Evaluation of ambient and chilled aeration strategies to maintain the quality of stored grain in tropical climates and during summer in temperate climates

by

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B.S., Universidad de Costa Rica, 2012
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A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Grain Science and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Approved by:

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Abstract

The use of grain aeration as a tool to minimize post-harvest losses requires lower ambient temperature (≤ 20°C) and relative humidity (≤ 70%) conditions than what is usually available during the summer season in temperate climates and throughout the year in some tropical climate regions. Warm and moist conditions contribute to pest problems and increase dependence on chemical control for pest reduction as part of grain management strategies. The grain chilling technology is a non-chemical alternative to cool grain stored under high risk climatic conditions. For this research project, the grain chilling technology was tested in a 1,350-ton low moisture content wheat silo during the 2015 and 2016 summer harvests in Kansas. The grain temperature was lowered from a maximum of 39°C to a minimum of 17°C in less than 250 hours. The results showed that chilled grain maintained at temperatures under 20°C reduced the development rate of insect pests compared to grain stored at temperatures over 25°C and cooled with ambient aeration. However, the cost of grain chilling was calculated to be between 0.26 and 0.32 $/t higher than using ambient aeration. Through computer simulation it was possible to evaluate the performance of the grain chiller against four different ambient aeration strategies for paddy rice stored under the tropical climatic conditions of the North Pacific coast of Costa Rica. After six months of storage, the minimum grain temperature achieved through ambient aeration was 30.8°C using an aeration strategy based on a grain-ambient temperature differential greater than 10°C. Grain chilling lowered the average grain temperature from 35°C to below 15°C in 117 hours and the maximum average temperature it registered after six months of storage was 15.5°C. The economic evaluation of the simulated ambient aeration and chilling strategy determined that the operational costs of grain chilling were between 2 and 4 $/t lower than ambient aeration plus fumigation. However, the initial cost of the grain chiller made the net

present cost (NPC) of the chilling strategy between 0.22 and 0.85 $/t higher than the cost of ambient aeration plus fumigation over a 10-year analysis. Several potential financial options were analyzed to make the grain chiller more economically feasible for a rice miller in Costa Rica. It was concluded that the grain chilling technology can reduce grain temperatures below 20°C in a relatively short period of time, which helps control insect populations and maintain grain quality during summer storage in temperate climates and in tropical climates. Utilizing grain chilling reduced operational costs between 78% and 88% when compared to using chemical control of pests. Additionally, it was determined that an initial cost of $74,700 for the grain chiller would require a 16% discount or at least 10,641 t to be chilled annually to make this technology viable for the Costa Rican rice milling industry. Leasing the grain chiller (ten equal payments of $10,926) or adding a premium sell price of 1 $/t to chilled rice would make this technology feasible compared to the traditional grain management strategies utilized in Costa Rica.

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Acknowledgements

First of all, I would like to thank my advisor Dr. Carlos A. Campabadal for all his support, advice, encouragement and valuable friendship. I have learned the value of hard work and dedication from your example. Thank you for believing in me and I look forward to our continued relationship.

I would also like to recognize the dedication towards this project of my committee members, Dr. Dirk E. Maier, Dr. Thomas Phillips, and Dr. John Lawrence. This project would not have been possible without your support, expertise and valuable guidance. I learned a lot from each one of you.

Special recognition to everyone involved in the collection, processing and analysis of data. To Drs. Flavio and Sonia Lazzari for their support during the field trials of the grain chiller. To Francisco Ayala and the grain chilling company Coolseed, for providing the grain chilling unit used in this project, as well as the technical support and valuable insights. To Sam Cook, for his hard work in the collection of samples, installation of temperature cables in the grain silos and most of all, for his great support and friendship. To the company TSGC Inc. for providing the temperature cables installed in the grain silos during the grain chilling trials. To Shawn Thiele and the undergraduate student helpers from the Hal Ross flour mill for their willingness to help me out in the grain sample collection. Special thanks to John Boley and all the staff of the Wakefield Farmer's Cooperative for allowing us to develop the grain chilling trials in their facilities and for all your help throughout the trials. To the Stored-product entomology lab for their help with the elaboration and analysis of the insect bioassays and probe traps. To Daniel Brabec from the USDA-ARS for providing the equipment for the detection of insect fragments and internal feeders. To the Kansas Grain Inspection Service in Topeka, KS for providing the grain quality and grading analysis of the wheat samples. To Kizito Nishimwe and the Seed Pathology laboratory at Iowa State University for their help in the analysis of the fungi samples. To Ben Plumier and Matthew Schramm for their patience and willingness to help me out with the grain aeration computer model. To Rodney Rulon for providing his original spreadsheet with the net present cost economic model utilized for the economic analysis. To all the entities, people and grain storage companies in Costa Rica that provided information for the economic analysis, especially to Miguel Hernandez and Ruben Gigena, whose vast knowledge of the grain industry and willingness to share it made this chapter possible.

I would also like to thank the IGP staff for their help in various administrative subjects and for their valuable friendship. Also, to the whole Grain Science family for the support.

Special acknowledgement to the Kansas Crop Improvement Association for the financial support of the grain chilling trials.

And of course, to my family and friends for always being there for me and giving me their support when I most needed.

Dedication

To my girlfriend Adriana. I would not have done it without you by my side. Te amo!!

To my mom and my aunt Sylvia. You made all this possible.

To God almighty Father, all the glory and honor.

Chapter 1- Introduction

1.1 Post-harvest losses

Cereal grains are the main food source of energy for most of the world population, and as so, the availability of this staple food source is an indicator of the level of food security. According to FAO (2013), cereals occupy more than half of the world's harvested area, but even though the per capita consumption has increased substantially in many parts of the world over the last decades, the cereal grains have only seen a net increase of 2% in yield over the last decade.

Currently the world faces an unprecedented challenge, to increase the food production for an estimated 60% increase in demand by the year 2050 (FAO, 2016). Added to this, we have the issue of a global climate crisis that puts in danger the food supply in the near future. This is probably the biggest challenge the world has ever faced, and in order to find a sustainable and long-lasting solution to it, there has to be a joint effort of all the sectors involved in developing regulations, research and implementation, in order to adapt and increase the efficiency of the agricultural and food systems (FAO, 2016).

According to the last report of the FAO (2016), about one-third of the food produced in the world is lost or wasted at post-harvest. Reducing post-harvest losses would not only improve the efficiency of the food system but would also reduce pressure exerted on natural resources due to the great amount of land, water, inputs, and energy that is wasted on producing food that does not even reach the consumer. At the same time, this issue also represents unnecessary emissions of millions of tons (t) of greenhouse gases.

Post-harvest loss of grain crops can be classified in many ways, but probably the most accepted is by classifying them in physical losses, which refers to the damaged product caused by inadequate drying, grain respiration, effect of insects, microorganism like fungi, and other pests. These losses also have an effect in product value that reflects in reduced market price. These losses occur throughout the various stages of the post-harvest operation but a great portion of it is due to poor storage conditions, which currently is more of a critical problem in developing countries (An and Ouyang, 2016; Guillou and Matheron, 2014).

1.2 Stages of grain post-harvest

After the grain is harvested, it has to go through a series of steps before reaching the final consumer. These steps include receiving, drying, storage and processing.

1.2.1 Receiving and grain grading

When the grain first arrives to the grain storage facility or grain elevator, as it is called in the U.S., the weight and moisture content (MC) is determined before the grain goes into the storage silos. After the MC and weight have been registered, and before unloading, the grain is usually sampled to determine its quality grades. This information will be used by the grain storage facility management to make informed decisions about the way the grain is going to be handled and commercialized, reason why the sampling has to be as representative as possible (Reed, 2006; Serna-Saldívar, 2010).

In order to minimize the possibility of error in the sampling and analysis of grain, standardization is key and has to be performed in the same way along the grain handling process. In the United States, the U.S. Department of Agriculture (USDA) through its Grain Inspection, Packers & Stockyards Administration (GIPSA) is the government agency that develops grain-grading standards. Inside GIPSA, the Federal Grain Inspection Service (FGIS) has the responsibility to provide grain grading services, deliver official grades for exported grain, and supervise private and state grain-grading agencies, among other duties (Reed, 2006).

According to the GIPSA-FGIS standards, the grain is given a grade depending on its quality, and this can be as high as one (U.S. #1) which is the best quality, down to six (U.S. #6) in some grains. These grades depend on several factors that are different for every type of grain. As an example, for wheat, these factors are (FGIS, 2016; Reed, 2006; Serna-Saldívar, 2010):

- Test weight: relationship between the weight of the commodity and the volume it occupies. This test is used to estimate bulk density or volumetric weight and is usually reported as pounds per bushel (lb/bu), which is equivalent in the SI units to kilograms per cubic meter (kg/m^3) or kilograms per hectoliter (kg/hL). It is an important piece of information to determine the total storage capacity of a grain elevator and milling yields; higher test weight usually means higher milling yield.
- Dockage: all matter other than wheat that can be removed from the sample by an FGIS approved device. Also underdeveloped, shriveled, and small pieces of wheat kernels. It is reported as a percentage. High concentrations of dockage are detrimental for test weight and also makes the grain more prone to deterioration during storage due to increased activity of molds and insects.
- Foreign material: all matter other than wheat that remains in the sample after the removal of dockage. Reported as percentage. Usually, foreign materials foster insects of stored-products, which is an undesirable trait.

- Damaged kernels: pieces or whole kernels, and other grains that are badly damaged by weather, diseases, insects, mold, etc. Reported as percentage. It is an undesired trait for grain processors.
- Shrunken and broken: all matter that is sieved out after the dockage and other impurities have been removed. Reported as percentage. This type of kernel damage causes a reduced size and endosperm, which reduces milling yield.
- Total defects: Sum of damaged kernels, foreign material, and shrunken and broken. Reported as percentage.
- Insect damaged kernels (IDK): wheat kernels with a distinctive perforation made by insect reproduction or feeding. Reported as a count. IDK is related to past or current level of infestation of a commodity and the possibility of finding live insects or potential insect fragments in the flour.
- Moisture content (not a grading factor): commercially, it represents the relationship between the water content of a grain and the total weight, which refers to the water content plus the dry matter (proteins, fiber, lipids, minerals and starch). This is known as wet basis MC and is reported as the percentage of water out of the total weight. Although MC is not taken into account for grading the wheat, it is extremely important for drying, storage and commercialization purposes (wheat price may be discounted if it is delivered with a high MC and requires drying).

1.2.2 Drying

Some grains, like maize, sorghum, paddy rice, among others, are harvested at MCs higher than those recommended for safe storage in order to reduce the probability of excessive field losses (lodging, ear droppage, kernel shattering) associated with allowing the grain to dry in the field. Nevertheless, this excess moisture must be removed from the grain before storage or else it will spoil very quickly, mainly due to the development of fungi on grain with a MC in equilibrium with a relative humidity (RH) above 70% (Loewer et al., 1994).

To reduce the moisture, grain dryers supply heat energy and low-moisture air so that the water can evaporate and the water molecules can break free of the forces that bind them to the grain (Reed, 2006).

There are many drying methods that have different advantages, disadvantages and limitations. According to Loewer et al. (1994), some of them are:

- Natural air drying: unheated air is forced through the grain mass until it reaches an equilibrium moisture content with the air.
- Low temperature drying: process by which the drying air is slightly heated (5°C above ambient conditions), which decreases the RH of the air, so improving the drying potential of the air.
- Batch drying: individual batches of grain are dried using high temperatures (70°C to 90°C) at high drying rates.
- Continuous flow drying: the constant flow of grain through the grain dryer allows the use of higher drying temperatures (80°C to 100°°C) than batch drying. This can be subcategorized in cross flow (drying air blown across grain column),

counter flow (drying air and grain flow in opposite directions) and concurrent flow (drying air and grain flow in same direction).

1.2.3 Storage

Immediately after harvest, dry grain has to be stored in an environmentally proper manner to maintain its quality until it has to be processed. Grain can be stored even for years under proper conditions (below 20°C and 70% RH) with almost no loss of quality, however, under improper conditions (above 20°C and 70% RH) grain can begin to spoil in just a few hours (Loewer et al., 1994).

The purpose of storage facilities is to protect the grain from weather, insects, fungi, and vertebrate pests like rodents, in order to maintain a stable supply of safe and nutritious food throughout the year, not only at harvest. Properly designed storage facilities should also facilitate the management of the commodity (Serna-Saldívar, 2010).

1.2.3.1 Stored-product insects

Insects of stored products are a very serious problem in most parts of the world, especially in tropical regions where climatic conditions are ideal for their development during the majority of the year. The physical and quality losses that these pests cause, plus the costs of control and eradication of infestations, account for a significant part of the value of most commodities (Rees, 2004).

Stored-product insects that feed directly from the grain are categorized as primary and secondary pests. Primary pests are those that can attack intact grain since they have mouth parts that are capable to chew through it. Once they perforate the grain they feed from the endosperm and germ. The damage that these insects cause is especially problematic in wheat, to an extent that is even given a separate designation to the rest of the damages. Kernels bored by these insects are categorized as IDK by the FGIS standards and reduce the market value of the wheat. Their immature stages develop and feed inside of the grain. The fact that these insects spend most of their lives inside the grain complicate their detection and control, and create additional issues in the processing stage due to contamination of the processed food with insect fragments. Some examples are the lesser grain borer (LGB) *Rhyzopertha dominica* and maize weevil (MW) *Sitophilus zeamais* (Reed, 2006; Rees, 2004).

Secondary pests are those that take advantage of the damage made by primary pests to feed from the remains. Some examples are red flour beetle (RFB) *Tribolium castaneum*, saw toothed beetle (STB) *Oryzaephilus surinamensis,* and rusty grain beetle (RGB) *Cryptolestes ferrugineus* (Rees, 2004). They may feed even from slightly damaged kernels and consume the endosperm and/or germ. Due to their high fecundity and relatively short developmental time, large infestations can develop quickly, which causes an increase of the bulk temperature and relative humidity (RH), which consequently can cause fungi problems (Reichmuth et al., 2007).

The control of these pests is based primarily on the use of chemicals, either as preventive control through the application to the empty structure before the new harvest is loaded, or by the use of protectants once the grain is loaded or being loaded into the storage structure. Grain protectants, either solid or liquid, can be mixed with the grain when loading the silo or applied to the top surface of the grain mass once it is loaded. Grain fumigants like aluminum or magnesium phosphide are also commonly used to eliminate insect infestations (Arthur and Subramanyam, 2012). The over dosage or inadequate use of the few chemicals that are used in store-product protection all over the world have created pesticide resistance. It is possible that at least one major pest species has developed resistance to the compounds used as stored-product pesticides somewhere in the world. In a globalized economy like the one we live in today, where millions of tons of grain are traded daily, it is very easy for insects with a resistance trait to be transferred from one country to another (Opit et al., 2012).

1.2.3.2 Stored-product fungi

Fungi that grow in cereal grains at MCs in equilibrium with air at RHs between 65% and 90%, are called storage fungi (Christensen and Meronuck, 1986). The most prevalent and damaging storage fungi are *Aspergillus* spp. (Christensen and Meronuck, 1986). If the conditions are adequate for the species of this mold to grow, the grain can spoil in a matter of days (Christensen and Meronuck, 1986; Reed, 2006)

Although *Penicillium* spp. and *Fusarium* spp. are more of a problem in the field than in storage, some species of these genera can invade grain in the field and continue to grow during storage if the grain is not properly dried and it goes into storage at a MC in equilibrium with air at RHs between 85% and 90% (Christensen and Meronuck, 1986).

The most common damage caused by fungi is caking, which refers to discolored kernels stuck together. Caked grain usually has a musty, unpleasant smell that makes it inadequate for consumption and also causes problems during unloading of grain in a storage structure since the caked parts of the bulk adhere to the floors and walls. Other effects of fungi during storage are: increased free fatty acid production, loss of processing properties, detrimental seed viability, and rapid heating of the bulk.

In addition to spoilage and the loss of quality the storage fungi cause, there is also the issue that under appropriate conditions, they can produce compounds that are toxic to humans and animals called mycotoxins (Christensen and Meronuck, 1986). These toxins are carcinogenic and some of them are tolerant to extreme temperatures, which means that even after cooking or processing these mycotoxins can still be present in the food or feed (Navarro et al., 2002a).

1.2.3.3 Control of temperature and relative humidity

Stored-product insects develop better at a certain range of temperature (Appendix A) and RH. For most species of insects, the optimal development range is between 25°C and 33°C with a RH above 70%, which is also the RH ideal for fungi growth (Christensen and Meronuck, 1986; Navarro et al., 2002). If the conditions inside the storage structure are modified and controlled to a point beyond this threshold, the safe storage time of the grain can be increased substantially.

One of the safest and most widely used technologies to control the conditions inside the grain structure is ambient grain aeration. By definition, grain aeration consists of blowing relatively low volumes of ambient or suitable conditioned air through a bulk of grain for the improvement of its storability (Foster and Tuite, 1992; Navarro, 1982). This technology is used commonly in bulk storage structures to reduce and equilibrate the temperature of the storage ecosystems with the purpose of creating unfavorable conditions for the development of all organisms that cause grain spoilage (Navarro et al., 2002). If aeration is properly managed, it is also considered the most cost-effective method to preserve grain quality (Reed and Arthur, 2000).

Although the primary objective of aeration is to cool grain in order to control fungi and insects, it has other benefits like holding wet grain for limited periods of time before it is dried, the elimination of temperature gradients, moderation of moisture gradients, and removal of small amounts of moisture (Reed, 2006).

In the last few decades, the use of artificial refrigeration or grain chilling has become very popular to control the temperature of stored grain in climates that are not suitable for ambient aeration. This technology is based on the removal of heat and moisture from the air before it is blown into the grain bulk. This is made possible by the passage of ambient air through evaporator coils in the refrigeration unit (Maier and Navarro, 2002).

Grain chilling makes it possible to achieve low temperatures (10°C to 15°C) in climates where this would not be possible using ambient air. These low temperatures reduce insect and fungi activity, thereby reducing the need of chemical control (Burks et al., 2000).

1.2.4 Grain processing

All cereals have to go through at least a minimum process of preparation to make them more palatable, digestible and convenient for consumption by humans and animals.

The process of milling is the most commonly used method to process cereal grains and give them added value. Milling consists of separating the different anatomical parts of the grain with the aim of obtaining the endosperm as a whole, pieces, meals or flours (Serna-Saldívar, 2010).

The objectives of milling may differ among grain species, for example, the objective of rice milling is to obtain high yields of white polished or head rice, but for wheat, depending on the class of wheat, the objective is to obtain high yields of semolina or flour (Serna-Saldívar, 2010). Although the end-product may be different for each grain, the main goal of any grain-processor is to deliver the best quality of a desired product to the end-consumer. This is only achievable by using grain that complies with the specifications required to produce a high-quality end-product. These specifications can be related to physical properties, nutritional value, or chemical characteristics.

Probably the industry that is most susceptible to quality changes from year to year or from location to location is the wheat milling industry, since it has very unique requirements for each of its end-products. End-product quality or flour quality, as it is called by wheat millers, has different connotations depending on the end-use of the flour and is dependent on flour strength, which refers to the presence or absence of strength factors. The strength factors are associated with flour or wheat protein. Higher concentration of protein is usually preferred for pan breads, while lower protein is preferred for some bake goods (Mailhot and Patton, 1988). There are many standardized methods to determine flour quality, among them are the analysis of protein content, dough tests like the mixograph and baking tests like the loaf volume.

