ESTIMATION OF POSTHARVEST LOSS IN US WHEAT SUPPLY CHAIN: BENEFIT-COST ANALYSIS FOR SENSOR MONITORING SYSTEM

By

XUECHENG CAI

Bachelor of Science in Agribusiness

Oklahoma State University

Stillwater, OK

2018

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2021

ESTIMATION OF POSTHARVEST LOSS IN US

WHEAT SUPPLY CHAIN:

BENEFIT-COST ANALYSIS FOR SENSOR

MONITORING SYSTEM

Thesis Approved:

Phil Kenkel

Thesis Adviser

Brian D. Adam

Eric DeVuyst

Name: XUECHENG CAI

Date of Degree: MAY, 2021

Title of Study: ESTIMATION OF POSTHARVEST LOSS IN US WHEAT SUPPLY CHAIN: BENEFIT-COST ANALYSIS FOR SENSOR MONITORING SYSTEM

Major Field: AGRICULTURAL ECONOMICS

Abstract: Postharvest loss occurs at each stage of wheat supply chain. Insects, mold, moisture content and heat damage decrease the quality of wheat. This paper apply a benefit-cost analysis for a wheat storage sensor monitoring system in three scenarios to evaluate the economic advisability of reducing postharvest losses with sensor technology.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

II. BACKGROUND 3

2.1. Definitions of Food Loss and Waste 3
2.2. Postharvest Loss in Developing Countries 4
2.3. Postharvest Loss in Developed Countries 6
2.4. Possible Solutions to Minimize the Costs of Postharvest Loss 7

III. U.S. WHEAT SUPPLY CHAIN 9

IV. SOURCES OF LOSS IN THE U.S. WHEAT SUPPLY CHAIN 12

4.1. Loss from Insects and Mold 12
4.2. Loss from Heat Damage 13
4.3. Loss from Moisture 14
4.4. The Relationship of Monitoring with Wheat Storage Loss 15
4.4.1. Constraints with Insects and Fumigants Monitoring 15
4.4.2. Constraints with Hot Spots Monitoring 16
4.5. Analysis of a New Technology 17

V. BENEFIT-COST ANALYSIS FOR THE SENSOR TECHNOLOGY 19

5.1. Benefit-Cost Analysis for the Optimistic Scenario 21
5.2. Benefit-Cost Analysis for the Conservative Scenario 22
5.3. Benefit-Cost Analysis for the Most Likely Scenario 23
5.4. Sensitivity Tests 24
5.4.1. Savings from Monitoring Labor Percentage 24
5.4.2. Savings from Reduced Postharvest Loss 25
5.4.3. Costs of Sensors 26

Chapter Page

VI. RESULT AND CONCLUSION 28

6.1. Result... 28
6.2. Conclusion 29

REFERENCES 30

LIST OF TABLES

Table Page

1. The Present Value of Cost of Sensors over a Span of 10 Years........................21
2. Benefit-Cost Analysis for the Optimistic Scenario 22
3. Benefit-Cost Analysis for the Conservative Scenario 23
4. Benefit-Cost Analysis for the Most Likely Scenario..23
5. Sensitivity Test for the Percentage of Monitoring Labor.................................24
6. Sensitivity Test for PHL Reduction...25
7. Sensitivity Test for Sensor Costs...26

LIST OF FIGURES

Figure Page

1. U.S. Wheat Supply Chain 9
2. Food Flow within Any Given Stage of the Food Supply Chain 10
3. Sensitivity Test for Monitoring Labor Percentage 25
4. Sensitivity Test for PHL Reduction 26
5. Sensitivity Test for Sensor Costs 27

CHAPTER I

INTRODUCTION

Demand for agricultural products is increasing because of the growing world population, while agricultural inputs of land, energy, water, and other resources are limited. A recent study argued global agricultural production may need to increase by 60%-110% to meet these increasing demands by the year 2050 (FAO, 2009). The Green Revolution dramatically increased the capacity to grow food during the 1950s, but slowing rates of yield gains are failing to keep up with population increases (Funk et al. 2009). Several studies indicated that food production might no longer be increasing in some regions of the world (Ray et al. 2012). One response way to effectively increase supply of food grains and oilseeds is to reduce food loss and waste.

Food loss and waste occurs both at the consumption level and in the food supply chain. Losses arising from harvest to final consumption are called postharvest losses. Postharvest losses are measured in terms of quality (e.g., wheat kernel damage) and quantity (e.g., soybeans drop spillage during transportation). Gains in agricultural food supply can be attained by reducing postharvest food loss. There is potential to effectively increase agricultural food supply by reducing postharvest losses, particularly in developing countries as postharvest losses of crops are lower in other developed countries than in less developed countries (Hodges et al. 2010).

Sonka (2015) reported Mato Grosso, Brazil farmers are disinclined to recover soybeans spilled during ground transportation. While recovering spilled food crops increases supply, it also requires labor. At harvest, the opportunity cost of labor may offset the value of recovered crops.

Wheat is one of the most economically-important agricultural commodities in the U.S. In 2020, the area planted for wheat was 44.35 million acres in the U.S., producing 1,826 million bushels (USDA NASS). In addition to serving as a major food crop, wheat plays a vital role in the U.S. livestock industry. Feed wheat accounts, on average share since 1974/75, 9.1% of total use of U.S. wheat (Farmdoc Daily 2016).

This paper discusses the U.S. wheat supply chain and examines postharvest losses at one level of the supply chain (off-farm grain storage). The feasibility of a technology that could potentially reduce postharvest losses at one particular level of the supply chain is then examined.

CHAPTER II

BACKGROUND

2.1. Definitions of Food Loss and Waste

Bellemare et al. (2017) indicated there is no standard definition of food loss and waste. The U.S. Department of Agriculture Economic Research Service defines food loss and waste as the amount of edible food, postharvest, that is available for human consumption but is not consumed for any reason (Buzby, Wells, and Hyman, 2014). The U.S. Environmental Protection Agency (EPA) defines food waste as food used for its intended purpose and is managed in various ways (EPA, 2018). The Food & Agriculture Organization of the United Nations (FAO) regards food loss as the decrease in quantity or quality of food reflected in nutritional value, economic value, or food safety of all food produced for human consumption but not eaten by humans (FAO, 2018). The European Commission defines food waste as the fraction of food and inedible parts of food removed from the food supply chain to be recovered or disposed of (FUSIONS, 2016). These different definitions result in food loss and waste measures that vary widely, from 39.73 million tons (EPA, 2018) to 1.3 billion tons (FAO, 2018). Therefore, food loss and waste measurements are not consistent and not generally comparable across different studies.

