted annually due to pests and a further 100 million tons to improper storage methods. This accounts for 10% of all stored grains worldwide (Godfray et al. 2010).

In addition to food loss, smallholder farmers in the developing world suffer economically from poor storage mechanisms. Of the 3.7 billion people worldwide subsisting on less than $8 USD per day; 70% depend on agricultural activities for their livelihoods, whether as farmers or other types of agricultural laborers (Jayas, White, and Muir 1994). Unreliable storage systems force smallholder farmers to sell their harvests immediately, instead of waiting for demand to increase. Decreased income prevents the purchase of improved storage systems, perpetuating a cycle of poverty. Low-cost but effective storage methods are needed to both decrease food waste and improve the livelihoods of small holder farmers in the developing world.

Grains, such as wheat, rice, and corn, are the most produced and most nutritionally important crops grown globally; wheat alone is responsible for about 20% of calories and proteins consumed worldwide (Shiferaw et al. 2013). This article discusses the barriers to effective long-term grain storage and analyzes why these barriers arise in a community. Current storage mechanisms, as well as the benefits and drawbacks of each, are reviewed. Finally, novel solutions and opportunities for innovation are identified. This synthesis of current knowledge on smallholder storage systems can inform the design of domestic food storage solutions to improve food security in the developing world.

Barriers to effective storage

The primary causes of food waste during storage on smallholder farms are the loss of nutrients, growth of bacteria, and infestation of pests. Over time, weight loss due to chemical changes in proteins, carbohydrates, and vitamins causes the nutritional value of food to degrade. For example, cowpea's protein levels decrease significantly when stored in metal drums or bags made from vegetable fibers called jute (Onayemi, Osibogun, and Obembe 1986). Fungal growth can make food unsafe to consume due to biochemical changes and the production of mycotoxins. Mycotoxins, which are poisonous metabolites, can cause acute and chronic toxic effects if ingested (Bankole and Adebanjo 2004). In addition, bacteria can grow on grains. They can grow at a wide range of temperatures (from 5 to 60 degrees Celsius (Wagacha and Muthomi 2008)), enabling them to thrive even in diverse environments. For example, food stored by street vendors overnight in high ambient temperatures can harbor high microbial populations. As a result, bacteria such as *Bacillus cereus*, which is a major causative agent of outbreaks of foodborne illnesses (Wagacha and Muthomi 2008), can infect consumers. Pests, such as rodents and insects, can cause the most destruction to inadequately protected food. Approximately 2% of world grain production is spoiled by pest infestation (Jayas, White, and Muir 1994). They can spoil food by eating, urinating and defecating on the grain. In East Africa, a small dark brown beetle known as *Osamas* can chew through plastic storage bags and contaminate maize within (Chang 2012).

Many of the causes of pest and bacterial contamination are context-specific. Tropical climates with high levels of humidity can increase stored grain moisture and accelerate food spoiling. Farmers resort to drying the grain to 10% moisture during the dry season and hope it does not rehydrate in the wet season (Donahaye et al. 2007). Large agricultural businesses remedy this with high-capacity storage systems, but these options are not suited for smallholder farmers. Smaller farms are limited by space, with holdings averaging only a few acres (Deshingkar et al. 2003). Large-scale storage systems, while beneficial in terms of cost due to economies of scale, are inappropriate for these farmers. These storage systems have higher cost and labor for maintenance potentially leading to more pest infestation and crop spoilage (Shepard 2013).

Appropriate and effective storage systems remain financially unaffordable for most smallholder famers. Low profits are part of a cycle in which the lack of money, education, and/or organization perpetuates the usage of low quality storage systems (Fig. 1).