Protein content or crude protein is the percentage of protein by weight in a sample. This is a very important factor, since it relates to many processing properties like water absorption and gluten strength. Depending on the class of wheat and end-product, low or high protein is desired (U.S. Wheat Associates, 2016).The ultimate criteria of flour quality are the dough and bake tests. These tests determine physical and chemical properties of the dough that are very important for final consumers. Among these characteristics, some that can be mentioned are strength, extensibility and water absorption. There are many methods that can be used to determine these properties but the most practical one remains to be the mixograph, which records the force needed to mix water and flour into dough and the time it takes to achieve the peak consistency of the dough. Long peak times indicate strong dough properties. This information is also used to develop the loaf volume tests, which determine the volume of the test loaf after baking. Higher volumes indicate better baking performance for pan breads (U.S. Wheat Associates, 2016).

1.3 History of grain aeration and chilling

Ambient aeration was first implemented in North America around the second half of the 20^{th} century and used as an alternative to the movement of grain from one silo to another with the purpose of drying and cooling the grain, since such movement caused breakage and represented a big investment of time and money (Fornari, 1982). Over the years, it has evolved and the knowledge about the implementation of ambient grain aeration in different latitudes of the world has been the focus of many scientific publications (Casada et al. , 2002; Foster and Tuite, 1992; Lawrence and Maier, 2011; Navarro, 1982).

Although the most extensive research has been developed in temperate climates, since the 1960s a few articles have been dedicated to the implementation of ambient aeration in tropical climates (Calderon, 1974; Navarro et al., 1969; Recio, 1999; Zeledon and Barboza, 2000). Nevertheless, grain aeration in tropical climates is still a challenge due to the inadequate conditions for ambient aeration that predominate. This issue has made it necessary to consider alternatives to ambient aeration, like grain chilling (Navarro et al., 2002)

The development of commercial grain chilling systems that can lower the temperature of stored commodities, even under unfavorable climatic conditions, has been the most significant technological innovation of the last few decades in the stored-product industry. This technology was first developed in Europe in the late 1950s to dry and preserve wet grain. In the United States, the first field trials in grain chilling date back to 1959, but the commercial implementation of this technology did not begin until the early 90's, when Purdue University in cooperation with AAG manufacturing (Milwaukee, WI) developed the first trials of a new grain chiller, which resulted in the commercialization of the first U.S.-built grain chillers (Maier, 1994). Since then, several field and computer simulation studies have demonstrated successful control of temperature using chilled aeration in maize, wheat and rice (Ileleji et al., 2007; Maier et al., 1996; Maier et al., 1992; Maier, 1994).

The first published grain chilling trials in warm climates came from Queensland, Australia where they used a locally manufactured unit to maintain grain temperatures below 13°C for about ten months (Sutherland et al., 1970). In 1970, this technology was implemented in Israel to chill wheat and soybeans (Calderon, 1972).

In Latin America, the field trials date back to the decade of the 80s in Argentina and Colombia, where the main use of the grain chilling technology was to preserve rice and oilseeds (Maier and Navarro, 2002).Since then, several wheat and rice industries adopted the grain chilling technology to preserve their product using European grain chillers coming from Spain (Consergra, Barcelona, Spain) and Germany (GraniFrigor, Amtzell, Germany). In the last few decades the acceptance of this technology has noticeably increased in South America mainly because of the emergence of local producers like the company Coolseed (Santa Tereza do Oeste, Brazil).

The use of this non-chemical method to preserve the quality of stored grain has seen an increase in popularity in the last decades due to the need for alternatives to chemical control like extreme temperatures, modified atmospheres, inert dust, among others (Subramanyam and Hagstrum, 2000). The recent findings of resistance of insects to the fumigant phosphine (aluminum or magnesium phosphide) and the current trends of chemical-free products, has increased the interest in this technology (Maier and Navarro, 2002).

Although grain chilling has been around since the 1950s, the information of feasible strategies that can be implemented in warm and humid climates is still scarce and very much needed, especially in regions like Central America where this technology is not that popular yet.

Chapter 2- Objectives

The main objective of this research was to evaluate the effectiveness and feasibility of the grain chilling technology to maintain the quality of stored-grain in tropical climates and during summer storage in temperate climates. The evaluations made in the field and applied to other latitudes through computer simulation will contribute valuable information to determine the technical feasibility and economic viability of the grain chilling technology for the given conditions. This study was pursued through the following three objectives, and each of which was addressed in a separate chapter.

1. Evaluate the advantages of using grain chilling technology to preserve the quality of wheat and reduce post-harvest losses caused by insects and fungi, compared to the conventional aeration and storage strategies used during summer storage in Central Kansas.

2. Develop potential ambient and chilled aeration strategies for paddy rice stored under the tropical weather conditions of the North Pacific coast of Costa Rica, using an existing computer simulation model that can analyze several aeration alternatives in a short period of time, and that can be adjusted to other tropical regions and stored-products in order to reduce post-harvest losses and increase safe storage time.

3. Compare the costs of the ambient and chilled aeration strategies developed for the tropical weather conditions of the North Pacific coast of Costa Rica and analyze them using a Net Present Cost (NPC) economic model, so that farmers and grain handling,

storage, and processing companies can objectively evaluate their options and determine what is best for them.

Chapter 3- Chilled aeration to control pests and maintain quality during the summer storage of wheat in north central Kansas

3.1 Introduction

Grain that is harvested during the summer season of the Northern Hemisphere presents the challenge that it is collected when the ambient temperature is high (26°C to 37°C). In these conditions, the grain goes into storage at a high temperature, which makes it prone to immediate insect infestation and mold growth that can affect its quality, therefore it is imperative that the stored-grain be cooled down as soon as possible (Reed and Arthur, 2000). Nevertheless, cool ambient conditions may be limited during part of the season, thus the use of chilled air could be considered. Chilled air refers to aeration air that is cooled before it comes contact with the grain by passing through an evaporator coil of a grain chilling unit (Maier and Navarro, 2002). When the chilled air comes in contact with the grain, it lowers the temperature of the grain, independent of ambient conditions (Maier and Navarro, 2002).

Grain chilling works independent of ambient conditions and provides the opportunity to cool grain temperatures below 15°C immediately after summer harvest, which reduces insect populations and consequently the need for chemical control (Navarro et al., 2002). Given that grain is an excellent insulator, in typical Midwest locations, once a silo is cooled down, it may only need short rechilling periods before cool ambient conditions are available in the late fall to lower temperatures further for storage through the winter and beyond (Maier, 1994).

The advantages of using grain chilling for cooling wheat, maize, sorghum, and rice have been documented in several studies performed in different locations of the United States

(Hellemar, 1993; Ileleji et al., 2007; Maier et al., 1989; Maier et al., 1996; Maier et al., 1992; Maier, 1994; Maier et al., 1997; Maier and Navarro, 2002).

According to Maier (1994), the first use that was given in the United States to the grain chilling technology was in 1959 to preserve the quality of damp sorghum for feeding purposes in Texas. The capability of storing damp grain using grain chilling was also studied by Maier et al. (1989) through the storage of 609 t of 18% MC maize during a seven-month period. Storing high moisture grain at low temperature (4°C to 6°C) resulted in significant savings in drying fuel and shrinkage given that the grain remained less hours in the grain dryer; it also represented higher profits due to the possibility of blending this maize with low moisture loads.

Based on field tests of chilled aeration in low-moisture wheat stored in Michigan, Maier (1992) simulated chilling in the Midwestern region of the U.S. The computer simulation showed that chilled aeration was capable of lowering the temperature of 579 t of wheat from 30°C to 15°C in just one week. Continuous ambient aeration took 1.5 times longer than chilled aeration to cool the grain down to 10°C, which caused that the dry matter losses (DML) were 63% to 67% times higher with the ambient aeration strategy than with the chilled aeration strategy. Field research results of wheat grain chilling in the Midwest support the observations made by Maier et al. (1992). The trials developed by the company PM-LUFT (Kvänum, Sweden) in 2,500 t silos located in Central Kansas compared chilled aeration vs. no aeration through a storage period of four months. The chilling trial reduced the temperature of the wheat from a range of 32°C- 35°C to 15°C- 17°C in six days, while the non-aerated wheat was kept at 35°C through the whole storage period which caused additional costs in fumigation, turning and shrink losses. While the grain chilling electric cost was less than $0.16/t, the cost of fumigating and turning the non-aerated silo was $0.67/t plus the additional shrink loss cost of approximately 7.5 t from the bulk (Hellemar, 1993).

In 1994, researchers at Purdue University developed and tested a prototype grain chiller to compare chilled aeration vs. ambient aeration in a commercial grain facility that stored popcorn in steel silos. The results showed significantly fewer Indianmeal moth (IMM) *Plodia interpluctella* in the chilled silos than in the conventionally managed silos. The chilled aeration also showed competitive usage costs compared to conventional aeration plus fumigation (Mason et al., 1997). Maier et al. (1996) demonstrated that grain chilling is also effective to control the maize weevil (MW) *Sitophilus zeamais*. They proved this through computer simulations that compared eight ambient and chilled aeration strategies in three different locations of the U.S. The strategies included combinations of fall aeration, fumigation and chilled aeration. Chilling the grain below 17°C in a short period of time proved to be the best strategy to avoid DML and also helped reduce the populations of MW. For all locations, controlled fall aeration with summer chilling was proposed as an adequate non-chemical preventive strategy. Similar results were observed by Ileleji et al. (2007).

Although the most popular benefit of using chilled air to lower the temperature of grain is the effective control of insect populations, there are other benefits that come from the grain chilling technology like the possibility of storing damp grain for a limited time, predictable drying capability and better preservation of end-use quality (Hellemar, 1993; Maier and Navarro, 2002). According to Wang and Flores (1999), the end-product quality of the flour and baking characteristics can be improved during wheat storage due to the aging effect it has on the wheat. Nevertheless, long-term storage can have a detrimental effect since the wheat is exposed for a longer time to changes in temperature, moisture, and pests. According to the experiments developed by Gonzalez-Torralba et al. (2013) in a Mediterranean climate, and Mhiko (2012) in Zimbabwe, Southern Africa, wheat stored at temperatures lower than 15°C will maintain the end-product quality for storage periods longer than five months.

According to the information given by Maier and Navarro (2002) grain chilling is also effective to maintain the end-product quality of rice and reduce the percentage of broken kernels that may be caused by using ambient aeration due to the fluctuations of moisture that crack the grain.

The objective of this study was to evaluate the advantages of using grain chilling technology to preserve the quality of wheat and reduce post-harvest losses caused by insects and fungi, compared to the conventional aeration and storage strategies used during the summer storage in Central Kansas.

3.2 Materials and methods

This research was developed at the Wakefield Farmer's Cooperative in Wakefield, Kansas located in Clay County, from August to November 2015 and from June to September 2016. The research trials were conducted in two 1,350 t steel silos of 11.3 m diameter and 16.8 m in height from the bottom to the eave. Before the 2015 and 2016 harvest, the walls of the silos were cleaned up to 6 m from the bottom with a pressure hose when all the grain from the previous harvest had been unloaded. The remaining grain on the floor of the silo was vacuumed out. In these silos there were two centrifugal fans, each with a 10 HP (7.5 kWh) motor (Baldor Electric Co., Fort Smith, AR). The fans were installed at the bottom of the silo in a parallel arrangement. Both silos were filled almost completely with hard red winter wheat (HRW) harvested in the summer of 2015 and 2016 from several locations within a 24 km radius of

Wakefield, Kansas. One of the silos was chilled (Chilled silo) and the other one was used as an experimental control silo (Control silo) managed by the Cooperative using their regular grain quality management strategies.

3.2.1 Grain chiller specifications and setup of trials

The grain chiller GCH-20 used in this project was provided by the Brazilian company Coolseed (Santa Tereza do Oeste, Brazil). This equipment has the rated capacity to chill 100 to 170 t per 24-hour continuous operation in silos of up to 1,800 t according to specifications of the manufacturer. The basic function of the grain chilling unit is described in Appendix B.

The grain chiller was connected to the grain silo through a 4.6 m thermally insulated duct of 0.4 m diameter into a steel connector of a “T” shape where it exit into two 1.8 m ducts of 0.5 m diameter that were connected into the two inlets of the fan transitions parts of the two aeration fans of the silo (fig. 3.1). To facilitate the entrance of the chilled air from the grain chiller into the treated silo, both aeration fans were removed. The plenum setup inside the silo consisted of two internal ducts (one per inlet) going straight to about the center of the silo. The silo’s roof had three outlet vents and two suction fans that occasionally worked during the length of the trials.

Figure 3.1. Grain chiller GCH-20 setup: a) Insulated duct connected to the chiller's outlet at one end and to a "T" connector at the other, b) Two ducts attached to the fan transition parts of the aeration fans that were removed.

3.2.2 Monitoring of air conditions, grain temperature, and moisture content

The conditions inside the Chilled and Control silos were monitored through temperature cables (TSGC Inc., Spirit Lake, IA) of 18.3 m in length with thermocouples every 1.8 m, which were installed in three locations inside both the treated and control silos. The cables were located at approximately 2.7 m from the West, North and South walls of the silo. The temperature measured by each of the cables was recorded every hour using a wireless monitoring system model Grain TRAC (AgSense LLC., Hugson, SD). Additionally, temperature and RH sensor type HOBOS (Onset, Bourne, MA) were placed in the fan transitions to record the temperature and RH of the air coming into the silos. HOBOS were also placed outside of the silos to record ambient conditions and inside the silos on the top of the grain mass. In the 2016 trials, additional HOBOS were placed in the fan outlet of the grain chiller and inside the steel "T" to determine how the temperature changed throughout the path of the air.

The wheat MC was measured on grain samples using a GAC 2500-UGMA (Dickey John, Auburn, IL). The grain samples were taken every 30 days from August 15th to November 20th, 2015, and from July 1st to September 27th, 2016. Grain samples were taken with a vacuum probe (Seedburo Equipment Co., Des Plaines, IL) next to each of the three temperature cables every 3 m in depth from the top of the grain mass to 9 m in depth. The samples collected per cable location were put together and homogenized to make up a composite sample per location in each of the silos. The composite sample from each cable was considered a replication for the calculation of significant differences between sampling dates. Statistical analysis was performed using the SAS statistical software (SAS Institute Inc., NC). Statistically significant differences were analyzed with Tuckey's test ($p < 0.05$).

3.2.3 Insect pest population monitoring and quantification

3.2.3.1 Survival and reproduction rate quantification

The effect of chilled aeration on the survival rates of the main insect pests was quantified using insect bioassays with the species Lesser Grain Borer (LGB), *Rhyzopertha dominica* and Red Flour Beetle (RFB), *Tribolium castaneum*. The bioassays consisted of plastic jars of 0.2 L with holes on the bottom and top, and covered with wire mesh to prevent the insects from coming out of the jars and to allow circulation of chilled or ambient air. The LGB jars were filled with approximately 70 g of wheat with 10 g of flour + 5% (wt:wt) yeast mix. The RFB jars were filled with 40 g of broken wheat kernels and 40 g of flour + 5% (wt:wt) yeast mix. This method was modified by the Stored-Product Entomology Laboratory of Kansas State University from the original version described by Chen et al. (2015).

In each of the silos, a bioassay of each species with an exact number of adult insects (50 in 2015 and 30 in 2016) was located in the center of the silo and next to each temperature cable, and buried 0.3 m below grain surface. A fifth bioassay per species was located in one of the fan transition parts. In 2016, three jars per location were put inside the grain mass and transition parts. This modification was made to determine the effect of the chilled aeration on insect population growth along the storage time. One jar from each location was taken out every 28 days.

When the jars were taken out of the silos in each sampling date, the number of dead and live adults were quantified and then discarded. The grain with the larvae, pupae and eggs (if any) were put back into the jars and put in an incubator at approximately 27°C and 70% RH with 16 hours of light and 8 hours of dark for another 28 days. Afterwards, the number of adult insects was counted again. The total progeny number was calculated by the total insect count (initial dead and live insects when cage was pulled out of the silo plus the progeny number after 28 days in the growth chamber) minus the original number of insects put into the jar.

Statistical analysis was performed using the SAS statistical software (SAS Institute Inc., NC). Statistically significant differences were analyzed with Tuckey's test ($p<0.05$).

3.2.3.2 Endemic insect population sampling

Insect populations inside the silos were quantified by placing five perforated insect probe traps model Storgard W.B. Probe II (Trece Inc., Adair, OK) of approximately 0.6 m in length in the North, South, East, West, and Center sections of the silos, approximately 1.5 m from the walls.

The insect probe traps were checked every 30 days from August 15th to November 20th, 2015, and from August 2nd to September 30th, 2016 (last samples were taken out earlier due to a structure damage on the Chilled silo). Insects inside the probe traps were identified (up to the genus level) and the adults of the main insect-pests of stored-products were counted.

3.2.3.3 Estimation of potential insect fragments in flour

Grain samples for this analysis were collected using the same procedure described to collect the MC grain samples. From each of the composite samples, a sub-sample of 500 g was obtained using a Boerner divider (Seedburo Equipment Co., Des Plaines, IL). The sample from each cable was considered a replication for the calculation of significant differences between sampling dates.

Each of the sub-samples were sieved out using a Carter Day Dockage tester (Seedburo Equipment Co., Des Plaines, IL). The dockage was analyzed under a magnifying glass to check for the presence of live insects. Afterwards, the samples were run through a laboratory-scale Entoleter designed by Finner and Singh (1983) and modified by the USDA-ARS Center for Grain and Animal Health Research (CGHAR), to determine the number of insect fragments in the wheat samples (Brabec et al., 2015). The rpm of the Entoleter was adjusted to obtain between 2.5% and 3% of breakage.

After passing through the Entoleter, the broken kernels were collected, sieved, and analyzed according to the procedure developed by Brabec et al. (2015). Finally, the remaining sample was put through an electrically conductive roller mill to detect immature stages (larvae and pupae) that are difficult to detect by the human eye, even under a magnifying glass. This roller mill consisted of two electrically charged steel rolls that created a distinguishable voltage signal when there was an insect infested kernel in the sample, at the same time, it was recorded in a computer connected to the roller mill (Pearson and Brabec, 2007). Each detection of the roller mill was assumed to contribute with one insect fragment.

Statistical analysis was performed using the SAS statistical software (SAS Institute Inc., NC). Statistically significant differences were analyzed with Tuckey's test$(p < 0.05)$. Through the model developed by Brabec et al. (2015), the average number of fragments per sample was related to the limit of 75 fragments per 50 g of flour established by the Food and Drug Administration (FDA) (1988), estimated through the method of analysis of the Association of Official Analytical Chemists (AOAC method 972.32, 1996).

3.2.4 Fungi identification and quantification

Grain samples for this analysis were collected using the same procedure described to collect the MC grain samples. Using the Boerner divider, for each location sample by the temperature cable, sub-samples of 250 g were obtained. The sample from each cable was considered a replication for the calculation of significant differences between sampling dates. The sub-samples were sent to the Seed Pathology Laboratory in Iowa State University, Ames, IA, for analysis.