Bellemare et al. provide a different perspective on how to measure food loss and waste. They think that those four measurements are all lacking in some ways. For example, food recovered for nonfood use is counted in these measurements as waste. However, that food can often be used as inputs, such as animal feed or fertilizers. Bellemare et al.'s definition of food waste assumes that as long as the food does not end up in a landfill, it is not wasted. For example, the grain that should be consumed by humans becomes animal feed because of quality degradation, which is counted as food loss under the EPA's definition. However, this grain is not wasted under Bellemare et al.'s definition. It goes to another stage of the meat supply chain. Food loss and waste in this example are in terms of quality, reducing economic value but not reducing it to zero (Bellemare et al., 2017).

2.2. Postharvest Loss in Developing Countries

Postharvest loss is a kind of food loss and waste. It occurs from food production to retailers, including losses and wastes during food handling, storage, processing, and transporting. Many factors contribute to postharvest loss, for example, poor infrastructure, early or late harvest, and unsuitable storage conditions. Developing countries may have more postharvest losses due to these factors.

A recent study by Sonka (2015) analyzed the causes of soybean postharvest losses in Mato Grosso, Brazil. Sonka found that a movement from single cropping to double cropping system was adopted in Mato because of a soybean disease. However, the key to a successful second soybean crop is that planting must be accomplished before the end of the region's rainy season. Therefore, there is considerable pressure to rapidly move the first soybean harvest to the market (Sonka 2015). However, the lack of on-farm storage and long distances to reach international markets contributed to soybean quality degradation. Additionally, the absence of government loan programs increased farmers' difficulty obtaining capital to construct storage facilities. Although this study did not estimate the percentage of postharvest loss in total production, the loss is considered to be higher than that of developed countries.

Gorgatti-Netto (1979) concluded several reasons for postharvest losses of cereal grains at the farm level in Brazil. At that time, maize was grown in most of Brazil's states, usually on small or medium-sized farms. Maize was mainly used for animal feed, so it was stored near or on the farm. Therefore, insects and rodents were the main factors of postharvest losses. Using bulk storage systems in metal or concrete was one solution, but it required a large initial investment that few small-sized farms could afford.

Another study estimated postharvest losses of cassava and maize in Nigeria. Thylmann et al. (2013) define food losses as the decrease in edible food mass throughout the supply chain that specifically destined for human consumption. They assumed that food losses also represent a waste of resources used in production, such as land, water, energy, and inputs. Thylmann et al.’s study focused on the environmental impacts of food losses using life cycle assessment methods. CO2 emission, water used, and land occupation were calculated to estimate the food losses in processing, transportation, and distribution. Thylmann et al. estimated the quantity of postharvest loss along the cassava chain from farmers to cassava starch. Their result showed that the quantification of postharvest loss of fresh cassava tuber at the farm gate is about 8.51%; the postharvest loss of cassava during processing is 14.81%, and the postharvest loss at the marketing is 9.5%. In the estimation of postharvest loss of maize, about 3.53% of maize grains were lost at farm gate, about 26.6% of maize grains were lost during marketing, and about 7.8% of maize grains were lost during feed milling.

Dessalegn et al. (2014) estimated postharvest loss of wheat in Ethiopia. They collected the primary data using a questionnaire, and about 200 wheat farming households were selected to analyze. They estimated the percentage postharvest loss of wheat grain at different stages. In all of the estimates, the postharvest loss was highest at harvesting: 6.7% loss when there was no rain during harvesting and 16.3% when it was raining. The huge difference was due to moisture loss. The second-highest loss was from threshing operations, 3.5%. The overall postharvest loss of wheat was estimated to be 17.1%. The most important causes of postharvest losses were moisture, rodents, and insects. Traditional methods of storing wheat were one of the significant factors that caused postharvest loss. Moisture content was high during rainy seasons so that insects developed quickly. Sun drying of wheat caused more losses due to rodents.

Farming households from developing countries use conventional methods to process and store grains. Those methods are not efficient against insects and rodents, which is a major factor in postharvest loss.

2.3. Postharvest Loss in Developed Countries

Johnson et al. (2018) conducted a case study of postharvest losses at the field level on a North Carolina farm. Johnson et al. (2018) describe a method for estimating amounts of available marketable and edible products that remain in the fields. Although previous calculations of food loss and waste did not include food that never reaches the supply chain, such as unharvested crops or crops that remain on the field after the primary harvest (Hall et al., 2009), Johnson et al. (2018) used a field sampling method to estimate vegetable crops that remained on the fields. Their studies divided vegetable crops into three categories, marketable, edible but unmarketable, and inedible. They estimated that only about 24.37% of the total production was marketable. The rest of the production was considered to be either edible but unmarketable, or inedible, which never goes into the supply chain. Without adequate replications for each crop, it is difficult to extrapolate the case study’s findings to other contexts (Johnson et al. 2018).

Research by ERS (2010) estimated postharvest losses in the U.S. The research covered food loss at the retail and consumer level of more than 200 agricultural commodities. They estimated that 10% of the edible and available food at the retail level went uneaten and 21% at the consumer level. Total postharvest losses would have been bigger if losses at harvesting and transportation level had been estimated. Among all these agricultural commodities, the percentage loss of grain products at the retail level was 12%, $4.3 billion annually. Similarly, the percentage loss of vegetables at the retail level was 12%, or $9.6 billion (ERS 2010).

2.4. Possible Solutions to Minimize the Cost of Postharvest Loss

The economic cost of postharvest loss for some crops, such as perishable fruits and vegetables, can be reduced at the distributing level. According to Johnson's study of estimating vegetable crops remaining in the field after primary harvesting, only 24.37% of total production is marketable. The crops remaining in the field comprised edible but unmarketable crops (41.45%) and inedible crops (34.18%). Although the quality (size and shape) of edible but unmarketable crops do not meet USDA-AMS Specialty Crops Inspection Division requirements, the crops are still edible (Dunning et al. 2019). A small but growing number of alternative markets exist for lower-grade products, such as "ugly produce" programs at grocery retailers. Food banks are another potential market for lower-quality products. Dunning et al. monetized on-farm produce loss to see if selling lower-quality crops to those markets could increase producers' profits. If picking up ugly products from the field is profitable, farmers are incentivized to have second harvests.