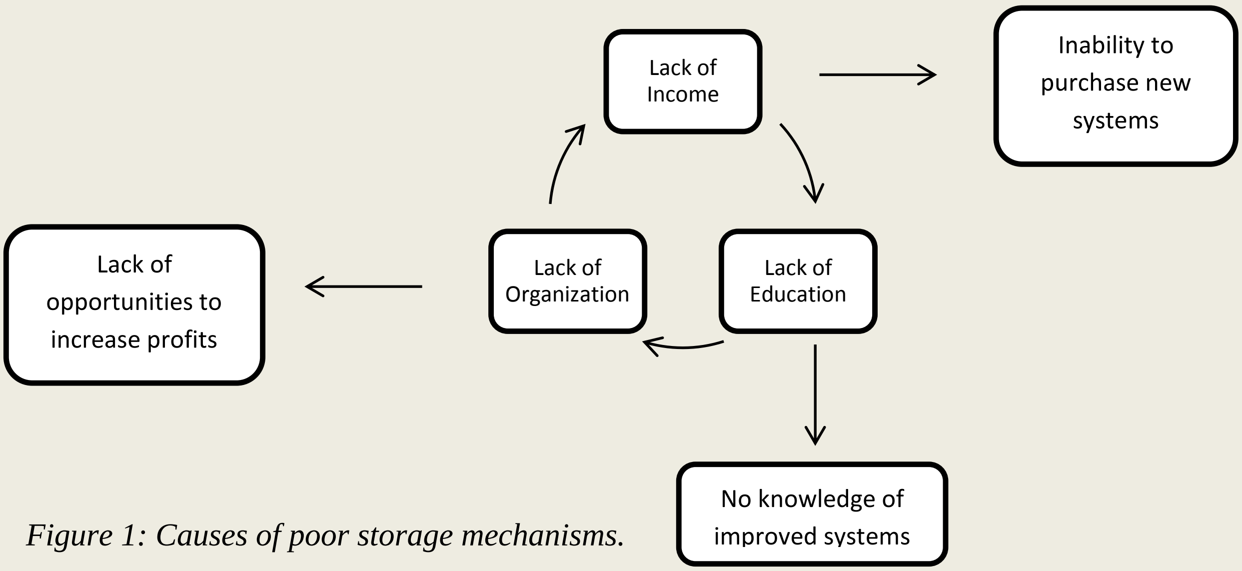

Figure 1: Causes of poor storage mechanisms.

For instance, farmers could earn higher prices if they could store and sell crops until later in the post-harvest season. But without this extra income, many people cannot invest in education that would allow them to gain more knowledge on grain storage mechanisms. This lack of education also contributes to a lack of organization among farmers. Limited demand for exports, lack of quality standardization, and nonexistent marketing systems are all consequences of this disorganization. These consequences limit opportunities for farmers to increase profits, thereby continuing the cycle of food shortage and poverty. Affordable storage systems could break this cycle by allowing farmers to delay sales until periods of greater demand and higher prices.

Storage mechanisms

Open Air Systems

Open-air systems have been used throughout the world for many generations. Farmers in different regions have adapted techniques to different climates, locations, types of grain, and personal preferences (Jayas et al. 1994). Table 1 details examples of traditional open-air systems from various countries in the developing world.

These techniques do not prevent insect infestation, moisture damage, or bacterial growth, all of which contribute heavily to crop loss. Rather, these methods remain common due to their simple construction, use of locally available materials, and ability to meet basic storage needs (Jayas, White, and Muir 1994). In fact, one or more of these methods is used in approximately 60-70% of farmers' households worldwide (Nagnur, Channal, and Channamma 2006). Many of these farmers distrust newer alternatives, believing them to increase risks of pest infestation and crop loss. In addition, many smallholder famers view their production levels as insufficient to warrant upgrading their storage systems (Boys et al. 2004). Therefore, instead of investing in better storage mechanisms, many farmers continue to sell their crops immediately post-harvest (Adejumo and Raji 2007).

Fumigants and Insecticides

The primary method of preventing insects from infesting stored grains is through the use of insecticides and fumigants. A variety of natural materials and synthetic chemicals are used to either kill pests or prevent them from reaching the grain. In Western countries, phosphine is the most effective fumigant in use today (Bell 2000). Some spices, which are chemical derivatives of plants, have shown great promise as alternative natural pesticides (Huang and Ho 1998). In developing countries where synthetic or refined chemicals are not available, farmers often resort to mixing local materials with their grains to prevent pest infestation. In Malawi, for example, mixtures of powders, dolomite, wood ash, tobacco dust, sawdust and sand are used to coat maize and protect it from pests (Golob et al. 1982). Sand and ash from cooking fires

Table 1. Open-air grain storage in the developing world

Method	Typical Grain Stored	Capacity	Benefits	Drawbacks
Giant Basket	Maize	Small quantities	- low cost - simple construction - locally available materials - easy to replace grains - low temperature - inexpensive materials	- not insect or moisture proof - minimal protection from environment - grains easily spoiled if not monitored
Wooden Box	Sorghum	Small quantities		
Mud Pots	Millet	Small quantities		
Open Weave Bags	Maize, Sorghum	50 kg		
Underground Pit	Cassava	1,000 – 6,000 kg	- minimal moisture damage - locally available materials - durable - inexpensive materials	- not insect or moisture proof - easily damaged due to weather - difficult to maintain
Mud Rhombus	Millet, Sorghum	1,000 – 8,000 kg		
Thatched Rhombus	Millet, Sorghum, Maize	500 – 8,000 kg		
Granary	Sorghum	6,000 – 14,000 kg		- loses over 30% of grain within 90 days

is used in a similar manner throughout sub-Saharan Africa (Obeng-Ofori 2007).