Each sub-sample was ground individually in the lab to approximately 0.5 mm using a Romer grinding/subsampling mill model 2A (Romer Labs, Union, MO). Each ground sub-sample was homogenized and 1.0 g was taken to make the dilutions. A 1:100 and 1:1000 dilution was made for each sub-sample using sterile deionized water and 0.1 mL was spread on three replications of 1/3rd concentration potato dextrose agar (13 g PDA+ 5 g Bacto agar+ 120 mg Neomycin Sulfate+ 200 mg of Streptomycin Sulfate+ 25 mg of Chlortetracycline per Liter) producing six total 100 mm diameter petri plates per sample, three for 1:100 and three for 1:1000 final dilutions. Afterwards, the plates were placed in an incubator at approximately 25°C, 12 h photoperiod, and were checked 3 and 5 days later for the growth of *Fusarium*, *Aspergillus* or

Penicillium species of fungi. The results were reported in CFU (Colony Forming Units)/g of wheat.

Statistical analysis was performed using the SAS statistical software (SAS Institute Inc., NC) Statistically significant differences were analyzed with Tuckey's test($p < 0.05$).

3.2.5 Grain and flour quality analysis

Grain samples for the grain and flour quality analysis were collected using the same procedure described to collect the MC grain samples. In 2015, the samples were only collected in the first two months of the trial, from August 15th to September 22nd, while in 2016, the sampling period was expanded for one more month, from July 1st to September 27th.

3.2.5.1 Grain analysis and grading

For this analysis, the composite samples from each silo were combined, homogenized and divided using the Boerner divider, so that for each sampling date there was one 2,500 g sub-sample for the Chilled silo and one for the Control silo.

The wheat grading procedure for MC, test weight, dockage, foreign material, damage, shrunken and broken, insect damaged kernels (IDK), and total defects was performed by the Kansas Grain Inspection Service (KGIS) in Topeka, KS.

3.2.5.2 Flour and baking quality analysis

From the composite samples of each cable, a sub-sample of 900 g was obtained using the Boerner divider. The sub-sample from each cable was considered a replication for the calculation of significant differences between sampling dates.

The sub-samples were evaluated in the Wheat Quality Lab (WQL) of Kansas State University. The variables analyzed were: MC and protein content (DA7200 NIR, Perten Instrument) and baking quality (AACC 10-10.03). For the baking quality analysis, all the samples were tempered to 15% before milling and then ran through a mixograph (National Manufacturing Co., Lincoln, NE) before baking in order to estimate mixing time.

Statistical analysis was performed using the SAS statistical software (SAS Institute Inc., NC) Statistically significant differences were analyzed with Tuckey's test$(p < 0.05)$.

3.2.6 Electrical cost of chilled and ambient aeration strategies

The energy consumption used during the chilling treatment was measured using a kWh counter that was installed at the entrance of the power inlet of the chiller. The energy consumed by the aeration fans in the Control silo were calculated according to the hours of operation reported by the Wakefield Cooperative.

The costs of the ambient and chilled aeration process were calculated based on the energy consumption, using an average cost of 0.084 $/kWh (obtained from the local electrical service provider), and taking into account additional charges for basic service and consumption fees.

3.3 Results and discussion

3.3.1 Ambient and chilled aeration trials

3.3.1.1 Trial of 2015

The chilling period spanned discontinuously from August 22nd to September 14th, 2015, for a total of 314 hours of active chilling. The temperature front reached the top of the grain mass much sooner than the 314 hours, but due to technical difficulties with the grain chiller during certain periods, the equipment was left running longer to test its capacity. The average temperature and RH of the chilled air going into the silo was 15°C and 70.5%, respectively (fig. 3.2).

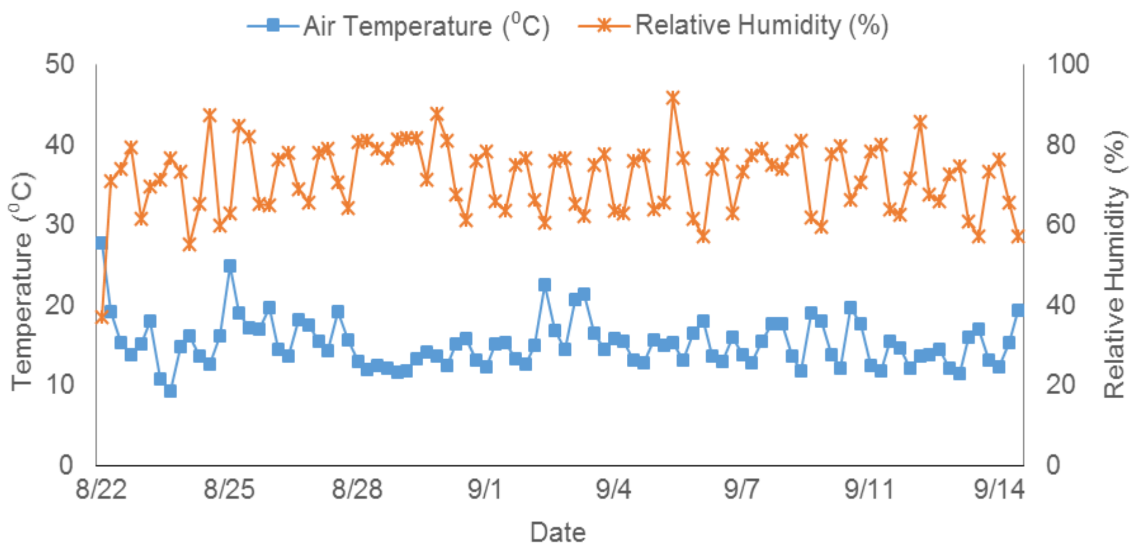

Figure 3.2. Chilling air conditions of temperature (°C) and relative humidity (%) going into the Chilled silo from Aug. 22nd to Sep. 14th, 2015 in Wakefield Cooperative, Clay County, KS.

The grain chiller was setup to work at 10°C, but according to data collected in the air inlet of the silo, the average temperature of the air introduced into the Chilled silo was 5°C over the set point, and showed significant fluctuations in temperature (9°C to 28°C) and RH (37% to 91%) during the trial. This could be explained by the heating of the air throughout the insulated ducts, steel "T", and fan transition parts, due to the high daily temperatures during this time of the year. During the trial, the ambient air fluctuated between 8°C and 37°C, with an average of 23°C (Appendix C, C.1). The average ambient RH was 63.5% with a minimum of 27.4% and a maximum of 93.1% (Appendix C, C.2). Maier et al. (1997) also observed a warming effect in the path from the grain chiller to the silo inlet in their trials.

Another possible explanation of the significant fluctuations of the chilled air delivered into the silo could have been the malfunction of the grain chiller during part of the trial. When the chilling temperature got dangerously close to freezing, one of the circuits (compressor) shut down in order to slightly increase the temperature and avoid major damage to the electric system of the unit due to freezing temperatures. When the chilling temperature increased to 13°C, a thermostat controller was supposed to turn on the second circuit, but it did not, so the chilled temperature would increase up to 24°C during warmer hours of the day. After a while the second circuit would turn on again but, again it would reach freezing temperatures fast, starting the partial shut down cycle all over again.

The average airflow coming from the grain chiller into the treated silo was of 0.07 m^3/min/t. The cooler air temperature front reached the top of the silo on September 2nd after 175 hours of treatment (fig. 3.3). Since it was not possible to install the temperature cables inside the silos in time for the start of the chilling treatment (August 22nd) it is estimated that the initial grain temperature was approximately 28°C, taking as reference the data of the HOBO inside the silo and the grain temperature observed initially inside the Control silo when the temperature cables were installed on August 27th (fig. 3.3).

Temperatures inside the Control silo did not lower to 17°C until mid-November, which would be about two months later after this temperature was reached in the Chilled silo. According to Hagstrum and Subramanyam (2006), for every month that cooling is delayed, populations of insects can grow 5- to 25-fold their original size. Actually, the grain temperature in the Control silo decreased because grain was unloaded from the silo in late September and again in November, which reduced the thermal insulation effect of the grain, making it prone to change with the cooler ambient temperatures in the fall.

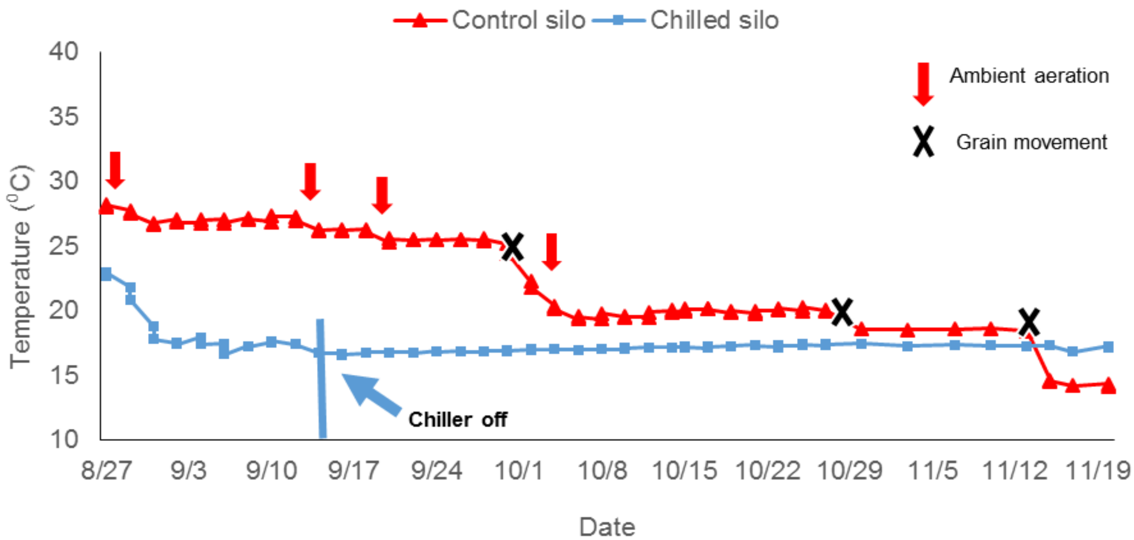

Figure 3.3. Grain temperature profile (°C) of the grain mass inside the Control and Chilled silo from Aug. 27th to Nov. 20th, 2015 in Wakefield Cooperative, Clay County, KS.

From the time the grain chiller was turned off on September 14th (which is indicated by a vertical line in figure 3.3) to November 20th, the average grain temperature inside the chilled silo was 17°C, with a minimum of 11°C and a maximum of 19°C. This demonstrates that the chilled aeration was effective to keep a uniform temperature throughout the grain mass, which lowered the risk of temperature and consequently moisture migration that could decrease the quality of grain (Navarro et al., 2002).

In the Control silo, the Coop management turned on the aeration fans from August 24th to October 5th. Their aeration strategy was based on turning on the fans when the ambient temperature was below 27°C during the summer, and below 18°C during the fall. The total active aeration time was of 308 hours at an average airflow of 0.11 m^3/min/t. The average temperature of the air going into the silo was 23°C, ranging from 10°C to 34°C. The average RH was 50%, with a minimum of 16% and a maximum of 94%. The first three aeration runs allowed the temperatures of the grain mass to decrease to approximately 25°C. The fourth aeration run coincided with the time when 545 t were taken out of the silo (fig. 3.3), which also helped to lower the grain temperature (thermal insulation effect decreased). From there on, more grain was unloaded in November, according to information provided by the Coop, which helped lower the grain temperature below 21°C since by this point the ambient temperature had dropped to an average of 13°C.

3.3.1.2 Trial of 2016

The 2016 grain chilling trial started on June 21st, a week after harvest season started, and ran discontinuously until July 12th, for a total of 384 hours of active chilling at approximately the same airflow rate of the previous year. Both silos were continuously loaded with incoming grain from the field until June 27th, and then they were cored down a week after.

The average temperature going into the Chilled silo measured at the transition parts was 15°C, with a minimum of 11°C and a maximum of 24.5°C. The average RH was 72.6%, with a minimum of 38.7% and a maximum of 92.2% (fig. 3.4). The average conditions of the chilled air going into the silo did not change much compared to 2015 since the thermostat controller issue persisted, although the controller was replaced.

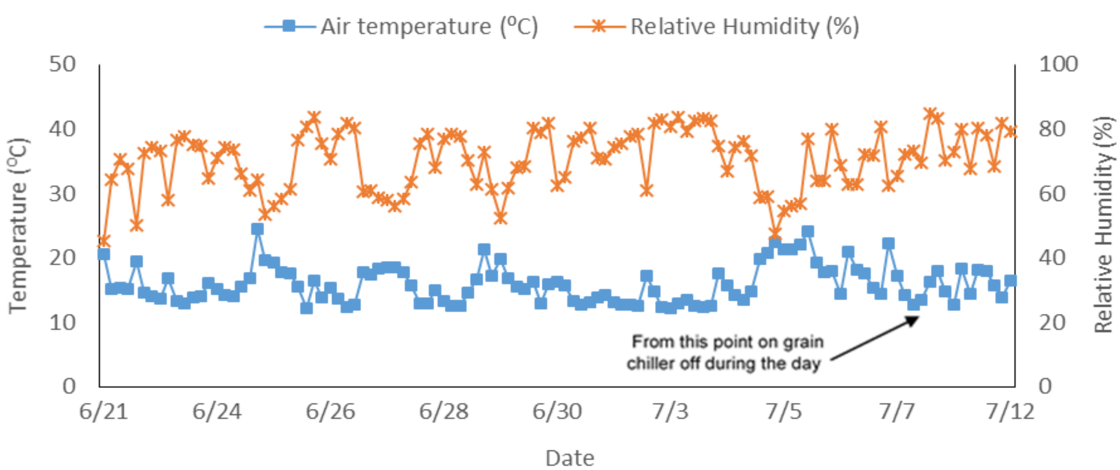

Figure 3.4. Chilling air conditions of temperature (°C) and relative humidity (%) going into the Chilled silo from June 21st to July 12th, 2016 in Wakefield Cooperative, Clay County, KS.

The additional HOBO sensors put in the steel "T" and chiller outlet in 2016 showed that the temperature of the chilled air coming out of the grain chiller was 12.5°C and increased by an average of 1°C in the steel "T" and by 3°C in the transition parts. The temperature differential between the chiller outlet and transition parts of the silo reached a maximum of approximately 10℃ during the warmer hours of the day and a minimum of 0.5℃ during the cooler hours. As well, the RH coming out of the grain chiller was 85%, and decreased by an average of 13% in the transition parts.

In 2016, the average initial temperature of the grain inside the Chilled silo was 39°C (fig. 3.5), which was higher than the initial grain temperature in the 2015 trial. This increase could have some influence on the extension of the cooling period compared to the previous year, but after 245 hours of active chilling the average temperature of the grain reached 17.6°C, approximately the same temperature as the minimum observed in 2015. These results are also comparable to those observed in other studies using the same grain chilling technology, but with lower initial grain temperature (below 27°C) and ambient conditions less extreme (13°C- 27°C) (Lazzari et al., 2006; Quirino et al., 2013).

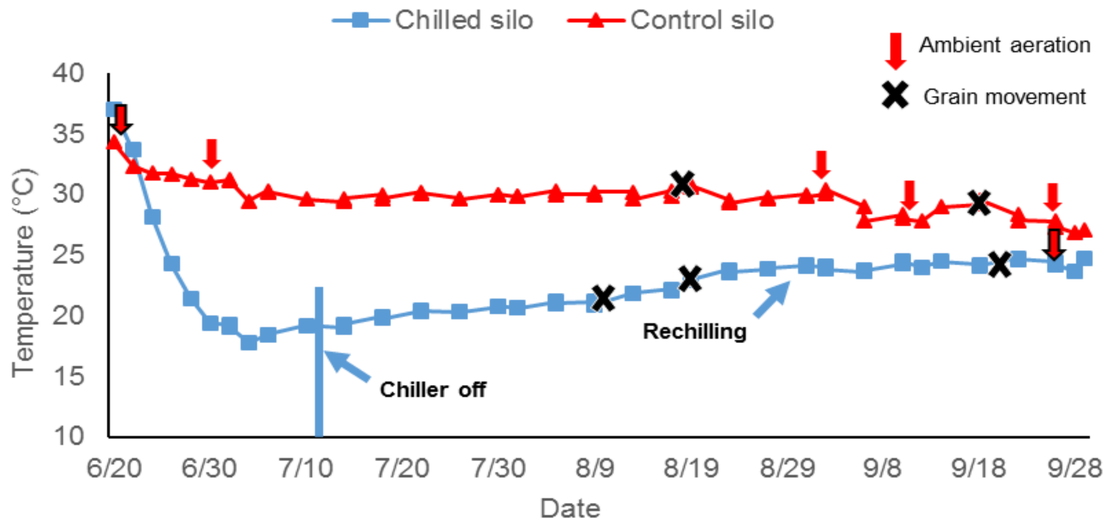

Figure 3.5. Grain temperature profile (°C) of the grain mass inside the Control and Chilled silo from June 20th to Sep. 29th, 2016 in Wakefield Cooperative, Clay County, KS.

During the chilling period, the average ambient temperature was 26°C, with 16.5°C and 38°C as minimum and maximum, respectively (Appendix C, C.3). The average relative humidity was 63.8%, with 22.7% and 91.2% as minimum and maximum, respectively (Appendix C, C.4). Overall, the ambient conditions during the chilling trial were much warmer than the ones observed during the 2015 trial, except for the first four days in July where temperatures decreased briefly. Even so, the chiller performance was comparable to the previous year, which allowed a significant drop in the temperatures inside the Chilled silo.

From July 8th to the 12th an alternative strategy was implemented in order to avoid the extreme temperatures during the day and try to cool down the chilled air going into the Chilled silo as much as possible. During this period the grain chiller was turned on only during the late evening to early morning which helped narrow the variation of the chilled air but it didn't do much to lower the temperature inside the Chilled silo (fig. 3.4). Actually, it slightly increased the average temperature of the grain (fig. 3.5), probably because during the day, heat accumulated in the insulated ducts, so when the grain chiller was turned on at night that heat was pushed in and came in contact with the grain. This strategy lowered the efficiency of the chilling process and actually caused a warming effect instead of a cooling effect.

After the grain chiller was turned off on July 12th (indicated by a vertical line in figure 3.5), the average temperature of the grain inside the chilled silo was 22°C, with a minimum of 18°C and a maximum of 25°C. The extreme high temperatures during most of July (over 32°C), the issues with the grain chiller, and the constant movement of grain, made it difficult to maintain the average temperature of the grain below the optimum insect development threshold (25°C to 33°C) (Fields, 1992).

Since the temperature inside the Chilled silo was increasing, a rechilling was proposed to bring the temperature of the grain back down. The grain chiller was reconnected in August 16th but was not turned on until September 2nd because a severe lightning storm caused damage in some parts of the machine which had to be replaced. The temperature inside the Chilled silo slightly decreased at the beginning, but unfortunately the cooling coils started to freeze after just a few hours of active rechilling and this again caused some issues with the thermostat controller resulting in air temperatures coming from the grain chiller coming very close to that of the ambient air, which was higher than the grain temperature and caused slight reheating in the bottom layers. Therefore, it was decided to stop the rechilling on September 7th to avoid the reheating of the whole silo. Instead, it was proposed to reinstall the aeration fans and use ambient air to cool the grain when the ambient temperature was below 20°C. The average temperature inside the Chilled silo was 24°C by that time. On September 26th, the ambient aeration fans were activated and after 23 hours of active aeration with ambient air at an average temperature of 16°C and 54% RH, the average grain temperature inside the Chilled silo was slightly reduced to 23°C.

During the night of September 29th, one of the eaves from the Chilled silo cracked and a side of the silo split open putting more than 136 t of wheat on the ground (Appendix C, C.5). The remaining grain inside the silo had to be moved to another silo to fix the crack. Given the incident it was decided to terminate the trial on this date.