The cost can also be reduced at the marketing level. Bolos et al. (2019)'s study aims to determine the effect of specific initiatives on consumer information processing, acceptance, and motivation. Consumers will not usually buy imperfectly shape or colored fruits and vegetables. However, these products are edible. According to Johnson et al.'s study, if consumers are willing to buy lower-grade products, more lower-grade crops could be harvested instead of leaving them on the fields. In this way, postharvest loss can be reduced.

Many factors influence consumers' decision making, and nudging is one of them. There are several nudging interventions: attention-focused interventions (pictures with information), interest-focus interventions (beautiful packaging or photographs), and action-focus interventions (a "grab and go" line where only a few products are presented, making them a more obvious choice). Retailers could use more nudges to persuade consumers to buy lower-grade products to reduce postharvest food waste.

CHAPTER III

U.S. WHEAT SUPPLY CHAIN

There are several stages in the U.S. wheat supply chain, including growers, elevators, transportations, processors, and consumers. Farmers grow and harvest wheat at the farm level. Then farmers ship the wheat to country elevators to store. U.S. wheat producers selling wheat to an elevator typically have the option of storing and selling later to earn a return to storage. Country elevator managers can ship the wheat to terminal elevators and final to the export elevator or ship them to the processing facilities. After processing, wheat can be shipped to retailers and finally go to consumers.

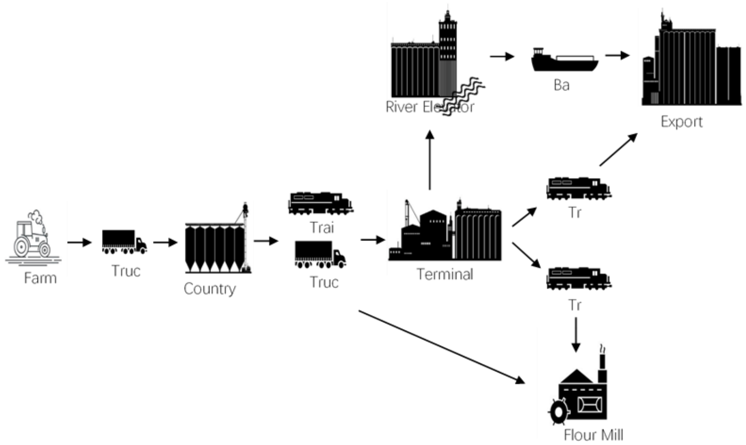

Figure 1: U.S. Wheat Supply Chain.

Bellemare et al.'s (2017) study indicated that a typical food item's life cycle is composed of phases that occur within its supply chain and phases that occur once the food is removed from its supply chain. A generic, stylized grain supply chain has four distinct stages from upstream to downstream: (1) growers, (2) processors, (3) retailers, and (4) consumers. As food moves from upstream to downstream, food loss occurs. Food that is lost either goes to the landfill or is put back into the supply chain or goes to nonfood productive uses.

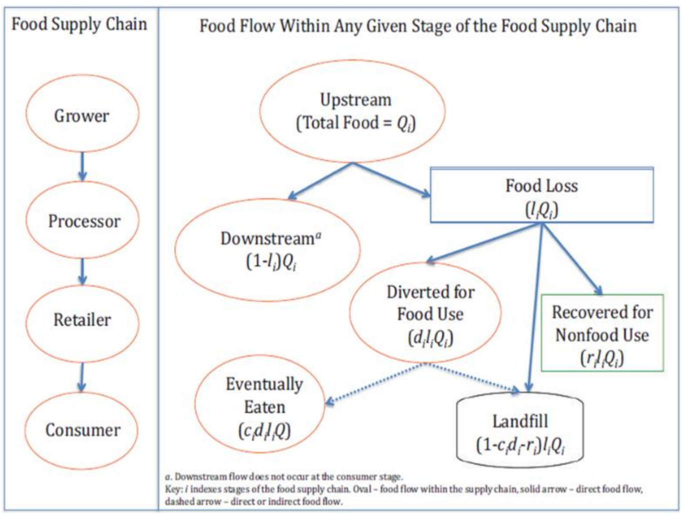

Figure 2: Food Flow within Any Given Stage of the Food Supply Chain. Source: Bellemare et al. (2017)

Postharvest losses occur at each level in the wheat supply chain. The postharvest loss of wheat in developing countries is estimated to be 20% - 40%. Although the loss is estimated to be much lower in the U.S. wheat supply chain, there is a lack of hard data on the actual magnitude. There are a number of reasons to expect postharvest loss in the wheat supply chain to be relatively low. Wheat is not a perishable product and can be stored for extended periods of time. Wheat has a hard kernel and is stored at relatively low moisture content. While wheat is susceptible to damage from molds and insects, the risk of that damage is much lower relative to perishable crops such as fruits and vegetables. Finally, wheat is used as an ingredient in multiple types of food products and also as a part of animal feed rations. For that reason, wheat that suffers storage damage is much more likely to be diverted to a lower value food product or to animal feed rather than to a land fill.

Kenkel and Adam (2019) used a Delphi approach with a panel of grain industry experts to develop a consensus opinion on wheat loss in the U.S. grain system. They estimated the total loss at 1.5% which consisted of 0.5% shrink, 0.25% quality discounts, 0.2% remediation and 0.5% opportunity costs. Their study focused on reduction in value and for that reason their estimate may overstate postharvest loss. For example, one of their larger categories: opportunity cost related to the cost of diverting wheat from the highest price channel such as a flour mill to an alternative market such as an export elevator. It is not clear whether that category reflected any diversion from food use or simply to use in a less valuable food product.

CHAPTER IV

SOURCES OF LOSS IN THE U.S. WHEAT SUPPLY CHAIN

4.1. Loss from Insects and Mold

Insect infestations could originate from the field. Insects enter the storage elevators with the harvested grains. The metabolic activities of insects within the elevators lead to molds germination, and broken kernels. Insect movements expose otherwise hidden endosperm surfaces to molds, transport mold to new areas, and encourage mold germination in microhabitats made moist by insect metabolic activity (Sinha and Wallace, 1996).

Some insects develop inside a grain kernel, and produce holes in the kernel when they exit as adults. Their entire life cycle takes place inside the kernel, and these insects only survive when kernels are intact. These insects are known as internal feeders. Examples include maize weevil, rice weevil, bean weevil and lesser grain borer. Other insects, which develop on broken kernels, are external feeders. They can enter kernels through holes bored by internal feeders. Some external feeders contaminate grain through their metabolic activities. Their metabolic activities create hot spots within the stored grain and produce water during this process, which encourages mold growth and grain spoilage (Magan et al. 2003).