Though effective, many of these insecticides have serious drawbacks. The primary issue is toxicity towards humans, but high prices and increased genetic resistance of pests also create problems (Tapondjou et al. 2002). For example, misuse of phosphine has resulted in several cases of phosphine-resistant pests (Chaudhry 2000). Environmental concerns have also restricted the use of many fumigants. The Montreal Protocol on Substances that Deplete the Ozone Layer, a United Nations treaty ratified in 1987, ended use of methyl bromide in developed countries in 2005 and developing countries in 2015 (Gonzalez, Taddonio, and Sherman 2015).

Controlled Atmosphere and Hermetic Storage Systems

As a result of increasing regulations on fumigants and insecticides due to toxicity and environmental concerns, many farmers are now using controlled atmosphere methods to both reduce pest infestation and limit bacterial growth. Controlled (CA) or modified atmosphere (MA) methods used increased carbon dioxide levels or decreased oxygen levels to kill pests without using chemical additives. The simplest way to achieve this modification is through the use of hermetically sealed containers. Respiration of living organisms in the container cause oxygen levels to decrease and carbon dioxide levels to increase (Jayas and White 2003). According to the International Rice Research Institute, in addition to the pest control benefits, hermetic storage also stabilizes moisture content of the grain, doubles its shelf-life, and maintains total yield (Donahaye et al. 2007). Low oxygen stops feeding activity in the larvae of the cowpea bruchid (Murdock et al 2012.). A 40% increase in carbon dioxide levels or a 2% decrease in oxygen levels can cause 100% mortality in the grain weevil (*Calandra granaria*) (Bailey 1955).

Several types of hermetically sealed containers are currently in use. The metal silo is a promising new technology being implemented in many parts of the developing world. Consisting of a cylindrical container made of galvanized steel and sealed with rubber tubing, the metal silo is simple to build and offers excellent protection against both pests and pathogens (Tefera et al. 2011). The primary deterrent to adoption of the silo is the high initial cost; many farmers lack the capital to purchase one (Gitonga et al. 2013). However, aside from the initial cost, metal silos require little in the way of maintenance and have been shown to provide a significant return on investment (Tefera et al. 2011). Recycled metal drums with airtight screw-top lids, such as those used to ship petroleum or liquid sugar, are very popular among farmers in Senegal, though they are not as readily available in other parts of the world (Murdock et al. 2012). Another method using more widely available low-cost local materials is called “triple plastic bagging” (Murdock et al. 2012). This series of tightly sealed but not airtight bags shares similarities with the above, but only renders the pests inactive and non-destructive (Kitch and Ntoukam 1991). Yet despite acknowledging that metal drums are the superior storage method, many famers in Senegal have switched to bag-based methods due to budgetary constraints (Boys et al. 2004).

In addition to changing the atmospheric composition, other forms of climate control can also reduce bacterial or fungal growth and pest infestation. The most important factor in preventing mold growth in crop storage is the presence of moisture. Fungal growth is limited when moisture content is less than 13.5%, bacteria at less than 20%, and mites at less than 13% (Jayas, White, and Muir 1994). To reduce moisture content, farmers often sun-dry crops before preparing them for storage. Solar dryers have also been developed to increase the effectiveness of this method and to double the benefit by heating grains to temperatures that are fatal to common pests (Murdock et al. 2003).

Recent developments

An ideal storage system for the developing world would be hermetic so as to avoid both pest infestation and bacterial growth. However, it would also be low-cost, easy to construct and long-lasting. The current gold standard is the metal silo, which was developed in Central America in 1983 (Bokusheva et al. 2012), but only recently introduced to other parts of the developing world, including Africa. It is estimated that farmers in Kenya who have adopted the metal silo have salvaged US $130 worth of grain per season (approximately equal to the amount consumed by two people annually) while also increasing their profits and saving money on insecticides (Gitonga et al. 2013).