In the Control silo the initial grain temperature was 34°C. The aeration fans were activated from June 20th until September 27th using the same criteria as last year (fig. 3.5). The total fan run hours were 371, and the average temperature of the air going into the Control silo was 26°C, with 11°C as a minimum and 39°C as maximum. The average RH of the air going into the Control silo was 54.7%, with 24% as minimum and 98% as maximum. Given the conditions of the air going into the Control silo, the average grain temperature throughout the trial was 29°C. The lowest temperature achieved was 25°C by late September (fig. 3.5). During the trial period there was also some loading and unloading of grain, mainly during August and September, which had some influence in the average grain temperature during the trial (fig. 3.5).

3.3.2 Moisture content during aeration

In both 2015 and 2016, the MC of the grain inside the Chilled silo did not change significantly throughout the trial. In both years the maximum variation was of 0.2% (table 3.1). This indicates that despite the variability of the temperature and RH, the overall conditions of the chilled air going into the silo were appropriate to maintain uniform MC throughout the evaluated storage period and avoid significant shrink loss.

Table 3.1. Average moisture content (%) of the grain inside the Chilled and Control silos from August 15th to November 20th, 2015, and from July 1st to September 27th, 2016.

Sampling date	2015		2016	
	Chilled silo	Control silo	Chilled silo	Control silo
July	-	-	10.2^{A}	10.6^{A}
August	11.4^{A}	11.4^{A}	10.4^{A}	10.6^{A}
September	11.3^{A}	11.1^{A}	10.4^{A}	10.0^{B}
October	11.2^{A}	10.6^{B}	-	-
November	11.3^{A}	10.5^{B}	-	-

[A,B] Mean values with the same letter within the same year and silo are not significantly different by Tuckey's test ($p > 0.05$).

The grain inside the Control silo did show significant loss of moisture in both years (table 3.1). In 2015, the average MC decreased by 0.5% in the last two months of evaluation. It seems like the long fan run hours and the conditions of the ambient air caused a slight drying effect on the grain. In 2016, the MC had a reduction of 0.6% in the last sampling date (September) which was about the same tendency observed in 2015.

Although 0.5% shrink loss is considered typical for aeration using ambient air (Navarro et al., 2012), it seems like this can be avoided or at least reduced by using grain chilling. This can have a direct impact on the income of the grain facility since the shrink loss represents a loss of weight of the bulk to be commercialized (Navarro et al., 2012).

3.3.3 Effect of chilled aeration on insect reproduction and survival rate

In 2015 a significant difference was observed between the Chilled and Control silo after only 28 days inside the silos. The average temperature in the grain surface of the Chilled and Control silo during the 28 days was 19°C and 27°C, respectively (fig. 3.6). This temperature difference apparently facilitated an increase of almost 1000 insect individuals of LGB in the Control silo and only two in the Chilled silo (table 3.2).

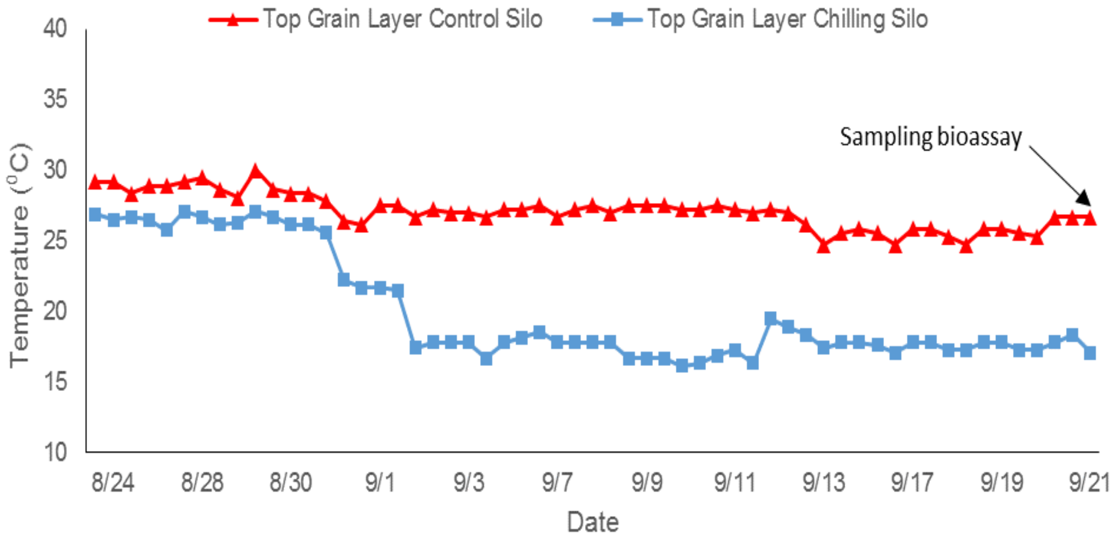

Figure 3.6. Temperature (°C) in the top of the grain mass of the Chilled and Control silo from Aug. 24th to Sep. 21st, 2015, in Wakefield Cooperative, Clay County, KS.

Table 3.2. Total progeny number (mean ±SE) of adults of LGB out of the original 50 for 2015 and 30 for 2016 bioassays located 0.3 m below grain surface and in fan transition parts of the Chilled and Control silo.

Year	**Days in the silo**	**Location in the silo**	**Silo**	
			Chilled	**Control**
2015	28	0.3 m below grain surface	2.3 ±0.7^{B}	974.3 ±33.7^{A}
	28	Transition	1.0	768.0
2016	28	0.3 m below grain surface	767.5 ±166.0^{A}	765.8 ±53.8^{A}
	28	Transition	82.0	978.0
	56	0.3 m below grain surface	1134.5 ±189.1^{A}	1349.8 ±224.8^{A}
	56	Transition	855.0	2063.0
	68[1]	0.3 m below grain surface	-	1484.6 ±116.5
	84	Transition	776.0	+

[A, B] Mean values with the same letter within the same line are not significantly different by Tuckey's test ($p > 0.05$) (n=4).
[1]Trial terminated earlier due to crack in Chilled silo.
-Bioassays lost when the Chilled silo split.
+Bioassay destroyed by some kind of rodent.

In the fan transitions of the 2015 trial there was an increase of 768 insect individuals of LGB in the Control silo while in the Chilled silo only one (table 3.2). The temperatures in the fan transition parts of the Chilled and Control silos were 17°C and 25°C, respectively (fig. 3.7).

The temperatures of 17°C and 19°C observed in the top of the grain mass and transition part of the Chilled silo, respectively, are considered "safe" for insect control management since the life cycle usually takes three months or more, and the oviposition and fecundity slows down to a point where population growth is almost insignificant (Navarro et al., 2002).

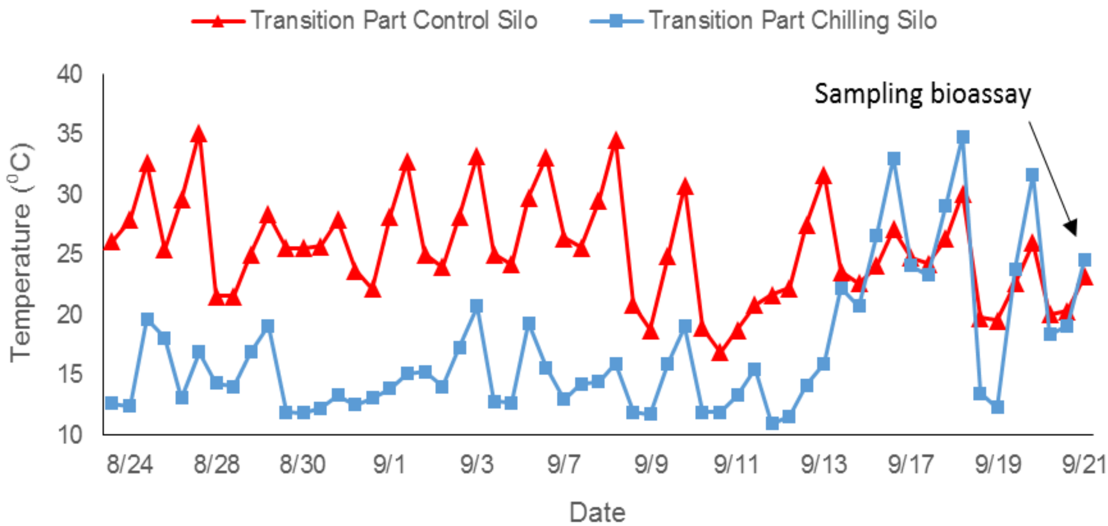

Figure 3.7. Temperature (°C) in fan transition parts of the Chilled and Control silo from Aug. 24th to Sep. 21st, 2015, in Wakefield Cooperative, Clay County, KS.

In 2016, the bioassays in the transition parts were put inside the silo 16 days before the bioassays in the top of the grain mass because it took the Coop two more weeks after the grain chiller was initially turned on to completely fill the silos and core them down. There was also a lot of movement in the silos during August and September which required for the bioassays to be removed from the silos and put in a room with controlled temperature while the silos were loaded and unloaded. This extended the sampling time to late September, which unfortunately overlapped with the time when the eaves of the Chilled silo collapsed, so the last bioassays in the top of the grain mass in the Chilled silo were lost and the ones in the Control silo were retrieved earlier.

It was observed from the LGB bioassays in 2016 that the temperature difference in the top of the grain mass was not enough to make a significant difference in insect development and reproduction. The average temperatures during the 68 days the bioassays were inside the silo were 23°C and 31°C in the Chilled and Control silo, respectively (fig. 3.8). Although the average temperature was lower in the Chilled silo, the temperature inside the silo started to have a fast increase after the grain chiller was disconnected due to the issues with the grain chiller and the extreme ambient temperature during most of July. Apparently, the upward tendency of the temperature caused an acclimation effect in the insect populations of the bioassays that basically after just one month eliminated the cooling effect on the development rate. According to Burks et al. (2000), if the temperature increases after the insect has been exposed to non-lethal cold temperatures, it may recover from the mild cold-injury effect. The introduction of the new loads of grain during August and September caused the temperature to increase even more, and although the rechilling cycle successfully decreased the temperature of the top layer of grain close to 21°C, this was not enough to see significant differences in the second sampling date. This shows why the chilling treatment should be used as a preventive method as soon as the grain is in the silo, since once the insect populations reach large numbers it is very unlikely that non-lethal low temperatures will have an effect on insects (Reed and Arthur, 2000).

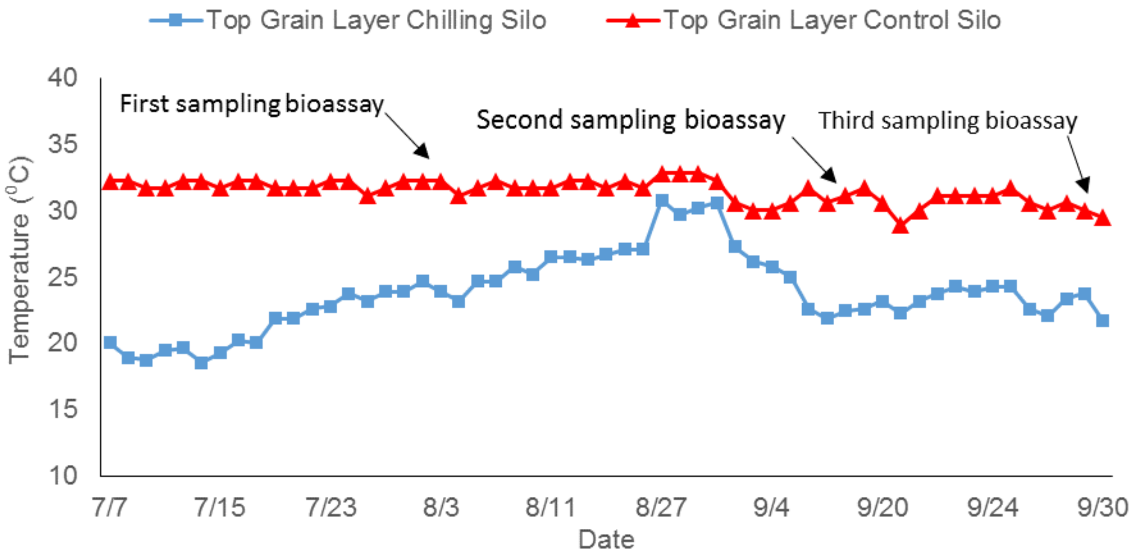

Figure 3.8. Temperature (°C) in the top of the grain mass of the Chilled and Control silo from July 7th to Sep. 30th, 2016 in Wakefield Cooperative, Clay County, KS.

In the transition parts, the average temperature of the air in the Chilled and Control silos were 24°C and 26.5°C, respectively (fig. 3.9). This was not much of difference overall, nevertheless during the first 28 days, when the grain chiller was connected to the Chilled silo, the temperature in the transition was approximately 13°C on average, and when the chiller was disconnected there were periods in which the temperature increased over 33°C which is the upper limit of the optimal insect development range (Fields, 1992). These extreme temperatures clearly slowed down the development rate of the insects in the transition of the Chilled silo.

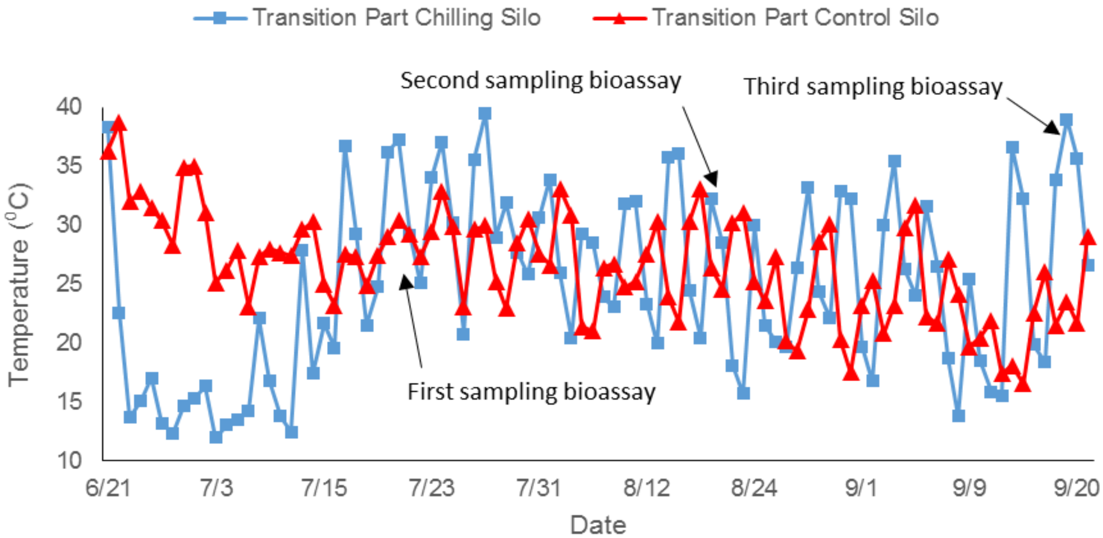

Figure 3.9. Temperature (°C) in the fan transition parts of the Chilled and Control silo from June 21st to Sep. 20th, 2016 in Wakefield Cooperative, Clay County, KS.

The results of the 2015 RFB bioassays showed significant difference in the top of the grain mass between the Chilled and Control silo (table 3.3). The development rate of this species was also faster in the transition of the Control silo. Although the difference between the Chilled and Control silo was notorious, it was not as notorious as it was in the bioassays of LGB since the development rate of the bioassays in the Control silo did not increase as much either. According to Mahroof and Hagstrum (2012) at temperatures close to 25°C, like the ones observed this year in the top grain mass and in the transition part of the Control silo, the development from egg to adult can take more than 40 days. For this trial, after the 28 days in the silo, plus the 28 days in the growth chamber, there were many larval stages but few adult stages which would suggest that other factors added to the temperature influenced on the extension of the development rate. Mason (2009) mentioned that there are 5-11 larval instars in RFB, and the number of instars depends on temperature, relative humidity, food, and individual insects. Based on the results of this trial, it seems that one of these factors had an influence on the extension of the development rate but is hard to determine which had the major influence based on the data available.

Table 3.3. Total progeny number (mean ±SE) of adults of RFB out of the original 50 for 2015 and 30 for 2016 bioassays located 0.3 m below grain and in fan transition parts of the Chilled and Control silo.

Year	Days in the silo	Location in the silo	Silo: Chilled	Silo: Control
2015	28	0.3 m below grain surface	5.3 ±1.4[B]	21.3 ±5.6[A]
	28	Transition	0.0	7.0
2016	28	0.3 m below grain surface	988.8 ±81.9[A]	880.0 ±88.3[A]
	28	Transition	29.0	1090.0
	56	0.3 m below grain surface	1393.3 ±209.2[A]	1496.3 ±108.6[A]
	56	Transition	639.0	+
	68[1]	0.3 m below grain surface	-	1501.5 ±141.2
	84	Transition	1030.0	1980.0

[A, B] Mean values with the same letter within the same line are not significantly different by Tuckey's test ($p > 0.05$) (n=4).
[1]Trial terminated earlier due to crack in Chilled silo.
-Bioassays lost when the Chilled silo split.
+Bioassay destroyed by some kind of rodent.

In 2016, the increase of temperature in the top of the grain mass of the Chilled silo also avoided a significant decrease of the development rate in the RFB bioassays, same situation observed with the LGB species (table 3.2). According to Reed and Arthur (2000), the effect that low temperature has on oviposition, number of eggs laid per female, and general survival rate, is most noticeable when the temperatures decrease below suboptimal levels (13°C- 20°C) which was barely attained during this trial and was just for a short period of time.

In the transition parts, the difference between Chilled and Control silos was of approximately 1,000 new progenies in the first and last sampling date. The extreme temperatures of higher than 33°C and lower than 20°C in the transition part of the Chilled silo had a similar effect to the one observed with the LGB species.

3.3.4 Insect species found in chilled and control silos

In both years, the species found in the probe traps of both silos were basically the same. The highest number of miscellaneous insects found in the traps were foreign grain beetle (FOGB) *Ahasverus advena* and hairy fungus beetle (HFB) *Typhaea stercorea*. Their presence could be related to the presence of dust layers in the top part of the walls and in the ceiling, which create a good media for these species to survive, develop, and reproduce (Hagstrum and Subramanyam, 2006). Other species found were: drugstore beetle (DB) *Stegobium paniceum*, *Trogoderma* spp., cadelle beetle (CB) *Tenebroides mauritanicus*, booklice *Liposcelis* spp. and the warehouse pirate bug (WPB) *Xylocoris flavipes.* In 2016, some individuals of the silken fungus beetle (SFB) *Cryptophagus* spp. and the lesser mealworm (LMW) *Alphitobius diaperinus* were also found.

The main insect pests found in the probe traps of both silos were: flat grain beetle (FGB) *Cryptolestes* spp., flour beetle (FB) *Tribolium* spp., sawtoothed grain beetle (STB) *Oryzaephilus surinamensis,* and grain weevil (WEV) *Sitophilus* spp. In 2016, some individuals of lesser grain borer (LGB) *Rhyzopertha dominica* were also found.

On the first sampling date of 2015 the number of insects were quite low in both silos (table 3.4). The most common genus in both silos was FGB, which was mainly found in the center core. One FB was found in the periphery of the Chilled silo, while four were found in the Control silo. Additionally, one WEV was found in the Control silo and none in the Chilled silo. No STB or LGB were found on this date.

Table 3.4. Total number of insects of main stored-product pests found in probe traps located in the periphery and center of the Chilled and Control silo on Aug. 15th, Sep. 22nd and Nov. 20th, 2015.