Insect infestations reduce grain quality by boring holes in kernels, reducing nutrition, and spreading molds. Additionally, the metabolic activities of insects creates hot spots within grain mass, which reduces storability. Insects also create grain dust, which reduces airflow through the grain when the aeration fans are used. Insects reduce the quality of grain, so the presence of insects in grain sampling leads to discounts for the grain.

4.2. Loss from Heat Damage

In the U.S. wheat is typically allowed to dry in the field to a safe storage moisture of 12% or less (wet moisture basis) and is initially placed into storage at harvest temperature. In the fall, the typical storage practice is to take advantage of ambient air temperatures to cool the grain mass to a lower temperature (below 15℃) which limits insect activity. Ambient air aeration is the most common method of cooling down the wheat. It requires fans and air flows. When the ambient air temperature is lower than the grain, heat can be transferred and the wheat cools down. However, several factors can make "hot spots" (small areas of higher temperature within the grain mass). First, the temperature may rise due to heat generated by the respiration of wheat. Insufficient drying of wheat before storage leads to a high moisture content, and a more active respiration rate of wheat. The respiration creates moisture, which further accelerates heat generation. Second, fines and broken kernels accumulate, slowing down the efficiency of aeration. Fines and broken kernels may be created during transportation and drying processes, or by insects within the storage. These tiny particles may accumulate and compact at the bottom of the storage, decreasing the number of airflow channels and the efficiency of heat transfer.

Extreme temperatures can damage wheat kernels and the number of heat damaged kernels is a grade factor under U.S. Grain standards. In most cases, the hot spots within grain storage do not reach the levels necessary to create heat damaged kernels but do reach an optimal temperature for insects and mold to develop. The concept of heat damage is therefore somewhat inter-related with insect and mold damage. The ability to detect areas of higher temperatures within a grain mass is important for stored grain management because those hot spots are precursors for mold, insects and, in extreme cases, kernel damage. Hot spots are difficult to detect from outside of grain bins and must be monitored by sampling the bin or through the use of installed temperature cables.

4.3. Loss from Moisture

As mentioned, wheat is typically harvested and placed into storage at a wet basis moisture content of 12% or less. Storing wheat at high moisture content increases the likelihood of mold, bacteria, and insect growth, which decreases the quality of grain. The respiration rate of wheat is also higher when the moisture content is higher. A lower respiration rate is preferred to maintain the quality of the wheat.

Aeration is primarily used for cooling, but aeration systems may also be operated periodically to equalize grain temperature throughout the bulk grain mass, or to remove fumigant residues and odors (Stored Product Protection 2012). The aeration process can also reduce the moisture content of the grain which reduces grain value since wheat is sold on a wet moisture weight basis. That moisture-related weight loss was likely a component of the 'shrinkage" loss estimated by Kenkel and Adam (2019). While moisture loss does represent a loss of value to grain handling firms, it is not a true loss since the intrinsic value of the grain is not affected. As a matter of fact, one of the initial steps in the flour milling process is to temper the wheat by adding water. The moisture loss during storage is therefore irrelevant in terms of the final yield of flour. While moisture loss is not a true loss in terms of postharvest loss, it can be minimized through the use of automated systems which operate fans based on humidity level and temperature, which reduces excess fan operation.

4.4. The Relationship of Monitoring to Wheat Storage Loss

As discussed previously, when wheat is placed into storage at an appropriate moisture content of 12% or less and cooled to a temperature below 15℃ when ambient air temperatures allow, it can typically be stored for relatively long periods of time with little storage loss. The management of wheat storage therefore includes periodic monitoring of the grain structures to detect the presence of “hot spots” or insect infestation. When those problems are detected in the grain mass they can be addressed through aeration and fumigation. The effectiveness of fumigation in eliminating insects is also dependent on the concentration of the fumigant throughout all areas of the grain mass which creates another monitoring issue. The topic of monitoring is relevant because it relates to our later discussion of a technology to reduce losses during wheat storage

4.4.1. Constraints with Insects and Fumigants Monitoring

One of the significant causes of quality loss during wheat storage is insect infestation. Fumigation of wheat with phosphine is a common and effective method of controlling insect infestations. The effectiveness of a fumigation strategy depends on two factors, the timing of the fumigation and management of the phosphine concentration during the fumigation. Fumigating too early allows the insect population to rebound and cause quantity and quality loss, increasing costs because additional fumigations are required. Fumigating too late allows the insect population to grow too large, causing quantity and quality loss (Adam et al. 2010). Some elevator managers use their experiences to determine the best time to fumigate, or use a calendar-based strategy. Highly variable weather and bin conditions can make those strategies ineffective.

While the concentration of fumigant over time is critical for determining the effectiveness of fumigations, continual measurement of the concentration is difficult or at least inconvenient, possibly leading to insufficient concentration and thus ineffective insect control if fumigation time is too short or too little fumigant is used, or excessive costs if too much fumigant is used.

4.4.2. Constraints with Hot Spots Monitoring

The least sophisticated method for detecting hot spots in the grain mass is for an employee to feel the temperature with their hands. For grain below the surface level, a metal rod can be used for monitoring temperature. Insert the metal rod into the grain at least 1 m for 30 minutes, then test it for warmth and wetness with hands. Any point of the rod that feels warm or wet indicates a hot spot in the grain. This traditional method is rarely used in modern grain facilities because it requires workers to enter the grain bins, which is considered unsafe.

The temperature probe method is similar to the hand-feeling method, but it involves inserting a thermometer into the grain mass. While providing a more accurate assessment of temperature relative to the hand method, temperature probes are also rarely used due to concerns over bin entry.

The most common methods currently used for monitoring grain temperature involves the installation of permanent temperature sensing cables in the bins. The sensors continually monitor temperatures and send data to a personal computer. The system can also be linked with automatic controls for aeration systems and other control devices. Systems are available which measure temperatures, relative humidity and the barometric pressure inside and outside the bin.

4.5. Analysis of a New Technology

A new technology that uses wireless sensors has the potential to reduce postharvest loss during wheat storage. The wireless sensors provide an alternative method to monitor fumigant concentrations as well as temperature and moisture. This system appears to have the potential to reduce some of the labor costs associated with grain monitoring and also reduce storage losses. While the level of those potential benefits has not yet been quantified, it is useful to conduct a cost benefit analysis using the best available estimates for the expected benefits.