Table 2. Hermetic storage systems in the developing world

Method	Cost	Benefits	Drawbacks	Capacity
Metal silos	\$35 - \$375	- completely airtight - effectively protects against pests and pathogens - create jobs for silo artisans - minimal maintenance costs - long-lasting (up to 10 years)	- high initial cost	100 kg – 3000 kg
Metal drums	\$15	- relatively inexpensive in some regions - long-lasting (10 + years) under certain conditions	- expensive in many other regions	160 kg
Triple plastic bagging	\$1 - \$3	- made of locally available materials - simple - prevents insects from becoming destructive	- not fully airtight - does not kill all pests	50 kg

While efforts such as the Effective Grain Storage Project (EGSP) are working to bring metal silos to smallholder farmers in East and Southern Africa, demand remains small (Gitonga et al. 2013). Trained artisans, though capable of making a profit through the fabrication and sale of silos (Bokusheva et al. 2012), are underused (Gitonga et al. 2013). Part of the lack of interest in this effective product, can be attributed to a lack of awareness and education. Another critical barrier is the high cost of the silos. Smallholder farmers often do not have the capital nor access to credit to purchase US \$200-\$460 silos (Gitonga et al. 2013). These barriers may be overcome through agricultural extension programs in conjunction with the development of storage systems that have similar benefits at a much lower cost.

Other methods of recreating the hermetic seal of the metal silo are being investigated, including the use of recycled plastic oil containers. These containers are easily accessible and can be priced as low as \$1.00 in Sub-Saharan Africa. In one study, hermetically sealed recycled plastic oil containers killed 100% of a weevil population while air permeable containers killed only 50%. (Bern et al. 2013). While these containers are limited in size, they do not require an investment of large amounts of capital.

Improvements in bag-based methods of storage are increasing the effectiveness of these lower-cost systems, which avoid the high initial cost of metal silos. One promising mechanism is Purdue Improved Cowpea Storage (PICS), which uses a hermetically sealed triple-layer bag to store cowpeas and other grains in West Africa (Ibro et al. 2014). At about US \$3 each, the triple layer bag is constructed from 80-um thick high-density polyethylene (HDPE) layers and has a capacity of 50 to 100 kg, which is an improvement over traditional bag materials. Each layer is tied securely, better mimicking a hermetic seal. The last layer is placed in a nylon or polypropylene bag used for protection from rodents (Bern et al. 2013). This method has been proven to reduce fungal germination in cowpea by 89% and to limit seed damage by cowpea beetles to less than 7% (Sanon, Dabiré-Binso, and Ba 2011). These bags can also be reused for roofing, tarps, or other storage needs after they are too damaged to maintain the hermetic seal (Baributsa et al. 2014).

Additional development of bag material is increasing the effectiveness of this type of storage. GrainPro Inc., which is located in Concord, Massachusetts, produces an extensive line of ultra-hermetic sealed bags. The SuperGrainbag III™ can carry between 30 to 100kg and costs only US $3.50 (Bern et al. 2013). The bag is made of 78-um thick multilayer polyethylene and includes a proprietary barrier that makes it much less permeable to oxygen than standard polyethylene. This barrier can reduce the moisture content to 1% (Bern et al. 2013). However, rodents can tear the bags open, which is not a danger with metal containers such as silos.

These non-traditional but hermetically sealed storage options are practical and allow the farmers to easily store their crops with inexpensive and locally available materials. These systems could prove to be viable replacements for traditional storage systems because they are hermetically sealed, low cost, and easy to implement. While these systems are proving to be affordable and effective alternatives to traditional storage systems, widespread adoption is limited by farmers' lack of education. The problem is compounded by the fact that relatively few resources are devoted to improving storage systems in comparison to other agricultural processes, such as irrigation or harvesting. Opportunities for innovation include developing methods to disseminate knowledge of improved storage mechanisms, creating avenues for smallholder farmers to obtain the capital to upgrade their storage systems, and providing support for farmers who wish to change their method of storing grains.

Conclusion

Lack of income, education, and organization constitute a cycle that perpetuates poor grain storage mechanisms in the developing world. Traditional open-storage systems do not offer protection from bacterial and fungal growth or pest infestations that cause crop loss. In addition, lack of adequate storage methods forces smallholder farmers to sell crops immediately after harvest, instead of at the most profitable times. Advances in hermetically sealed storage systems such as the metal silo offer more effective ways to store and protect grains. Unfortunately, these methods remain prohibitively expensive for many farmers in the developing world. The ongoing development of plastic bag and container storage mechanisms show promise in providing low-cost, insect- and bacteria-proof storage. Further development and dissemination of these methods may improve grain storage in the developing world and improve food security worldwide.

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