Silo	Insect species	8/15		9/22		11/20	
		Periphery[1]	Center[2]	Periphery[1]	Center[2]	Periphery[1]	Center[2]
Chilled	FGB	12	15	57	27	119	12
	FB	1	0	53	27	53	21
	STB	0	0	27	10	2	0
	WEV	0	0	10	0	257	13
	LGB	0	0	0	0	0	0
Control	FGB	5	28	1910	1370	326	1000
	FB	4	0	806	544	51	91
	STB	0	0	2	2	0	0
	WEV	1	0	0	0	1	0
	LGB	0	0	0	0	0	0

[1]Sum of four probe traps.
[2]One probe trap.

During the second sampling date on September 22nd (after chilling treatment) a clear difference was observed between the Chilled and the Control silos on the number of adult insects found in the probe traps (table 3.4). The temperature by this date in the Chilled silo was below 19°C, while the temperature in the Control silo was 27°C. On this date the predominant genera found in the traps were FGB and FB, and the populations were considerably lower in the Chilled silo than in the Control silo (table 3.4). While there were only four STB found in the Control silo on the second sampling date, there were 37 found in total in the Chilled silo and the reason could have been that this genus was in competitive disadvantage with the high populations of FGB, and especially FB which is known to prey on other insects and have a great impact on population dynamics of other species when present in large numbers (Rees, 2004). This may have also been the reason there were no WEV found in the Control silo and 10 were found in the Chilled silo, since this primary pest tend to move away when they are in competitive disadvantage with large populations of secondary pests like FGB or FB (Navarro et al., 2002a).

During most of the month of October the probe traps had to be taken out of the Control silo for the grain to be taken out, therefore no results were quantified during this month.

On November 20th, the temperature in the Control silo had decreased to 18°C due to the movement of grain that diminished the insulation effect and the additional aeration run with cooler air during the previous month, but even so the FGB and FB populations were greater in the Control silo than in the Chilled silo (table 3.4). On this date, an increase of the population of WEV was observed in the Chilled silo, nevertheless, the grain samples from the insect fragments (table 3.6) and grain quality analysis (table 3.8) indicated that it was not causing noticeable damage or reproducing inside the silo. Since the development rate of this species would take more than 220 days at temperatures close to the low temperatures present in the Chilled silo (Navarro et al., 2002a), it is unlikely that an infestation of WEV would develop, despite of its presence.

In the first sampling date of 2016, at approximately the same date as in 2015, the most abundant species in both silos was RGB again, followed by RFB (table 3.5). This seems to be a common tendency in wheat silos since this was also observed in other research projects developed in Kansas and Oklahoma (Reed et al., 1989; Toews et al., 2005). This is probably because these species are very active, which makes them more prone to be caught in the traps (Cuperus et al., 1990). These species were more abundant in the Control silo than in the Chilled silo. Contrary to 2015, this year most of the insects were found in the periphery, probably because they did core down the silos. Comparing the results in the Chilled silo with the ones of 2015 on the same date, it was observed that there were less insects caught, which demonstrates that the sooner the grain is cooled down, the less time insect populations have to develop and increase their size.

Table 3.5. Total number of insects of main stored-product pests found in probe traps located in the periphery and center of the Chilled and Control silo on Aug. 2nd, Sep. 20th and Sep. 30th, 2016.

Silo	Insect species	8/2		9/20		9/30[3]	
		Periphery[1]	Center[2]	Periphery[1]	Center[2]	Periphery[1]	Center[2]
Chilled	FGB	7	2	41	130	-	-
	FB	3	2	48	30	-	-
	STB	0	5	0	0	-	-
	WEV	1	0	20	9	-	-
	LGB	2	0	0	0	-	-
Control	FGB	27	17	377	342	231	97
	FB	8	5	485	237	937	304
	STB	0	3	0	0	0	0
	WEV	0	0	2	6	8	4
	LGB	0	0	4	0	0	0

[1]Sum of four probe traps.
[2]One probe trap.
[3]Trial terminated earlier due to the accident in Chilled silo.
-Probe traps lost when the Chilled silo cracked.

This year, species that were not observed on the previous year in the first sampling date in the Chilled silo, like LGB, WEV and STB were observed here. This presence of insects was probably because the chilling treatment started earlier in the year, so the population of FGB, FB, and other species like FOGB and HFB that are usually present in the silos before the grain is loaded, feeding on the dust of the walls, were reduced, which meant less competition for wandering insects like LGB and especially WEV which is also more resistant to lower temperatures (Mason and McDonough, 2012).

On the second sampling date on September 20th, once again the most abundant species were FGB and FB, but this time higher concentrations of insects were detected in the center core then in the periphery due to new loads of grain that created a cone which concentrated the debris and chaff in the center. The populations of these two species were more numerous in the Control silo than in the Chilled silo, although it seems like the populations in the Chilled silo were not as low as the onces observed in 2015, probably because of the grain temperature was higher in 2016. The presence of LGB was observed in the Control silo on this date and none in the Chilled silo. The WEV was present on both silos but more abundantly in the Chilled silo, equal to the situation of 2015. No STB was present in either of the silos.

The last sampling date on September 30th, just 10 days after the previous sampling date due to the structural damaged issue of the Chilled silo, showed an increasing presence of FB and WEV in the Control silo, and a reduction of FGB. No presence of LGB or STB was observed.

3.3.5 Calculation of insect fragments

The overall results of the laboratory Entoleter and conductive roller mill were below 0.5 and 0.3 insect fragments per 500 g in 2015 and 2016, respectively (table 3.6), which would be below the FDA action limit of 75 flour-frags per 50 g of flour according to the prediction model developed by Brabec et al. (2015).

A great variability was observed in both years in the number of insect fragments found in each of the 500 g samples collected from both silos, probably due to the low populations of internal feeding insects according to the probe trap results. According to Reed (2006), at low population densities, it is more probable to detect insect presence with the probe traps, which have higher sensitivity, than with grain samples. The correlation between both methods is dependent on many variables like interaction among different species, spatial patterns of insect populations, number and size of grain samples, location of traps in the grain mass, temperature of the grain mass, among others (Athanassiou and Buchelos, 2001; Hagstrum et al., 1998).

Table 3.6. Number of insect fragments (mean ±SE) found per 500 g of wheat in the Chilled and Control silos from Aug. 15th to Nov. 20th, 2015, and from July 1st to Sep. 27th, 2016.

Year	Silo	July	August	September	October	November
2015	Chilled	-	0.2 ±0.2*	0.3 ±0.1*	0.3 ±0.1*	0.1 ±0.1*
	Control	-	0.2 ±0.1*	0.4 ±0.1*	0.5 ±0.2*	0.4 ±0.2*
2016	Chilled	0.0	0.0	0.3 ±0.3	-	-
	Control	0.0	0.3 ±0.3	0.0	-	-

[*] No significant difference within the same year and silo but at different sampling dates according to Tuckey's test ($p > 0.05$).

In general, insect fragment detections were higher in 2015 than in 2016, although in both years there was no significant increase of detections throughout the evaluated period. This seems to contradict the results of the probe traps since a steady increase of WEV was observed in both years as cooler ambient temperature of the late-fall season appeared. Again, this can be explained by the difference in the sampling methods and that insect populations are generally higher in the top of the grain mass (Hagstrum and Flinn, 2012). The fact that the presence of internal feeders on the probe traps increased while there was no detectable increase of detections in the grain samples suggests that these insects were coming from external sources and were not reproducing inside the silos. Both LGB and WEV are strong fliers and may survive in a wide variety of commodities, including seeds out in the field (Mason and McDonough, 2012).

3.3.6 Fungi identification and quantification

The most common fungi in the 2015 and 2016 trials found in both silos was *Fusarium* spp. (table 3.7). *Fusarium* spp. was detected at the first sampling date in 2015, which indicates that the grain might have been inoculated in the field. Actually, it is more common to find *Fusarium* spp. in fields worldwide, than in storage (unless grain is stored at high moisture) because it requires higher ERH (over 85%) to germinate and develop (Christensen and Meronuck, 1986; Woloshuk and Moreno Martinez, 2012). The “scab” damage (caused by *F. roseum*) found in the grain quality analysis of 2015 (table 3.8), as well as the reports of high disease pressure during the 2015 growing season (Hillderbrand, 2015), support this hypothesis. Since the ERH inside the silos was low (below 70%), the inoculum of this fungi did not increase significantly in either of the silos.

Penicillium spp. was sporadically detected in both silos but they were quite low, especially in the Chilled silo, and there was no significant growth over the storage period in either of the silos. There was no detection of *Aspergillus* spp. in 2015.

Table 3.7. Number of colony forming units (CFU) (mean ±SE) of *Fusarium* spp., *Aspergillus* spp., and *Penicillium* spp. found per gram of wheat in samples collected from the Chilled and Control silos from August 15th to November 20th, 2015, and from July 1st to September 27th, 2016.

Year	Sampling date	Chilled silo			Control silo		
		***Fusarium* spp.**	***Aspergillus* spp.**	***Penicillium* spp.**	***Fusarium* spp.**	***Aspergillus* spp.**	***Penicillium* spp.**
2015	August	166.7 ±66.7*	0.0	33.3 ±33.3*	300.0 ±57.7*	0.0	0.0
	September	33.3 ±33.3*	0.0	0.0	66.7±33.3*	0.0	66.7 ±33.3*
	October	133.3 ±33.3*	0.0	0.0	133.3 ±133.3*	0.0	133.3 ±88.2*
	November	33.3 ±33.3*	0.0	33.3 ±33.3*	0.0	0.0	0.0
2016	July	44.4 ±29.4*	0.0	0.0	77.8 ±48.4*	0.0	0.0
	August	44.4 ±44.4*	0.0	0.0	133.3 ±33.3*	0.0	0.0
	September	2,000.0 ±1151.0*	66.7 ±66.7	0.0	77.8 ±44.4*	11.1 ±11.1	0.0

[*] No significant difference within the same year, silo and species but at different sampling dates according to Tuckey's test ($p > 0.05$) (n=3).

Fusarium spp. was also detected right from the first sampling date in 2016, but again the CFU/g of wheat did not increase significantly throughout the trial due to the low ERH inside both silos. On the last sampling date of this year, the concentration (CFU/g) of *Fusarium* spp. increased to 2,000, and although it was not statistically significant it was indeed noticeable. The reason for this could have been that the new grain loaded during August and September had higher concentrations of broken and fine material as indicated by the grain quality analysis (table 3.9). This material is more susceptible to fungi and can be infected at lower MC (Christensen and Meronuck, 1986).

In 2016, *Aspergillus* spp. was detected in both silos in the September sampling date, nevertheless the concentration was very low and had no statistical significance in either of the silos. The higher concentration of fines, broken kernels and dockage of the new grain loaded into both silos could have also been the reason for this. There was no detection of *Penicillium* spp. this year.

Overall, it seems that temperature had little effect on the fungi colonies since the wheat in both years was stored at MCs between 10% and 11% (ERH< 70%), which would be considered safe for storage (Christensen and Meronuck, 1986).

3.3.7 Grain quality evaluation

The grain quality results from 2015 indicate that there was no change in grade from samples taken before and after the chilling treatment in either of the silos (table 3.8). According to the KGIS officials, the variations of the quality values from one date to the next are low enough to be considered sampling errors. Similar results were obtained by Reed et al. (1989) after they evaluated 31 wheat silos for approximately seven months and did not see substantial variations in foreign material, TW and MC from the beginning of the storage season to the end.

Table 3.8. Grain quality analysis of wheat stored in the Chilled and Control silos from samples taken on Aug. 15th and Sep. 22nd, 2015.

Silo	Sampling date	MC (%)	Test Weight (kg/hL)	Dockage (%)	Foreign material (%)	Damage (%)	Shrunken & Broken (%)	Insect Damaged Kernels (#/100 g)	Total Defects (%)	Grade
Chilled	August	11.4	78.6	0.5	0.1	0.7	0.3	1.0	1.1	1
	September	11.3	79.7	0.3	0.2	1.3	0.7	1.0	2.2	1
Control	August	11.4	78.9	0.4	0.3	0.8	1.0	0.0	2.1	1
	September	11.2	78.9	0.4	0.3	0.4	0.9	0.0	1.6	1

The damage observed in both silos in 2015 was most likely due to the "scab" damage observed in the fungi analysis (table 3.7). The shrunken and broken kernel parameter was slightly higher in the Control silo which may have also contributed to the higher populations of externally-feeding insects, added to the higher temperature registered in this silo. One IDK/100 g was detected in the Chilled silo in each sampling date which indicates that, although this damage was present before the grain chiller was turned on, it did not increase, probably due to the effect of the chilled temperatures. The combination of all these factors graded the grain in both silos as U.S #1.

In 2016, the quality of the grain in the Chilled silo did not change much in the first two sampling dates, but in September a decrease of TW, an increase of shrunken and broken kernels, and total defects was observed (table 3.9). According to Reed et al. (1989), the most probable reason for the increment of damaged (broken) kernels is due to handling and movement of grain. Since more wheat was loaded into the Chilled silo in late August and mid-September, it could be assumed that it was the cause of the increment of the damage, and it would also explain why the presence of *Fusarium* spp. and *Aspergillus* spp. increased on September 20th (table 3.7), since broken and damaged kernels are a great substrate for fungi to develop (Christensen and Meronuck, 1986).

Table 3.9. Grain quality analysis of wheat stored in the Chilled and Control silos from samples taken on July 1st, to September 27th, 2016.

Silo	Sampling date	MC (%)	Test Weight (kg/hL)	Dockage (%)	Foreign material (%)	Damage (%)	Shrunken & Broken (%)	Insect Damaged Kernels (#/100 g)	Total Defects (%)	Grade
Chilled	July	10.5	81.0	0.1	0.0	0.0	0.5	0.0	0.5	1
	August	10.6	81.5	0.1	0.0	0.0	0.4	0.0	0.4	1
	September	10.7	80.1	0.3	0.2	0.4	1.2	0.0	1.8	1
Control	July	10.7	81.3	0.3	0.0	0.3	0.9	0.0	1.2	1
	August	10.7	80.8	0.3	0.0	0.0	0.9	0.0	0.9	1
	September	10.4	81.2	0.3	0.1	0.0	0.9	1.0	1.0	1

In the Control silo the most noticeable factor was the IDK increase on September 27th. Since this was the only factor that had a noticeable change from August to September, it is possible that the IDK did in fact come from inside the silo and was not coming from the grain that was loaded. Reed et al. (1989) also observed that the only quality indices that changed significantly throughout the storage period was the IDK. Although internal-feeding insects were detected in both silos according to the results of the probe traps, it seems like the slightly lower grain temperatures in the Chilled silo discouraged the insect damage. Even though the average grain temperature in the Chilled silo had increased to approximately 24°C by September, this was still within the suboptimal range of development (13°C- 24°C) in which the development rate would be slower (Fields, 1992).

3.3.8 Flour and baking quality evaluation

The flour and baking quality analysis of the Chilled silo did not show any significant variation of the quality parameters between the August and September sampling dates (table 3.10). Meanwhile, in the Control silo there was a significant decrease of flour protein, mix time, and loaf volume. These results seem to suggest that the end-product quality of wheat is better preserved at low temperatures. Mhiko (2012) determined that wheat stored at 15°C presented less quality deterioration than wheat stored at ambient temperature (20°C- 40°C).

Table 3.10. Flour and baking quality analysis (mean ±SE) of wheat stored in the Chilled and Control silos from samples taken in Aug. 15th and Sep. 22nd, 2015.

Quality Parameters	Chilled Silo		Control Silo	
	August	September	August	September
MC Wheat (%)	10.5 ±0.1 ^{A}	10.4 ±0.1 ^{A}	10.4 ±0.1 ^{A}	10.3 ±0.1 ^{A}
Wheat Protein (%)	12.5 ±0.2 ^{A}	12.4 ±0.1 ^{A}	13.3 ±0.2 ^{A}	12.6 ±0.2 ^{A}
Flour Protein (%)	11.1 ±0.1 ^{A}	11.0 ±0.1 ^{A}	11.9 ±0.2 ^{B}	11.3 ±0.1 ^{A}
Absorption (%)	63.8 ±0.2 ^{A}	64.3 ±0.3 ^{A}	64.7 ±0.3 ^{A}	65.3 ±0.3 ^{A}
Mix Time (min)	3.7 ±0.1 ^{A}	3.4 ±0.0 ^{A}	3.5 ±0.1 ^{B}	3.0 ±0.1 ^{A}
Loaf Volume (cm^3)	741.1 ±42.5 ^{A}	814.3 ±7.9 ^{A}	818.3 ±2.9 ^{B}	767.0 ±3.0 ^{A}

[A,B] Mean values with the same letter within the same silo and quality variable but at different sampling dates are not significantly different by Tuckey's test ($p > 0.05$) (n=3).

The lower protein content observed in the Control silo on the second sampling date could be explained by the higher temperature inside the silo that was of approximately 27°C. Higher temperatures during storage tend to increase the proteolytic activity in the wheat, which causes that the endo- and exopeptidases' break the polypeptide bonds into simple peptide chains and decrease the measured protein content (Mhiko, 2012). It has also been demonstrated that higher temperatures tend to decrease the baking quality. Gonzalez-Torralba (2013) observed that at temperatures of approximately 30°C during storage, dough extensibility decreased while tenacity and strength increased due to enhanced oxidation of thiol to disulfide groups. Similar observations were made by Wrigley and Batey (1995). This has a negative impact in loaf volume and crumb softness (Gras et al., 2001).

Although the deterioration of protein and other quality variations due to high temperatures during storage has been observed in other research trials, most of them observed significant changes after long storage times (Kibar, 2015; Mhiko, 2012; Tipples, 1995).

In 2016 there were no significant variations for any of the flour quality factors for either of the silos after three months of storage (table 3.11), except for the mixing time of the dough coming from the wheat stored in the Chilled silo, which decreased from 3.42 min in July to 2.92 min in September. Since this was the only factor that saw any significant variation throughout the trial, it is probable that the reason was a change in the protein quality not the protein quantity. As the grain quality results showed (table 3.9), the grain loaded in August and September into the Chilled silo had more damaged kernels, and these kernels usually have higher concentrations of enzymes that slightly alter gluten quality and strength, which is indirectly estimated by the mixing time parameter through the determination of dough stability during mixing (longer mixing time, higher stability) (Serna-Saldívar, 2010; U.S. Wheat Associates, 2007). Although the mixing time decreased, this did not affect the overall baking quality, probably because the protein content was quite stable throughout the storage period which maintained balance that avoided any detrimental effect on the end-product quality.

Table 3.11. Flour and baking quality analysis (mean ±SE) of wheat stored in the Chilled and Control silos from July 1st to Sep. 27th, 2016.