The specific system analyzed includes phosphine sensors, temperature sensors, moisture sensors, wireless communications, data collection software, data analysis, and internet access. Those sensors can monitor remotely at a regular time interval and send data to the cloud-based system. Data is analyzed, and the grain storage manager can decide what activity should be taken. Wireless monitor techniques not only can monitor the current conditions of wheat, but this sensor monitoring system also provides predictions of the wheat temperature, moisture content, and the risks of mold development throughout the storing period with advanced data analysis techniques. The system therefore provides information that was not available from previous monitoring methods.

As mentioned previously, the benefits of the sensor system in a commercial grain storage setting have not been quantified. It is anticipated that the system would reduce the hours of labor dedicated to monitoring the stored wheat and could also reduce storage losses. The rationale for anticipating a reduction in storage losses is that the system would allow the stored grain manager to detect areas of high moisture, heating or insect presence on a more timely basis and implement control strategies. The system could also more accurately measure phosphine concentrations during fumigation which would increase fumigation effectiveness and reduce insect damage.

CHAPTER V

BENEFIT-COST ANALYSIS FOR THE SENSOR TECHNOLOGY

Considering the possible contribution of new technology in the storage monitoring system, a cost-benefit analysis was conducted. Due to the lack of data on the effect of the sensors, three scenarios are analyzed. The scenarios include: a.) An optimistic scenario in which the postharvest loss of the storage is relatively high (1.5%), and the cost of labor used in monitoring is 50% of average labor cost in grain cooperatives ($0.089/bushel). The metric of the average total labor in grain cooperatives is discussed later in this section. In this scenario and in the following scenarios the sensor technology was assumed to reduce both monitoring labor and storage loss by 50%. b.) A most likely scenario where the postharvest loss is set at 1% and labor cost of monitoring is $0.044/bushel, which is equivalent to 25% of the average total labor of a grain cooperative Sensitivity analysis, was conducted on that assumption. and c.) A more conservative scenario where the postharvest loss of the storage remains 1% and monitoring labor is $0.022/bushel which is equivalent to 12.5% of average labor cost for grain cooperatives.

The wheat storage bin is assumed to have a storage capacity of 50,000 bushels. A wheat price of $5.00 per bushel was assumed. The wheat price was relevant in converting USDA statistics on wage expense in grain cooperatives (which were expressed as a percent of sales) into an amount per bushel. The wheat price was also used to convert the assumed change in wheat loss to a dollar amount. A benchmark for this assumption is the average wheat future price on July contract from 2014 to 2019, adjusted to dollars per bushel in the base year 2019 using the producer price index (U.S. Bureau of Labor Statistics), which yields an average of $5.15/bushel.

There are no good available estimates for the labor costs of monitoring grain in a commercial storage. As a means of deriving a reasonable estimate the per bushel labor of grain cooperatives was determined from the 2017 USDA Agricultural Cooperative Service statistics . Those statistics provide common size income statements for grain cooperatives with each income or expense category expressed as percent of sales, for elevators of comparable size. The reporting of common size income statements was discontinued in 2018 so the 2017 statistics represent the best available data.

The common size statements are reported for three size categories (based on gross revenues) of grain cooperatives. Wage expense for the middle category was reported at 3.54% of sales, or $0.177/bushel, using our assumed wheat price. That salary expense represents the total personnel expense for the cooperative including the salaries of the manager and administrative personnel as well as the labor involved in receiving and shipping grain. The labor expense associated with monitoring grain would be assumed to be a portion of that total labor. As described previously, assumptions that monitoring labor equaled 50%, 25% and 12.5% of all labor are used in our cost benefit scenarios. According to the Bureau of Labor Statistics, the United States Department of Labor, the average hourly wage for farm workers and laborers of the United States was $15.07 in 2019. If elevator managers set wages at that level and paid an amount equal to 30% of their wages for insurance and other benefits, the elevator employee's average hourly cost would be

$19.59. The most likely scenario includes an assumption for labor in monitoring grain equal to 113 hours per year or around 2 hours per week.

The sensor monitoring system assumed here includes wireless phosphine sensors, moisture content sensors, temperature sensors, and a gateway. The costs include the initial costs of installing sensors and gateway, and subscription costs of using their software each year, and the battery of each sensor. The costs of installing each sensor and gateway are $800 and $400. The subscription cost is $200 for using the monitoring system software each year. The lifetime of sensors is ten years, and the battery of each sensor needs to be changed every two years at a cost of $200. Subscription and battery costs are discounted over a span of 10 years with a discount rate of 6%.

Interest rate of return	Year	Subscription	Battery	Sensors installing	Gateway	Total cost
6%	0	$ 800.00	$ 800.00	$ 3,200.00	$ 400.00	$ 5,200.00
	1	$ 800.00				$ 800.00
	2	$ 800.00	$ 800.00			$ 1,600.00
	3	$ 800.00				$ 800.00
	4	$ 800.00	$ 800.00			$ 1,600.00
	5	$ 800.00				$ 800.00
	6	$ 800.00	$ 800.00			$ 1,600.00
	7	$ 800.00				$ 800.00
	8	$ 800.00	$ 800.00			$ 1,600.00
	9	$ 800.00				$ 800.00
Total cost PV		**$12,314.08**				

Table 1: The Present Value of Cost of Sensors over a Span of 10 Years

5.1. Benefit-Cost Analysis for the Optimistic Scenario

In this scenario, the postharvest loss of the storage is relatively high, and the sensor technology significantly reduces the loss while eliminating labor cost at a high wage rate.

The postharvest loss is assumed to be 1.5% of total stored wheat, including quantity and quality loss. The sensor technology was assumed to reduce storage losses by 50%. Monitoring labor was assumed to be 50% of total labor or $0.089/bushel. The sensor was also assumed to reduce labor costs by 50% or $0.045/bushel. A 6% discount rate was used for the present value calculations along with a 10 year useful life for the system. The present value of using sensors technology for the future ten years was $17770 and the benefit cost ratio was 2.44.

Costs		
	Sensors	$12,314.08
	Total Cost	**$12,314.08**
Benefits		
	Wage savings	$16,284.19
	PHL savings	$13,800.16
	Total Benefits	**$30,084.36**
Net Present Value B-C		**$17,770.28**
Benefit-Cost Ratio B/C		**2.44**

Table 2: Benefit-Cost Analysis for the Optimistic Scenario

In this scenario, the total costs unchanged, but the savings from monitoring labor hours elimination and PHL reduction is $16,284 and $13,800. The net present value of profit is $17,770. The benefit-cost ratio is rounded at 2.44, showing that using the sensors gives the increases net present value of storage.

5.2. Benefit-Cost Analysis for the Conservative Scenario

In this scenario, the postharvest loss was assumed to be 1% and the monitoring labor was assumed to be $0.022/bushel which is equivalent to 12.5% of total labor. The sensors were again assumed to reduce postharvest loss by 50% or 0.5% and reduce monitoring labor by 50% or $0.011/bushel.

Costs		
	Sensors	$12,314.08
	Total Cost	**$12,314.08**
Benefits		
	Wage savings	$4,071.05
	PHL savings	$9,200.11
	Total Benefits	**$13,271.16**
Net Present Value B-C		**$957.08**
Benefit-Cost Ratio B/C		**1.08**

Table 3: Benefit-Cost Analysis for the Conservative Scenario.

In this scenario, the total costs unchanged, but the savings from labor hours elimination and PHL reduction decrease to $4,071 and $9,200. The present value of using sensors technology for the future ten years is $957 and the benefit-cost ratio is 1.08.

5.3. Benefit-Cost Analysis for the Most Likely Scenario

In this scenario, considered to be the most likely, the postharvest loss was assumed to be 1% and monitoring labor was assumed to be $0.04/bushel which was 25% of total labor. The sensor was assumed to reduce monitoring labor by 50% or $0.022/bushel and reduce postharvest loss by 50% or by 0.5%. The present value of using sensors technology for the future ten years is $5028 and the benefit-cost ratio was 1.41.

Costs		
	Sensors	$12,314.08
	Total Cost	**$12,314.08**
Benefits		
	Wage savings	$8,142.10
	PHL savings	$9,200.11
	Total Benefits	**$17,342.21**
Net Present Value B-C		**$5,028.13**
Benefit-Cost Ratio B/C		**1.41**

Table 4: Benefit-Cost Analysis for the Most Likely Scenario.

5.4. Sensitivity Tests

The sensitivity test is taken in the most likely scenario. The postharvest loss is 1%, monitoring labor takes 25% of total labor, and the sensor reduces both postharvest loss and monitoring labor by 50%.

5.4.1. Savings from Monitoring Labor Percentage

Keep postharvest loss and loss reduction by sensors constant, and change the percent of monitoring labor to 15%, 20%, 25%, 30%, and 35% of the total labor. The sensor cost is not affected by the change of monitoring labor, while the present value of benefit continuously increases when the percentage of monitoring labor increases. The benefit-cost ratio increases, which indicates that using sensors would be more profitable if the monitoring labor percent is higher before using sensors.

The percent change in profit is 367.74% while the percent change in monitoring labor is 20%, so the sensitivity of monitoring labor is 1838.68%. The sensitivity is greater than 100%, which shows that the profit is quite sensitive to the percent change in monitoring labor.

Monitoring labor%	15.00%	20.00%	**25.00%**	30.00%	35.00%
PV cost	$12,314.08	$12,314.08	**$12,314.08**	$12,314.08	$12,314.08
PV benefit	$14,085.37	$15,713.79	**$17,342.21**	$18,970.62	$20,599.04
NPV	$1,771.29	$3,399.71	**$5,028.13**	$6,656.54	$8,284.96
B/C ratio	1.14	1.28	**1.41**	1.54	1.67

Table 5: Sensitivity Test for the Percentage of Monitoring Labor.

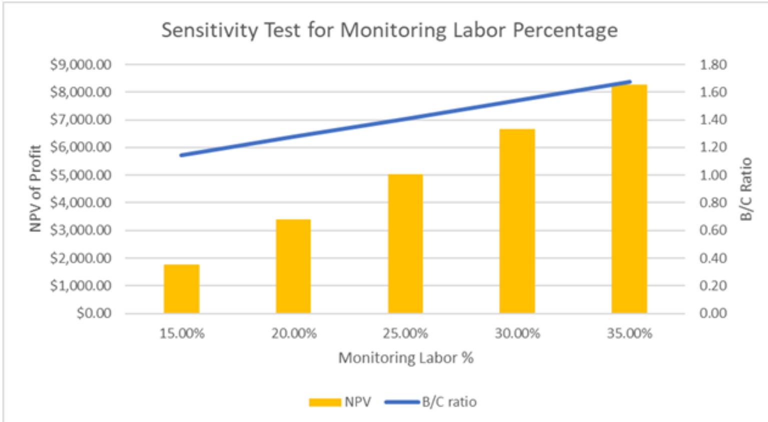

Figure 3: Sensitivity Test for Monitoring Labor Percentage.

5.4.2. Savings from Reduced Postharvest Loss

Keep postharvest loss and the percentage of monitoring labor unchanged, and change the percentage of sensor reducing postharvest loss at 40%, 45%, 50%, 55%, and 60% of that loss. The present value of cost does not change, while the benefit increases from $15502 when sensors reducing PHL at 40% to $19,182 at 60%. The benefit-cost ratio increases while the loss reduction increases, which indicates that the storage is more profitable if the sensor technology can reduce PHL at a higher percentage.

The present value of profit increases from $3,188.10 to $6,868.15, so the percent change is 115.43%. The percent change in loss reduction of sensor is 20%, so the sensitivity is 577.15%. The result is greater than 100%, which shows that the profit is so sensitive to the change in loss reduction.

Loss reduction	40.00%	45.00%	**50.00%**	55.00%	60.00%
PV cost	$12,314.08	$12,314.08	**$12,314.08**	$12,314.08	$12,314.08
PV benefit	$15,502.18	$16,422.19	**$17,342.21**	$18,262.22	$19,182.23
NPV	$3,188.10	$4,108.11	**$5,028.13**	$5,948.14	$6,868.15
B/C ratio	1.26	1.33	**1.41**	1.48	1.56