Quality parameters	Chilled silo			Control silo		
	July	**August**	**September**	**July**	**August**	**September**
MC Wheat (%)	9.8 ±0.2^{A}	9.9 ±0.1^{A}	10.2 ±0.1^{A}	10.1 ±0.1^{A}	10.2 ±0.1^{A}	9.9 ±0.1^{B}
Wheat Protein (%)	10.4 ±0.2^{A}	10.7 ±0.2^{A}	10.7 ±0.2^{A}	10.2 ±0.1^{A}	10.5 ±0.2^{A}	10.2 ±0.1^{A}
Flour Protein (%)	8.9 ±0.1^{A}	9.2 ±0.1^{A}	9.3 ±0.2^{A}	9.0 ±0.2^{A}	9.1 ±0.1^{A}	9.0 ±0.1^{A}
Absorption (%)	59.0 ±0.0^{A}	59.3 ±0.3^{A}	59.7 ±0.3^{A}	59.3 ±0.3^{A}	59.3 ±0.3^{A}	59.0 ±0.0^{A}
Mix Time (min)	3.4 ±0.2^{A}	3.0 ±0.1^{AB}	2.9 ±0.2^{B}	3.2 ±0.4^{A}	3.7 ±0.4^{A}	3.2 ±0.0^{A}
Loaf Volume (cc)	657.7 ±20.5^{A}	630.3 ±20.5^{A}	661.7 ±21.3^{A}	673.7 ±7.4^{A}	671.0 ±13.4^{A}	657.7 ±10.1^{A}

[A,B] Mean values with the same letter within the same silo and quality variable but at different sampling dates are not significantly different by Tuckey's test ($p > 0.05$) (n=3).

3.3.9 Power consumption and cost analysis

In 2015, the grain chiller worked from August 22nd to September 14th, 2015. On average it worked on a 28-kWh load. The total power consumption was 8,794 kW for the 314 hours the grain chiller was running which resulted in an electrical cost of 2.35 $/h and 0.54 $/t using a kWh average cost for the Wakefield, KS region of 0.084 $/kWh (table 12).

In the Control silo the two centrifugal fans worked on a 7.5 kWh load each from August 24th to October 5th, 2015. The ambient aeration fans ran for 308 hours for a total power consumption of 4,620 kW, which resulted in an electrical cost of 1.26 $/h and 0.28 $/t (table 3.12). The difference in cost between the ambient and chilled aeration was 0.26 $/t.

Table 3.12. Power consumption (kWh) and cost per hour ($/h) and metric ton ($/t) for running chilling and ambient aeration in 2015 and 2016.

Year	Silo	Average Load (kWh)	Hours of Operation	Total Energy Consumption (kW)	$/hour[3]	$/t[3]
2015	Chilled	28[1]	314	8,794	2.35	0.54
	Control	15[2]	308	4,620	1.26	0.28
2016	Chilled	28[1]	384	10,752	2.35	0.66
	Control	15[2]	371	5,565	1.26	0.34

[1] Average load of system: 1 centrifugal fan of 7.5 kW+ 2 axial fans of 950 W/ea+ 2 compressors of 9.325 kW/ea.
[2] Two centrifugal fans of 7.5 kWh/ea. connected to the Control silo.
[3] Based on an average cost of 0.084 $/kWh

In 2016, the grain chiller worked discontinuously from June 21st to July 12th for a total of 384 hours. The total power consumption during this time was 10,752 kWh which came out to a cost of 2.35 $/h or 0.66 $/t. Since, this year the trial started earlier in the summer and the grain temperature was higher, it was expected that the grain chilling cost would increase. The fan run hours in the Control silo also incremented this year to 371, from June 20th to September 27th. The total power consumption this year was 5,565 kWh for a total cost of 1.26 $/h or 0.34 $/t (table 12).

In both years, the cost of the chilled aeration nearly doubled that of ambient aeration. These results agree with those reported by Quirino et al. (2013). Nevertheless, it has to be taken into consideration that the temperature of the Chilled silo was taken down to levels considerably lower (approximately 17°C) in only 175 hours in 2015 and 245 in 2016.

Although there was no fumigation during the present research trials, previous research has demonstrated that grain chilling is economicallly feasible compared to the use of ambient aeration plus fumigation. Maier et al. (1997) determined that the annual operting cost for chilling wheat from 25°C- 27°C to 15°C- 17°C in 182-240 hours was 1.48 $/t while the cost of in-house fumigation plus ambient aeration was 2.96 $/t.

According to Rulon et al. (1999), a management strategy based on grain chilled aeration would lower the exposure of a elevator business to changes in input price levels such as fumigation materials and labor, and would also be highly competitive in a market where premium quality or post-harvest pestcide-free wheat is demanded.

3.4 Conclusions

Overall, the grain chilling technology proved to be a valuable tool to preserve the quality of grain and more effective to control insect populations compared to the conventional aeration and storage strategies used during the summer storage in Central Kansas. The specific conclusions of this section are:

- In 2015, the grain chiller lowered the average temperature of 1,350 t of wheat from 28°C to 17°C in 175 hours, and in 2016 the grain temperature was lowered from 39°C to 17.6°C in 245 hours. In both years the shrink loss was of approximately 0.2%.
- Using ambient aeration, the average grain temperature inside the Control silo remained over 25°C all summer during both years and there was a shrink loss of approximately 0.5%.
- The bioassays of LGB and RFB showed that the population growth can be controlled with low temperatures (below 20°C), but if grain temperature increases, the insect populations can recover quickly.
- Lower grain temperatures in the Chilled silo decreased drastically the populations of the most common insect species (FGB and FB) found in both years in the probe traps.

- The most common internal-feeder found in the probe traps of both silos was the WEV, although proof of increasing levels of IDK were only found in the Control silo in 2016.
- The detection of insect fragments did not increase significantly throughout the trials in either of the silos, neither did it exceeded the FDA threshold for insect fragments found in flour.
- The low MC of the grain avoided significant fungi growth in the silos, independent of temperature.
- The inconsistent results of the flour and baking quality analysis, did not allow to make definitive conclusion on the effect of temperature during storage on the end-product quality.
- The cost analysis of the trials, based only on the power consumption of both aeration strategies, showed that the cost of grain chilling is between 0.26 $/t- 0.32 $/t higher than ambient aeration.

3.5 Future research

Based on the observations made throughout the development of the field trials and the potential of the grain chilling technology in other post-harvest scenarios, the following research is suggested for future work:

- Test the utilization of a grain chiller on other stored-grains, especially high-value commodities like popcorn and rice, and its effect on end-user quality.
- Develop grain chilling trials on high-moisture stored grain and the effect this can have on fungi development.

- Expand the research on the effect of grain chilling on the end-product quality of wheat.
- Evaluate the advantages of the grain chilling technology vs. traditional grain management strategies that include the use of chemical control of pests during summer storage.

Chapter 4- Evaluation of chilled and ambient aeration strategies for paddy rice stored in the tropical climate of the Northwest region of Costa Rica using computer simulation

4.1 Introduction

The conditions of high temperature and relative humidity during most of the year in tropical climates make ambient aeration of stored grain problematic. Due to the limited access to suitable ambient air conditions for aeration, stored pest management strategies so far have been based primarily on chemical control in this type of climate.

Since cool temperatures (below 20°C) are virtually unavailable in tropical climates, maintenance aeration is the only option using ambient aeration. The objective of maintenance aeration is to use ambient air to maintain the grain temperature and moisture content (MC) in equilibrium with the average ambient conditions. This will avoid the development of hot spots, remove heat produced by biological activity, prevent condensation on cold walls and roofs, maintain the free-flowing characteristics of grain, and maintain more uniform grain temperature and MC in the grain mass (Lawrence and Maier, 2011; Noyes and Navarro, 2002).

Limited number of research studies have come up with strategies that give viable options for aeration in tropical climates. One of these studies was presented by Sinicio and Muir (1998), in which they evaluated the effect of different airflow rates and fan control methods for preventing spoilage in wheat in tropical and sub-tropical climates using a one-dimensional non-equilibrium, forced convection model to simulate aeration using ten years of Brazilian weather data. For the tropical location, this study determined that the best aeration conditions were present when the difference between the average grain temperature and the ambient temperature was 6°C, utilizing an airflow between 0.08 and 0.16 m^3/min/t (~1 and 2 L/s^1/m^3). These aeration parameters allowed wheat at 13% initial MC to be stored for a maximum of eight months under tropical conditions, with minimum shrink loss (0.1%) and reasonable number of fan run hours (645 h at 0.08 m^3/min/t and 397 h at 0.16 m^3/min/t) compared to the fan run hours required by the rest of the strategies (no data of final grain temperature shown).

Lawrence and Maier (2011) studied 15 possible ambient aeration strategies for wheat stored in the sub-tropical climate of North India using a 2D aeration model. The strategies were selected based on combinations of equilibrium moisture content (EMC), temperature, morning and/or evening aeration, and airflow rates. They determined the best strategy based on low dry matter loss (DML), insect development, fan run hours, and average grain temperature and MC. The best strategy ran the fan for four hours during the morning (5:00 a.m. to 9:00 a.m.) and evening (7:00 p.m. to 11:00 p.m.) with an airflow rate of 0.11 m^3/min/t with EMC control during the maintenance period and temperature and EMC control during the cooling period.

For some years now, night time or early morning aeration has been considered as an option for ambient aeration in tropical climates. Aeration during this time of day takes advantage of the lower daily temperatures for having a reasonable cooling effect in the stored grain without rewetting it (Monroy and Valencia, 1978; Noyes and Navarro, 2002; Reed, 2006).

Zeledon and Barboza (2000) studied the conditions of the plenum before and during ambient aeration of a rice metal silo located in Heredia, Costa Rica, in the Central region of the country. Zeledon and Barboza (2000) noticed that the conditions in the plenum were less variable than those of the ambient air. This led to the conclusion that aeration during the early morning hours (cool and humid conditions), when the air conditions in the plenum are warmer and dryer than ambient air, would be suitable for grain aeration. Recio (1999) came to a similar conclusion when maize was aerated with low temperature and high relative humidity (RH) (over 80%) air. The experimental trials performed in a scale model silo (0.75 m of diameter) demonstrated a favorable cooling effect of the stored maize of 4°C and 9.5°C, on average, for initial grain temperatures of 25°C and 30°C, respectively. The MC decreased by 0.1% and 0.2%, on average, for initial grain temperatures of 25°C and 30°C, respectively. They did observe some condensation in the upper layers of the grain mass when initial grain temperature was over 30 °C.

Maier et al. (1992) used computer simulations to compare ambient aeration vs. grain chilling to preserve maize and rice under summer conditions of the sub-tropical region of Texas, U.S. They compared four ambient aeration strategies which included continuous aeration, aeration when ambient RH is low, mid-day aeration, and night aeration. Among these strategies, the best option was considered the continuous aeration one because it had the minimum overdrying effect. However, none of the strategies was able to lower the grain temperature from 38°C to less than 28°C. In contrast, chilled aeration lowered the grain temperature to 15.5°C in 120-160 hours with minimum MC variation (from 13.0% to 12.9%) at an airflow rate of 0.1 m^3/min/t.

It seems evident that the only way to cool stored-grain in most tropical climate areas is by using grain chilling. This technology has been proven to be effective in tropical and sub-tropical climates and has been used successfully to maintain the quality of stored-grain and control insects. In the province of Santa Fe, Argentina, Roskopf and Bartosik (2009) used a grain chiller to lower the temperature of 1,200 t of maize from 24.3°C to 13.8°C in 104.5 hours with an airflow rate of 0.26 m^3/min/t. In Israel, Calderon (1972) chilled 543 t of wheat at 12% MC using a chilled aeration unit with a capacity of 42,500 Kcal/h and with an automatic temperature controller that adjusted the airflow to the get the desired temperature. They were able to chill the grain from 30°C to 12°C in 80 hours, with an airflow rate of 0.42 m^3/min/t. They were also able to remove a hot spot of 47°C in 220 t of soybeans harvested during the summer, down to a range of 13°C to 21°C using the same unit.

In Brazil, extensive research in grain chilling has been undertaken in the past 20 years, mainly due to the collaboration of national universities and private grain chilling companies like Coolseed (Santa Tereza do Oeste, Brazil). One of these studies was developed by Volk and Afonso (2009), in which they chilled one 5,000 t silo and two 2,500 t silo of wheat using a Coolseed grain chiller in the subtropical region of Parana, Brazil. They were able to reduce the temperature of the 5,000 t silo from 30°C to an average grain temperature of 16°C in approximately 300 hours. The two 2,500 t silos were cooled from 29°C to an average temperature of 17.5°C in approximately 250 hours of active chilling.

In the tropical state of Goiás, Brazil, Quirino (2008) chilled 29,000 t of maize in a section of a flat storage bunker, using a Coolseed grain chiller with a capacity of 363,636 Kcal/h. Utilizing chilled aeration they were able to maintain the grain at an average temperature of 17.6°C for four months of storage. This significantly decreased the number of insects per kg of maize from 2.77 live insects/kg at the start of the storage period to 2.23 live insects/kg after four months of storage, while in the section of stored maize that was aerated with ambient air the number of insects increased from 1.12 live insects/kg to 3.74 insects/kg.

Lazzari et al. (2010) reported the use of chilling technology as part of a chemical-free program to store rice in Rio Grande do Sul, Brazil. In this research trial the grain temperature was successfully lowered from 32.9°C to temperatures between 12°C and 14°C in 86 hours using an airflow rate of 0.14 m^3/min/t. This helped to keep the grain free of external insects for eight months.

Since rice is considered a high value commodity, grain chilling becomes an even more attractive option, especially for the chemical-free market. Due to the particularities of this commodity and the way it is sold to the end-consumer (whole kernel white or brown rice), preserving the integrity of the kernel is even more important for commercial purposes than in other commodities.

Being the main food for more than half of the world’s population and an important part of the diet in many Latin American countries, including Costa Rica, the stability of the rice supply is many times related to the food security status of a country (IRRI, 2016). In Costa Rica alone, the per capita consumption is approximately 50 kg, which indicates the great importance rice has in households (Conarroz, 2016).

The objective of this study was to develop potential ambient and chilled aeration strategies for paddy rice stored under the tropical weather conditions of the North Pacific coast of Costa Rica, using an existing computer simulation model that can analyze several aeration alternatives in a short period of time, and that can be adjusted to other tropical regions and stored-products in order to reduce post-harvest losses and increase safe storage time.

4.2 Materials and methods

4.2.1 Grain aeration model inputs

The scenario considered for this research is based on the weather data from the region of Guanacaste, Costa Rica (10°26’N, 85°24’W) in the North Pacific coast of the country. This region was chosen because more than 60% of the paddy rice harvest is stored in this area (Conarroz, 2016). Harvest in this area starts around mid-November and extends to January.

Paddy is stored for a period of 4 to 6 months, depending on demand. Given this situation, the weather data analyzed for the development of the aeration strategies consisted of a period from November 15th to May 15th of the following year.

For the analysis of the present research project, the initial MC and grain temperature were defined at 13% and 35°C because in this region the paddy rice is stored at a MC between 11% and 13%, and it usually comes out of the dryer and into storage at a temperature between 35°C and 37°C.

The size of the corrugated steel silos modeled were 14.58 m in diameter and 14.57 m of side wall height with an average storage capacity of 1,500 t, which is the standard capacity of long term storage silos in this region. Each silo usually has one centrifugal fan of 20 HP (15 kWh) connected to a fully perforated floor. Based on the fan and storage structure size, it was determined, through the FANS program (University of Minnesota, MN), that the resulting airflow rate for aeration was 0.22 m^3/min/t and the total static pressure (SP) was 2,070 Pa (8.3 in. w.c.). This SP generated a temperature increase of 4.6°C in the aeration air due to the fan warming effect, based on the rule of thumb that for every 1-inch water column (w. c.) of SP the temperature of the air passing through an aeration fan increases by 1°F (Noyes and Maier, 2002). Calculations of the fan warming effect are shown in Appendix D.

4.2.2 Development of ambient and chilled aeration strategies

Five years of hourly weather data (2010-2014) were analyzed to develop potential ambient aeration strategies. The weather data was retrieved from the National Renewable Energy Laboratory (NREL, 2012) and included ambient air temperature, RH, wind speed, and solar radiation. According to this data, the available fan run hours were calculated based on the EMC and temperature relation. The EMC was calculated based on the modified Henderson equation for paddy rice (ASAE D245.6).

Based on the weather data analysis and taking into consideration the fan warming effect, the following ambient aeration strategies were developed:

1. Run ambient aeration fan when ambient temperature is less than or equal to 24°C and ERH after fan warming (i.e., in the plenum) is less than 70%.
2. Run ambient aeration fan from 6:00 a.m. to 8:00 a.m. and from 5:00 p.m. to 7:00 p.m.
3. Run ambient aeration fan from 5:00 a.m. to 9:00 a.m. and from 5:00 p.m. to 9:00 p.m.
4. Run ambient aeration fan whenever ambient temperature is 10°C lower than grain temperature in the top section of the center core at 1.5 m below the grain surface.

In order to lower the fan warming effect of the airflow rate (0.22 m^3/min/t), a lower airflow rate (0.13 m^3/min/t) was also considered to reduce SP. A higher airflow rate (0.32 m^3/min/t) was also suggested to decrease the fan run hours required to move the temperature front all the way to the top of the grain mass, although this would increase even more the fan warming effect. The specifications of each of the airflow rates considered are shown in table 4.1.

Table 4.1. Fan power, airflow rate, static pressure and air temperature increase for the four ambient aeration strategies evaluated in this study.

Fan power (HP)	Airflow rate (m^3/min/t)	Static pressure (in. w.c.)	Temperature increase[c] (°C)
60[a]	0.32	13.1	7.3
20[b]	0.22	8.3	4.6
7.5[b]	0.13	4.7	2.6

[a]High speed (3,500 rpm) centrifugal fan
[b]Low speed (1,750 rpm) centrifugal fan
[c]Assumes 40%-50% fan efficiency.

For the chilling strategy, the temperature and RH of the conditioned air going into the silo were determined based on the information compiled from the GCH-20 in the 2015-2016 trials conducted in Kansas (Chapter 3), but ignoring the extreme temperatures measured in the transition duct (over 15°C). This data is shown in Appendix E. Using this information, the temperature and RH of the chilled air were predicted for the climatic conditions of Costa Rica using multiple linear regression equations (eq. 1 and 2). The empirical equations developed for the prediction of the conditions of the chilled air were:

$$(eq. 1) \quad T = 11.04810 + 0.13784x_1 - 0.01104x_2 \qquad \text{RMSE} = 0.5925,\ r^2 = 0.4539$$

and

$$(eq. 2) \quad RH = 82.12998 - 0.62475x_1 + 0.11189x_2 \qquad \text{RMSE} = 2.0232,\ r^2 = 0.7082$$

where,

T= Predicted temperature of chilled air going into the silo (°C)

RH= Predicted relative humidity of chilled air going into the silo (%)

x_1 = Ambient temperature (°C)

x_2 = Ambient relative humidity (%)

The chilled aeration strategy developed for the grain chiller was the following:

1. Run grain chiller continuously until the paddy rice temperature of the center core at 1.5 m below the grain surface is equal to 15°C or less.

4.2.3 Parameters of aeration model

The three-dimensional PHAST-FEM computer simulation model developed by Lawrence and Maier (2011) was used to predict the temperature and MC of the stored paddy rice based on the ambient and chilled aeration strategies developed. The model is an adaptation of the

Montross et al. (2002) two-dimensional model. This computer model is based on the finite element method. The governing equations used to predict the grain temperature and MC under realistic boundary conditions of ambient temperature, RH, solar radiation, and wind speed are described by Montross et al. (2002). Due to programming issues with the computer model, it was not possible to include in the model the effect of solar radiation during the periods of non-aeration on the walls that are most exposed to sunlight in the tropics (east and west walls). Nevertheless, due to the large size and structural dimensions (diameter-to-height ratio of 1.0) of the silo modeled, it is assumed that if the solar radiation effect were included, the temperatures of the sun-facing walls would differ by less than 3°C, according to findings of previous research (Alagusundaram et al., 1990). Maier (1992) states that the level of accuracy of the model with no temperature difference among walls should be adequate for the grain temperature prediction.