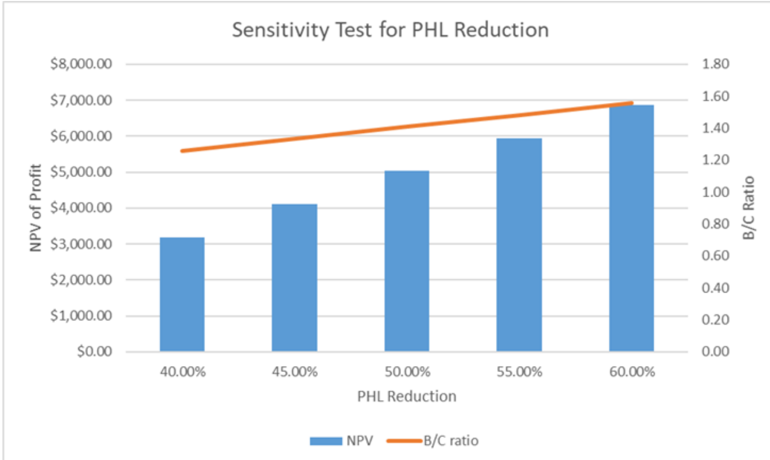

Table 6 & Figure 4: Sensitivity Test for PHL Reduction

5.4.3. Costs of Sensors

Keep the percentage of loss reduction by sensors and the percentage of monitoring labor constant, and change the costs of sensors at 90%, 95%, 100%, 105%, and 110% of the previous costs. The present value of benefit does not change, while the total cost increases from $11082.67 when the costs is at 90% of previous costs to $13,545.49 at 110%. The benefit-cost ratio decreases when the sensor costs increases.

The present value of profit decreases from $6,259.53 to $3,796.72, so the percent change is -39.35%. The percent change of sensor cost is 20%, so the sensitivity is -196.73%. This result is smaller than -100%, which shows that the profit is so sensitive to the change of sensor costs.

Sensor costs	90.00%	95.00%	**100.00%**	105.00%	110.00%
PV cost	$11,082.67	$11,698.38	**$12,314.08**	$12,929.78	$13,545.49
PV benefit	$17,342.21	$17,342.21	**$17,342.21**	$17,342.21	$17,342.21
NPV	$6,259.53	$5,643.83	**$5,028.13**	$4,412.42	$3,796.72
B/C ratio	1.56	1.48	**1.41**	1.34	1.28

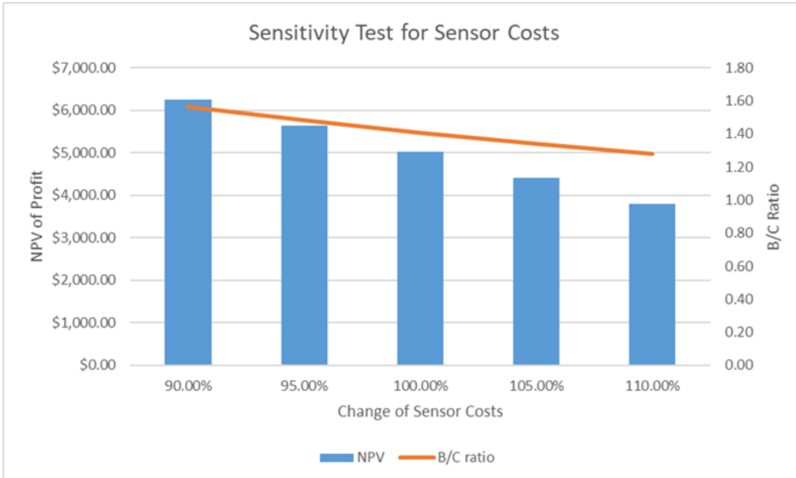

Table 7 & Figure 5: Sensitivity Test for Sensor Costs

CHAPTER VI

RESULT AND CONCLUSION

6.1. Result

In three assumptions, the costs of using sensor systems are unchanged, and the benefits of using the system is coming from the reducing monitoring labor and PHL reduction. The highest benefit-cost ratio is obtained in the optimistic scenario, which is rounded at 2.44; and the lowest one is obtained in the more conservative scenario, which is rounded at 1.08. In the most likely scenario, the benefit-cost ratio is rounded at 1.41. In these assumptions, using sensor technology is profitable, even in the more conservative scenario. Savings from monitoring labor is one of the two sources of benefits. In the optimistic scenario, saving monitoring labor takes up about 54.13% of the total benefits. It decreases to 46.95% in the most likely scenario and 30.68% in the conservative scenario.

Although we assumed a most likely scenario, there are some insufficiencies in this analysis. First, the scale of the storage industry may be too small. It is assumed that the storage only has one grain bin with a capacity of 50000 bushels. The situation would be more convincing if the scale of storage is larger and the number of bins is higher. Second, the storage industry is not labor-intensive, even in developing countries. There is a lack of accurate data for the percentage of monitoring labor in storage industries. We assumed that the monitoring labor is about two hours per week, which may or may not representative. Third, the overall costs are too ambiguous. There are many processes during the storing period, including fumigation, cooling, turning, and aeration, and so on. If there are more data on how the sensor system affects those processes, the assumptions would be more convincing.

6.2. Conclusion

Postharvest loss is a kind of food loss and waste. It occurs from food production to retailers, including losses and wastes during food handling, storage, processing, and transporting. Many factors contribute to postharvest loss, including poor infrastructure, early or late harvest, and unsuitable storage conditions. Developing countries may have more postharvest losses due to these factors.

There are several stages in the U.S. wheat supply chain, including growers, elevators, transportations, processors, and consumers. Postharvest loss occurs at any stages of within the supply chain. The postharvest loss of wheat in developing countries is estimated to be 20 – 40%, while in the U.S. the loss is estimated to be lower. Insects and mold, heat, and moisture content are the sources of postharvest losses during the storage process of wheat. Therefore, monitoring conditions in the wheat storage bin is essential for the wheat quality that is related to the grade and selling price. After applying a benefit-cost analysis to three scenarios, we come to a conclusion that adopting sensor technology that can continually monitor the conditions of wheat in the storage bin may be a profitable investment.

REFERENCES

An, Kun., and Yanfeng Ouyang. 2016. "Robust Grain Supply Chain Design Considering Post-harvest Loss and Harvest Timing Equilibrium." *Transportation Research* Part E 88 (2016) 110-128.

Bellemare, M.F., M. Çakir, H.H. Peterson, L. Novak, and J. Rudi. 2017. "On the Measurement of Food Waste." *American Journal of Agricultural Economics* 99(5): 1148–1158.

Bolos, L.A., C.J. Lagerkvist, and R.M. Nayga Jr. 2019. "Consumer Choice and Food Waste: Can Nudging Help?" *Choices*. Quarter 1. Available online: https://www.choicesmagazine.org/choices-magazine/theme-articles/examining-food-loss-and-food-waste-in-the-united-states/consumer-choice-and-food-waste-can-nudging-help

Buzby, J., H.F. Wells, and J. Hyman. 2014. *The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States.* Washington, DC: U.S. Department of Agriculture, Economic Research Service, Economic Information Bulletin EIB-121.

Capps, O. and Ariun Ishdorj, Peter Murano, and Maureen Storey. (2016). Examining Vegetable Plate Waste in Elementary Schools by Diversity and Grade. *Health Behavior and Policy Review*. 3. 419-428. 10.14485/HBPR.3.5.2.

Capps, O., A. Ishdorj, P.S. Murano, L. Field, A. Hutto, and M. Storey. 2019. "Waste Not Want Not: Examining Plate Waste of Vegetables in Elementary School Lunches." *Choices*. Quarter 1. Available online: https://www.jstor.org/stable/26758661?seq=1#metadata_info_tab_contents

Dessalegn, T., T. Solomon, T. Gebrekiristos, A. Solomon, S. Seboka, Y. Chane, F. Abay, R. Mahroof, K.A. Roberts, and B. Subramanyam, 2014. "Assessment of Wheat Post-Harvest Losses in Ethiopia." Available online: https://www.k-state.edu/phl/what-we-do/baseline-reports/Ethiopia%20-%20Economics%20of%20Wheat%20post%20harvest%20losses.pdf

Dunning, R.D., L.K. Johnson, and K.A. Boys. 2019. "Putting Dollars to Waste: Estimating the Value of On-Farm Food Loss." *Choices*. Quarter 1. Available online: https://www.choicesmagazine.org/choices-magazine/theme-articles/examining-food-loss-and-food-waste-in-the-united-states/putting-dollars-to-waste-estimating-the-value-of-on-farm-food-loss

Food and Agriculture Organization of the United Nations. 2009. Global Agriculture towards 2050. Food and Agriculture Organization of the United Nations. Available online: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

Food and Agriculture Organization of the United Nations. 2018. Technical Platform on the Measurement and Reduction of Food Loss and Waste. Food and Agriculture Organization of the United Nations. Available online: http://www.fao.org/platform-food-loss-waste/en/

Funk, C.C., and M.E. Brown. 2009. "Declining global per capita agricultural production and warming oceans threaten food security." *Food Security* 1(3):271–289. Available at: https://doi.org/10.1007/s12571-009-0026-y.

FUSIONS (Food Use for Social Innovation by Optimizing Waste Prevention Strategies). 2016. *Estimates of European Food Waste Levels*. Available online: https://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf

Hall, K.D., J. Guo, M. Dore, C.C. Chow, 2009. The progressive increase of food waste in America and its environmental impact. PLOS ONE 4 (11). Available online: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0007940&version=meter+at+null&module=meter-Links&pgtype=Multimedia&contentId=&mediaId=&referrer=&priority=true&action=click&contentCollection=meter-links-click

Hodges, R.J., J.C. Buzby, and B. Bennett. 2010. "Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use." The Journal of Agricultural Science 149(S1):37–45. Available at: https://www.cambridge.org/core/services/aop-cambridge-core/content/view/BF391D722265530B3964F03AD1A7199D/S0021859610000936a.pdf/postharvest_losses_and_waste_in_developed_and_less_developed_countries_opportunities_to_improve_resource_use.pdf.

Johnson, L., R. Dunning, J.D. Bloom, C. Gunter, M. Boyette, and N. Creamer. 2018. "Estimating On-Farm Food Loss at the Field Level: A Methodology and Applied Case Study on a North Carolina Farm." *Resources, Conservation & Recycling* 137: 243–250.

Kenkel, Phil., and Brian Adam. 2018. "Economic Theory Versus Reality in Stored Grain IPM: Theory and Practice in Stored Product Management" Recent Advances in Stored Product Protection. https://doi.org/10.1007/978-3-662-56125-6_12.

Kenkel, Phil and Brian Adam. 2019," Estimating Storage and Handling Losses in U.S. Supply Chain, unpublished report to Centaur Ag, 8-4-2019.

Magan, N., R. Hope, V. Cairns, and D. Aldred. 2003. Postharvest fungal ecology: impact of fungal growth and mycotoxin accumulation in stored grain. Eur. J. Plant Pathol. 109: 723–730.

Ray, Deepak, and Navin Ramankutty, & Nathaniel Mueller, & Paul West, & Jonathan A Foley. (2012). Recent patterns of crop yield growth and stagnation. Nature communications. 3. 1293. 10.1038/ncomms2296.

Sinha, R.N. and H.A.H. Wallace. 1966. Ecology of insectinduced hot spots in stored grain in Western Canada. Res. Pop. Ecol. 8: 107–132.

Sonka, Steve. 2015. "Mitigating Postharvest Loss: Addressing Causes Rather than Symptoms." ADM Institute for the Prevention of Postharvest Loss at the University of Illinois at Urbana-Champaign. Available at: http://publish.illinois.edu/phlinstitute/2015/01/15/mitigating-postharvest-loss-addressing-causes-rather-than-symptoms/.

Thylmann, D., E. Druzhinina, and S. Deimling. 2013. "The Ecological Footprint of Cassava and Maize Post-Harvest-Losses in Nigeria." https://nigeriaagribusinessregister.com/wp-content/uploads/2018/10/Part-II-Food-Losses-Maize-andCassava-Nigeria-Life-cycle-assessment.pdf.

U.S. Environmental Protection Agency. 2018. *Advancing Sustainable Materials Management: 2015 Fact Sheet*. Washington, DC: U.S. Environmental Protection Agency.

Wilson, N.L.W, R. Miao, and C. Weis. 2019. "When in Doubt, Throw It Out! The Complicated Decision to Consume (or Waste) Food by Date Labels." Choices. Quarter 1. Available online: http://www.choicesmagazine.org/choices-magazine/theme-articles/examining-food-loss-and-food-waste-in-the-united-states/when-in-doubt-throw-it-out-the-complicated-decision-to-consume-or-waste-food-by-date-labels

VITA

Xuecheng Cai

Candidate for the Degree of

Master of Science

Thesis: ESTIMATION OF POSTHARVEST LOSS IN US WHEAT SUPPLY CHAIN: BENEFIT-COST ANALYSIS FOR SENSOR MONITORING SYSTEM

Major Field: Agricultural Economics

Biographical:

Education:

Completed the requirements for the Master of Science in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in May, 2021.

Completed the requirements for the Bachelor of Science in Agribusiness at Oklahoma State University, Stillwater, Oklahoma in 2018.

Completed the requirements for the Bachelor of Science in Agricultural Economics at China Agricultural University, Beijing, China in 2018.