The mesh of elements used for the simulation of the grain storage structure was developed using digital drawing program Gambit (Fluent Inc., NH) and the specifications described in section 4.2.1. The physical properties of the paddy rice, like bulk density, porosity, and thermal properties were retrieved from the ASABE standards D241.4 and D243.4 (Appendix F).

Multiple simulations were run for the ambient and chilled aeration strategies using the five years of weather data, taking November 15th as the start date and May 15th as the end date. The strategies were analyzed and ranked based on the results of MC, grain temperature and fan run hours.

4.3 Results and discussion

4.3.1 Weather data analysis

The five-year average hourly weather data (2010-2014) is shown in figure 4.1. The region of Guanacaste is characterized for being the warmest location in Costa Rica, with a yearly average temperature of 28°C and an average maximum temperature of 33°C (Solano and Villalobos, n.d.). In this part of the country, the dry season starts in December with November the transition month from the rainy season into the dry season, and ends in March, with April the transition month into the rainy season (IMN, n.d.).

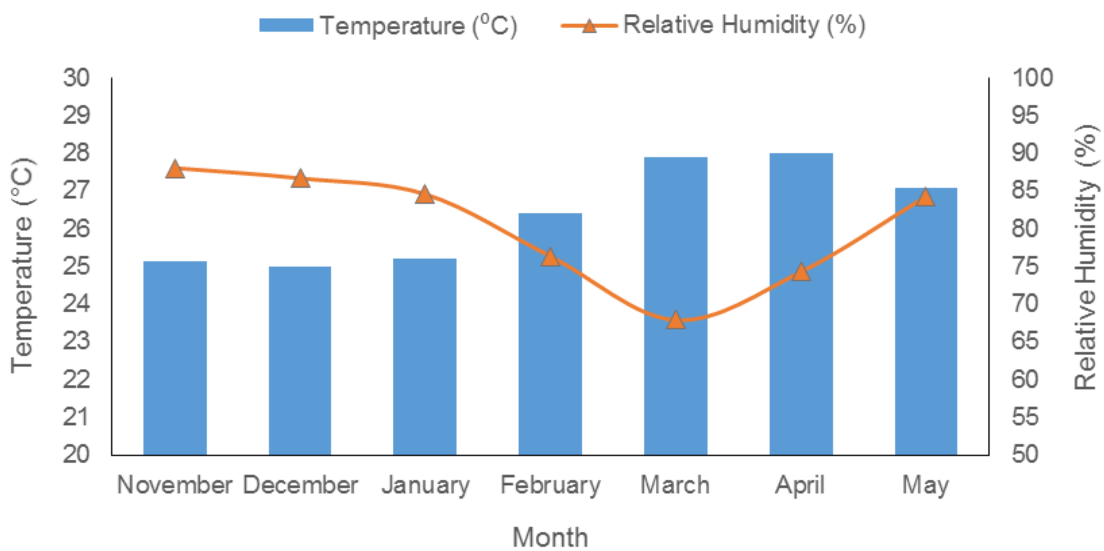

Figure 4.1. Monthly five-year average temperature (°C) and relative humidity (%) from November 15th to May 15th for 2010-2014 in the region of Guanacaste, Costa Rica.

From the analysis of the five-year average weather data, it was observed that during the first part of the dry season (November to January) the ambient temperature is slightly lower than the rest of the year (fig. 4.1). During this period of the year the average temperature was about 25°C, with 21°C as the average minimum and 31°C as the average maximum. During this time of the year the average RH was about 86%, with 63% as the average minimum and 97% as the average maximum. In February, the average temperature increased to 26.5°C and later on to 28°C in March (fig. 4.1). During these last two months of the dry season, the average minimum and maximum temperatures registered were 21°C and 37°C, respectively. The average RH decreased to 76% in February and then to 68% in March (fig. 4.1). The average minimum and maximum RH registered during these two months was 32% and 95%, respectively. In the transition period from the dry to the rainy season during April and then May, the average temperature did not change much and remained at 28°C during April and slightly decreased to 27°C in May (fig. 4.1). The average minimum and maximum temperatures registered during this period of the year were 23°C and 36°C, respectively. In April, the average RH increased to 74% and then to 84% in May (fig. 4.1). The average minimum and maximum RH registered during these two months was 38% and 96%, respectively.

Considering the high temperature of the region, the best option to try to cool the bulk temperature close to the daily average temperature (27°C- 30°C) would be to implement ambient aeration during nighttime, especially from November to January when the ambient temperature is slightly cooler. However, given that the RH increases during the cooler hours, in order to avoid rewetting the grain the ambient aeration fans should only be activated during the hours when the temperature and RH are not extreme and based on considering the fan warming effect on the ambient air. This commonly occurs in the late evening and early morning. Figure 4.2 shows an example of daily variations of temperature and RH in January and the periods during which it would be better to use ambient aeration (marked by arrows).

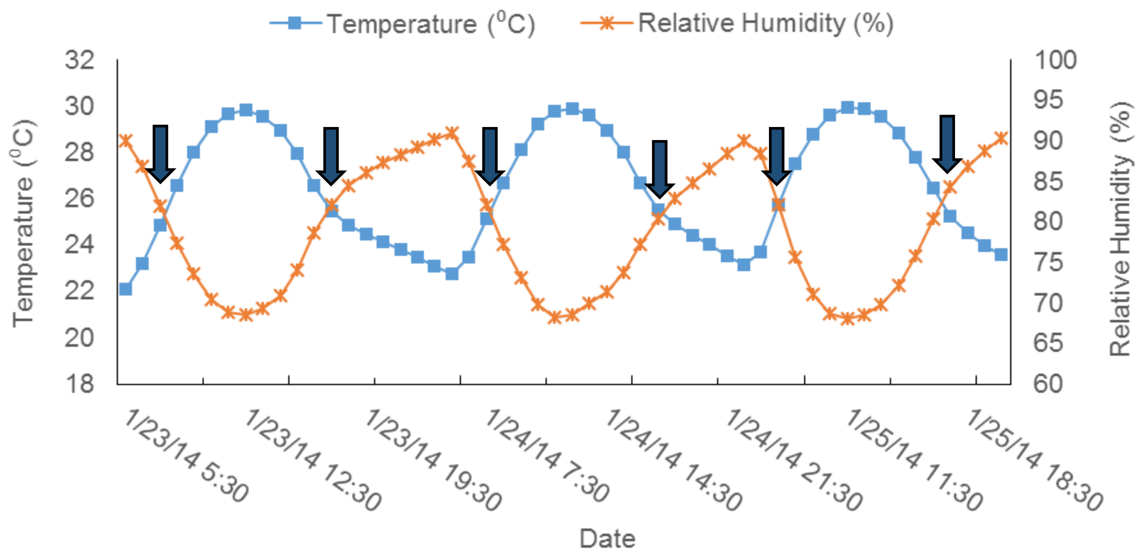

Figure 4.2. Daily variations of ambient temperature and relative humidity from January 23rd to the 25th, 2014 in Guanacaste, Costa Rica.

Based on the analysis of this weather data, it is possible to calculate the average of the available fan run hours during the storage period (table 4.2). Ambient temperatures below the daily average (27°C- 30°C) were considered in order to maintain the grain temperature and MC in equilibrium with the daily average ambient conditions, taking into account that fan warming would increase the temperature and reduce the relative humidity of the aeration air.

Table 4.2. Five-year average fan run hours estimated for different times of the year based on different ambient air temperature and EMC upper limits (without considering fan warming effect) in the region of Guanacaste, Costa Rica.

Upper limit ambient air temperature	23°C			24°C			25°C			26°C		
Upper limit EMC, w.b. (ERH)	13% (65%)	15% (79%)	17% (90%)	13% (66%)	15% (80%)	17% (90%)	13% (66%)	15% (80%)	17% (90%)	13% (67%)	15% (81%)	17% (90%)
November-January	0	1.75	40.5	0	4.7	93.8	0.25	12.5	186.3	0.75	37.3	402
February-March	1.25	5.75	62	2	17.3	170.5	3.25	56.6	291	4.5	115	396
April-May	0	0.5	8.25	0	4	34.75	0	12.25	77	0	27	141
Total	1.25	8	111	2	26	299	3.5	81	554	5.25	179	939

The calculation of the available fan run hours showed that at temperatures between 23°C and 26°C there were basically no fan run hours available with conditions suitable to aerate grain at ERH< 70% (EMC≤ 13%) throughout the storage period. However, taking into account the fact that the 20 HP motor fan would create a fan warming effect that would increase the temperature of the aeration air in the plenum by 4.6°C and reduce the ERH of the aeration air by 20% on average, it is possible to use ambient air up to 90% ERH (EMC≤ 17%), since the fan warming effect decreases the ERH of the aeration air to levels below 70% (EMC≤ 13%), which increases the This increases the number of fan run hours available at air temperatures below 26°C (30.6°C after fan warming effect) (table 4.3).

Table 4.3. Five-year average fan run hours estimated for different times of the year based on effective air temperature and EMC upper limits (considering a fan warming effect of 4.6°C at the plenum) in the region of Guanacaste, Costa Rica.

Upper limit air temperature	27.6°C			28.6°C			29.6°C			30.6°C		
Upper limit EMC, w.b. (ERH)	11% (50%)	12% (59%)	13% (67%)	11% (51%)	12% (60%)	13% (68%)	11% (52%)	12% (60%)	13% (68%)	11% (52%)	12% (61%)	13% (69%)
November-January	0	1.25	40.5	0	3.5	94	0.25	7.75	186.3	0.75	24.75	242
February-March	2	5.25	60	2.75	10	170.5	4.25	32.5	354	4.5	83.5	396
April-May	0	0	10	0	4	34.75	0	10	14	0	18.5	141
Total	2	7	110	3	18	299	5	50	555	5	127	780

Based on the airflow rate of 0.22 m^3/min/t (20 HP motor fan), which is the one commonly used for rice in this region, the minimum time it would take a temperature front to move all the way through the grain mass would be 56 hours (MWPS, 1999). Table 4.3 indicates that the total fan run hours of 110 h at air temperatures below 27.6°C and EMC< 13% at the plenum, would suffice to move that temperature front through the rice mass, however, it would take more than three months for it to reach the top. As the upper limit increases from 28.6°C to

30.6°C, the number of fan run hours available to move the aeration front through the rice at EMC<13% in the first three months of storage increases from 94 h to 242 h, respectively. This means that there are enough fan run hours with conditions at the plenum of 28.6°C (24°C ambient air) and EMC<13% to move the aeration front through the rice in the first three months.

Increasing the airflow rate from 0.22 m^3/min/t to 0.32 m^3/min/t reduces the number of fan run hours required to move the aeration front through the grain mass from 56 h to 38 h, respectively, according to the MWPS (1999). This would allow the temperature front to reach the top of the grain mass faster, but would also increase the temperature of this front by 7.3°C as observed in table 4.4. The effect that increasing the airflow rate has on the final temperature and EMC of rice is discussed in section 4.3.2.2.

Table 4.4. Five-year average fan run hours estimated for different times of the year based on effective air temperature and EMC upper limits (considering a fan warming effect of 7.3°C at the plenum) in the region of Guanacaste, Costa Rica.

Upper limit air temperature	30.3°C			31.3°C			32.3°C			33.3°C		
Upper limit EMC, w.b. (ERH)	11% (51%)	12% (60%)	13% (68%)	11% (52%)	12% (61%)	13% (69%)	11% (52%)	12% (61%)	13% (69%)	11% (53%)	12% (62%)	13% (70%)
November-January	1.75	163	479	4.75	327	882	11.5	507	1158	34	691	1355
February-March	5.75	163	257	17	322	439	55	466	590	113	578	705
April-May	0.5	21	33	4	81	158	12	179	421	26	308	647
Total	8	347	769	26	730	1479	79	1151	2168	173	1577	2706

On the other hand, reducing the airflow rate from 0.22 m^3/min/t to 0.13 m^3/min/t reduces the fan warming effect to 2.6°C. This allows lower air temperatures in the plenum as shown in table 4.5., which helps lower the temperature of the grain bulk, although the temperature front would require a longer time to move through the rice, which is approximately 112 h according to MWPS (1999). The effect that decreasing the airflow rate has on the final temperature and EMC of rice is discussed in section 4.3.2.3.

Table 4.5. Five-year average fan run hours estimated for different times of the year based on effective air temperature and EMC upper limits (considering a fan warming effect of 2.6°C at the plenum) in the region of Guanacaste, Costa Rica.

Upper limit air temperature	25.6°C			26.6°C			27.6°C			28.6°C		
Upper limit EMC, w.b. (ERH)	11% (51%)	12% (60%)	13% (68%)	11% (52%)	12% (61%)	13% (69%)	11% (52%)	12% (61%)	13% (69%)	11% (53%)	12% (62%)	13% (70%)
November-January	0	0	0.25	0	0	1.25	0	0	3	0	0.5	13.5
February-March	0	2.5	4.75	0.25	3.25	10	0.5	5	34	1	8.25	82.5
April-May	0	0	0.5	0	0	3.25	0	0	8	0	0.5	18
Total	0	2.5	5	0.25	3	11	0.5	5	37	1	9	114

4.3.2 Ambient aeration strategies

The assessment of the weather conditions and the available fan run hours indicated that the two biggest drawbacks for applying ambient aeration in this region are the significant fan warming effect due to the high SP generated by the aeration fan and the lack of cooler temperatures that can off-set the high fan warming effect, which limits the "cool-down" effect of the ambient aeration strategies. Nevertheless, this fan warm also decreases the RH by an average of 20%, which helps increase the number of hours with an appropriate ERH for aeration of paddy rice under these climatic conditions.

Based on this assessment the four ambient aeration strategies were developed. The first strategy had a temperature and EMC limit based on running the aeration fans when the ambient temperature was less than or equal to 24°C (i.e., 28.6° plenum air temperature) and the ERH of the aeration air was in equilibrium with the paddy rice at 13% EMC in the plenum. Strategies 2 and 3 were based on morning and evening aeration with no temperature or EMC control. Strategy 2 ran for two hours in the morning (6:00 a.m. to 8:00 a.m.) and two in the evening (5:00 p.m. to 7:00 p.m.). In order to move the temperature front faster to the top of the grain mass, the fan run hours were extended in the third strategy to four hours in the morning (5:00 a.m. to 9:00 a.m.) and four in the evening (5:00 p.m. to 9:00 p.m.). The fourth strategy turned on the aeration fans whenever the ambient temperature was 10°C less than the temperature of the grain in the top section (1.5 m below the rice surface) of the center core and had no EMC limit. This strategy controlled the aeration fans exclusively based on a temperature differential, without limits on ambient temperature or RH, so long as the condition of 10°C temperature difference between the grain temperature at one location in the grain mass and ambient temperature was fulfilled. Given the number of hours that fulfilled this condition reduced as the grain temperature decreased, this was enough of a restriction to limit the number of fan run hours. This strategy was developed based on published studies that suggested a minimum temperature difference of 5-7°C effectively decreases grain temperature (Reed and Arthur, 2000; Sinicio and Muir, 1998), and considering that the fan warm effect would increase the temperature of the aeration air by approximately 5°C, the minimum temperature would have to be 10°C.

4.3.2.1 Ambient aeration strategies with 0.22 m^3/min/t airflow rate

The outcome of the ambient aeration simulations at 0.22 m^3/min/t are shown in table 4.6. The results of temperature, MC, and total fan run hours are shown for better comparison of the proposed strategies for three key dates throughout the storage period. Table 4.6 also shows the average variability (SD) of the grain temperature and MC inside the grain bulk of each year of simulation.

Table 4.6. Five-year average of average grain temperature, moisture content, total fan run hours and standard deviation of ambient aeration strategies at 0.22 m^3/min/t for paddy rice stored in Guanacaste, Costa Rica.

Ambient aeration strategy	Temperature, °C (SD)[a]			MC, % (SD)[a]			Total fan run hours (SD)[b]
	Dec 1	Feb 28	May 15	Dec 1	Feb 28	May 15	
1	35.0 (0.2)	31.7 (2.0)	33.0 (1.1)	13.0 (0.0)	13.0 (0.1)	12.9 (0.1)	288 (57)
2	34.1 (0.7)	34.3 (1.4)	35.0 (0.4)	13.0 (0.0)	12.9 (0.5)	11.8 (0.6)	729 (2)
3	33.7 (0.4)	35.2 (1.5)	35.2 (0.5)	13.0 (0.0)	12.6 (0.5)	12.4 (0.5)	1458 (4)
4	32.2 (0.5)	30.6 (0.7)	30.8 (0.5)	13.0 (0.1)	13.1 (0.1)	13.1 (0.1)	214 (43)
2- Aeration from Nov.15th to Jan 31st	34.1 (0.7)	32.7 (0.3)	32.8 (0.4)	13.0 (0.0)	13.0 (0.1)	13.0 (0.1)	312 (0)
3- Aeration from Nov.15th to Jan 31st	33.7 (0.4)	33.1 (0.3)	33.2 (0.4)	13.0 (0.0)	12.9 (0.1)	12.9 (0.1)	624 (0)

SD= ± Standard deviation.
[a]Average of the grain bulk SD of each year.
[b]SD of the total fan hours from year to year.

The data shows that from all the proposed ambient aeration strategies, Strategy 4 was the one that showed the lowest average temperature of the paddy rice (30.8°C) at the end of the storage period (table 4.3). It appears that the fan warming effect of 4.6°C is substantial enough to avoid lower grain temperatures, especially considering that cool temperatures below 24°C are relatively scarce in this region.

The first strategy did not have much of an effect on five-year average of the average grain temperature during the first two weeks of storage because not many hours satisfied the temperature and EMC conditions available during these days (fig. 4.3). By late February the five-year average of the average grain temperature decreased to 31.7°C. In May, it slightly increased to 33°C, probably due to the higher ambient temperatures during March and April (fig. 4.1). The five-year average of the average MC was basically unchanged throughout the storage period using this strategy (table 4.6).

Compared to the other strategies, Strategy 1 was the least effective one to maintain uniform grain bulk temperature through the storage period (table 4.6). This was probably caused by the uneven distribution of the fan hours during the storage period.

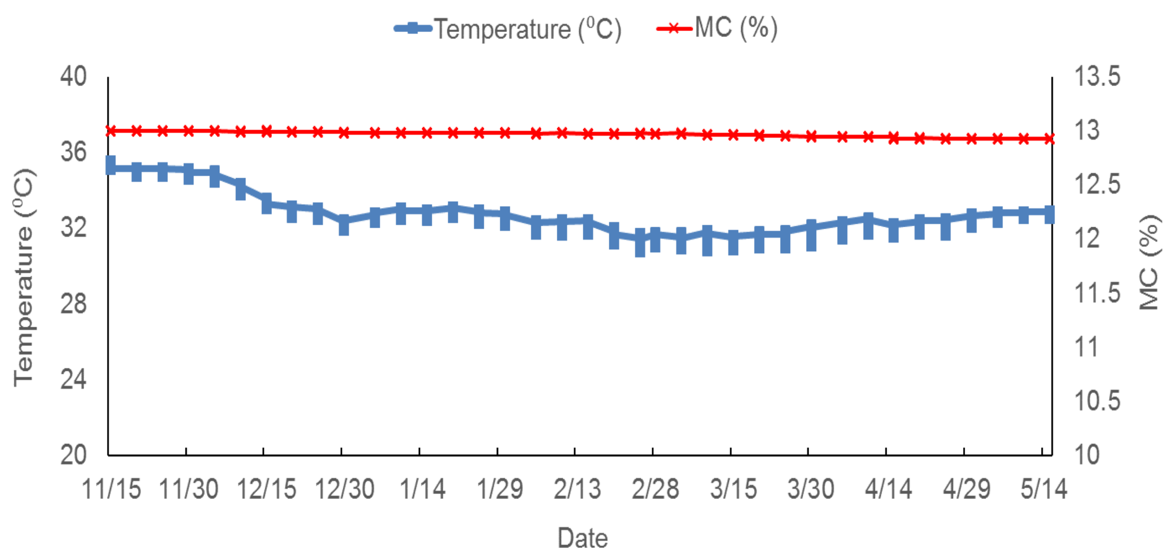

Figure 4.3. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 1 at 0.22 m^3/min/t.

Strategies 2 and 3 were not effective in lowering the average grain temperature and also caused the biggest MC reduction or shrink loss (table 4.6). The issue with these strategies is that because they have no temperature limit, they rewarm the grain in March and April when the average ambient temperature increased. It was during that same period when moisture loss aeration caused the most substantial MC loss. Therefore, by the end of the storage season the rice had basically the same temperature as when it was initially stored but shrank by 0.4 to 1.2 percentage points (fig. 4.4 and 4.5). The maximum moisture shrink occurred with Strategy 3 by mid-April.

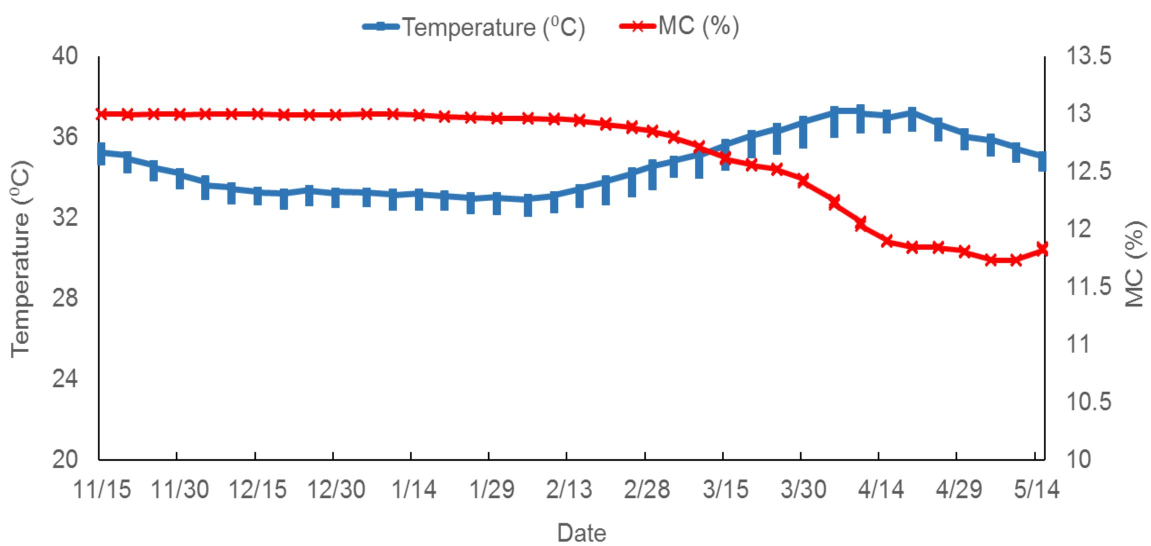

Figure 4.4. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 2 at 0.22 m^3/min/t.

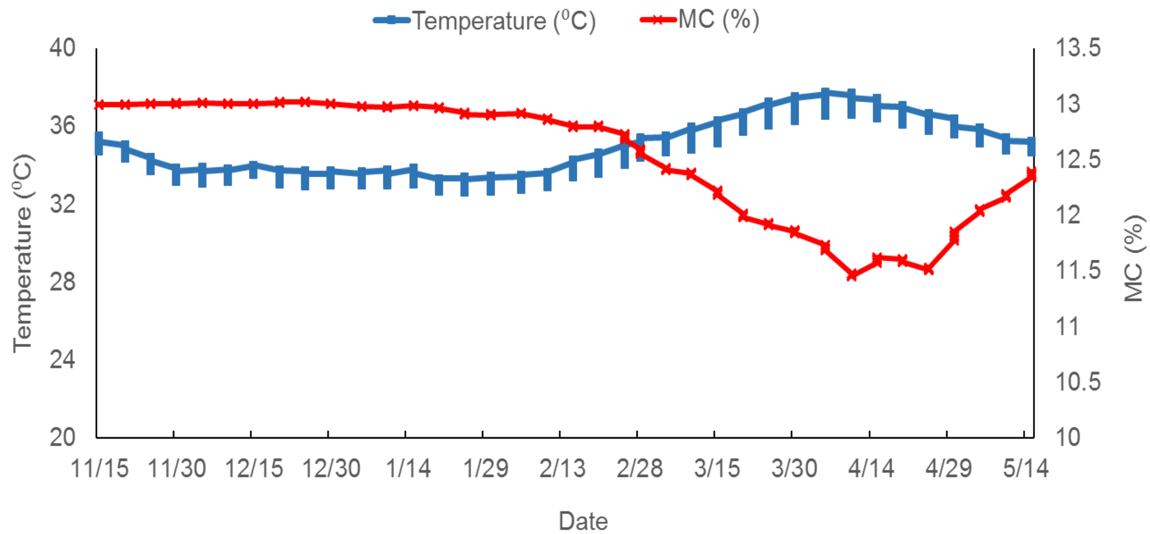

Figure 4.5. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 3 at 0.22 m^3/min/t.

Given the initial results of Strategies 2 and 3, they were re-evaluated with the restriction that the fans would only run during the time of year when the coolest nighttime temperatures are available (November to January) (fig. 4.1). This modification avoided rewarming of the grain, reduced the grain temperature and MC variability (according to SD in table 4.6) and lowered the average grain temperature to approximately 33°C with both strategies, all the way to May (fig. 4.6 and 4.7). This variation also reduced average shrink loss due to fewer hours of aeration (table 4.6). Fewer fan run hours also represent savings in energy cost.

Although Strategies 2 and 3 were not as effective to lower the average grain bulk temperature as Strategy 4, the results of these strategies are considered good enough, based on MC and temperature profiles. Therefore, these two strategies (2 and 3) could be considered as an option instead of Strategy 4 for this specific region if the storage facility has no appropriate instrumentation of weather station or temperature cables inside the silos. Therefore, Strategy 2 would be the preferred option since it requires fewer fan run hours than Strategy 3. However, if the appropriate instrumentation is available, Strategy 4 is the preferred option since Strategy 2 requires more fan run hours because it activates the fans every day during early morning and evening hours, no matter the weather conditions.

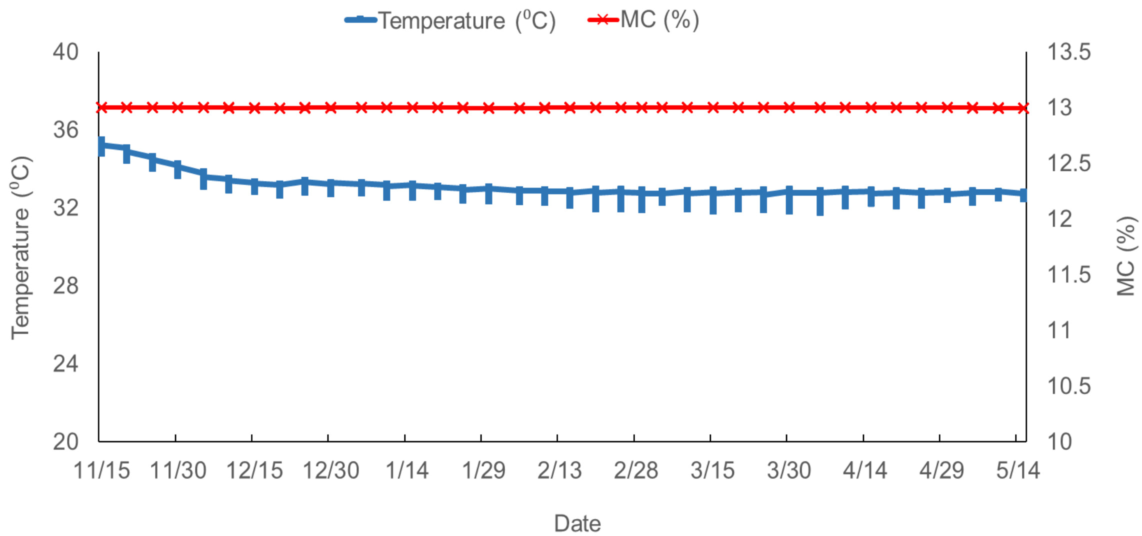

Figure 4.6. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 2 at 0.22 m^3/min/t only from Nov. to Jan.

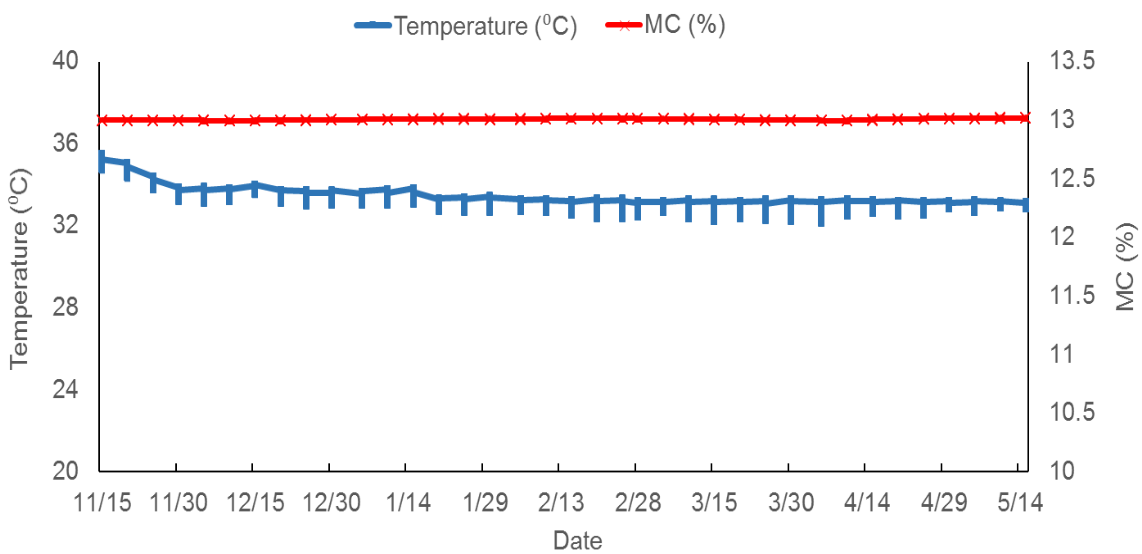

Figure 4.7. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 3 at 0.22 m^3/min/t only from Nov. to Jan.

Strategy 4 reduced the five-year average of the average grain temperature to 32.2°C by early December, which is lower than it ever got with Strategies 2 and 3, and slightly higher than the minimum grain temperature achieved in late February with Strategy 1 (table 4.6). By late December the average grain temperature reduced to 30.8°C and basically maintained this temperature for the rest of the storage period (fig. 4.8). The fact that this strategy had no EMC restriction allowed for lower ambient temperatures to be utilized for aeration. This helped lower the average grain temperature and also allowed the temperature front to move faster because more fan run hours were available at the beginning of the storage period.

Despite the fact that this strategy allowed air with ERH slightly higher than 70% (approximately 75%) after fan warming to be utilized for aeration, the average EMC did not increase more than 0.1%, which was mainly caused by the increase at the lower levels of grain by 0.2%. The reason that the MC increase was restricted to the bottom layers is that moisture fronts may travel up to 100 times slower than temperature fronts up a grain bulk (Thorpe, 2002). Given that Strategy 4 required the least amount of fan run hours to achieve the set temperature criteria, it was possible to avoid significant rewetting of the whole grain bulk.

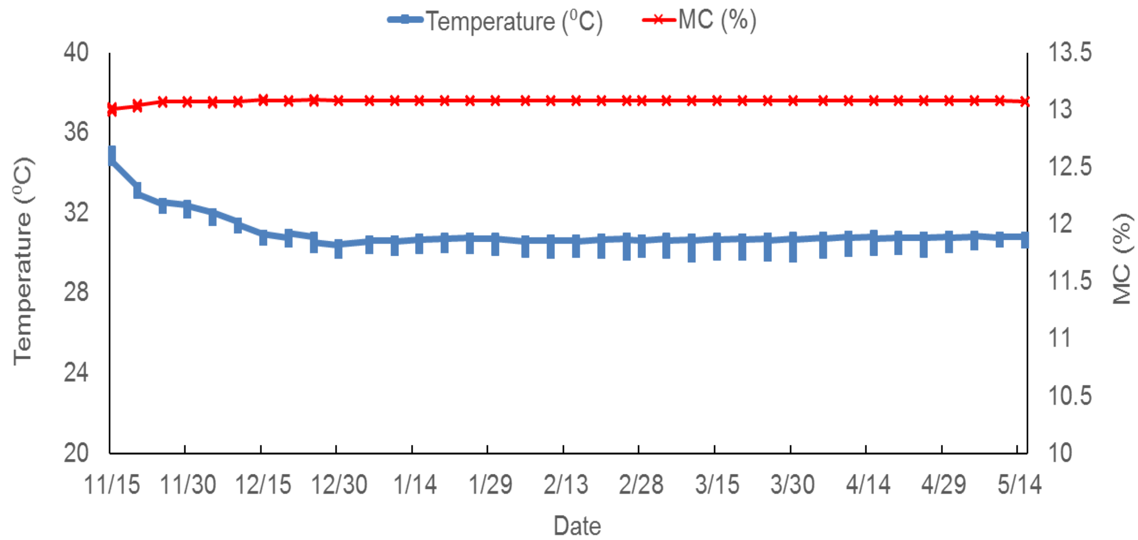

Figure 4.8. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 4 at 0.22 m^3/min/t.

4.3.2.2 Ambient aeration strategies with 0.32 m^3/min/t airflow rate

The purpose of increasing the airflow rate from 0.22 to 0.32 m^3/min/t was to make better use of each available hour with appropriate conditions for aeration because they are scarce in this region and to be able to move the temperature front faster to the top of the grain mass.

Even though increasing the airflow rate moves the temperature front faster through the grain mass, it can be observed from table 4.4 that increasing airflow rate also increases the fan warming effect and offsets the potential for cooling as it can be observed by the higher grain temperatures in table 4.7.

Table 4.7. Five-year average of average grain temperature, moisture content, total fan run hours and standard deviation of ambient aeration strategies at 0.32 m^3/min/t for paddy rice stored in Guanacaste, Costa Rica.

Ambient aeration strategies	Temperature, °C (SD)[a]			MC, % (SD)[a]			Total fan run hours (SD)[b]
	Dec. 1	Feb. 28	May 15	Dec. 1	Feb. 28	May 15	
1	37.1 (0.2)	37.0 (0.4)	37.6 (0.9)	12.6 (0.2)	12.3 (0.3)	12.2 (0.1)	1422 (221)

2- Aeration from Nov.15th to Jan 31st	38.3 (0.6)	37.3 (0.6)	37.2 (0.4)	12.8 (0.4)	12.2 (0.2)	12.2 (0.2)	312 (0)
3- Aeration from Nov.15th to Jan 31st	39.0 (0.9)	38.2 (0.4)	38.1 (0.2)	12.6 (0.5)	12.1 (0.2)	12.1 (0.2)	624 (0)
4	39.7 (0.8)	39.0 (0.9)	41.0 (1.0)	12.1 (0.2)	11.9 (0.1)	11.8 (0.1)	3248 (187)

SD= ± Standard deviation.
[a]Average of the grain bulk SD of each year.
[b] SD of the total fan hours from year to year.

Increasing the airflow rate in Strategy 1 caused a quick rewarming of the grain that reached 37°C by early December and basically maintained that temperature through the rest of the storage period (fig. 4.9). Given that the temperature and EMC restrictions in this strategy were not modified, the number of fan run hours increased dramatically because the higher fan warming effect decreased even more the RH of the plenum aeration air, extending the number of hours suitable for aeration under the given restrictions (table 4.7). This extended number of fan run hours caused a shrink loss of almost 1.0% point by the end of the storage season.

Lowering the upper limit ambient temperature below 24°C, like to 21°C, for example, would not increase the efficiency of this strategy because the 7.3°C fan warming effect would increase the temperature of the aeration air to 28.3°C, similar to the plenum air temperature with the 0.22 m^3/min/t airflow rate, therefore obtaining similar results. Additionally, setting the upper limit below 24°C will limit even more the available fan run hours due to the limited number of cooler temperatures below 24°C recorded in the five-year history data.

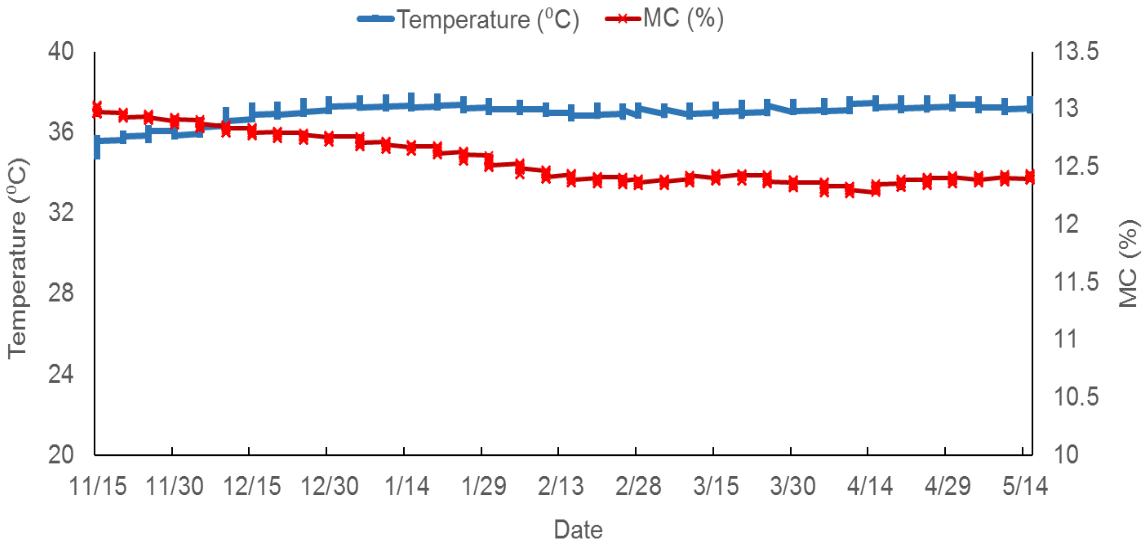

Figure 4.9. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 1 at 0.32 m^3/min/t.

Basically, the same results as for Strategy 1 were observed for Strategies 2 and 3 (fig. 4.10 and 4.11). The higher fan warming effect caused warmer and drier air in contact with the rice which increased the average grain temperature to 37.2°C and 38.1°C in Strategy 2 and 3, respectively, by the end of the storage season. It also reduced the average MC to approximately 12%. Modifying the hours when the aeration fans would be on could probably help take more advantage of this strategy using a higher airflow rate, but again this would probably not be sufficient to lower the grain temperature below the level obtained with the 0.22 m^3/min/t airflow rate.

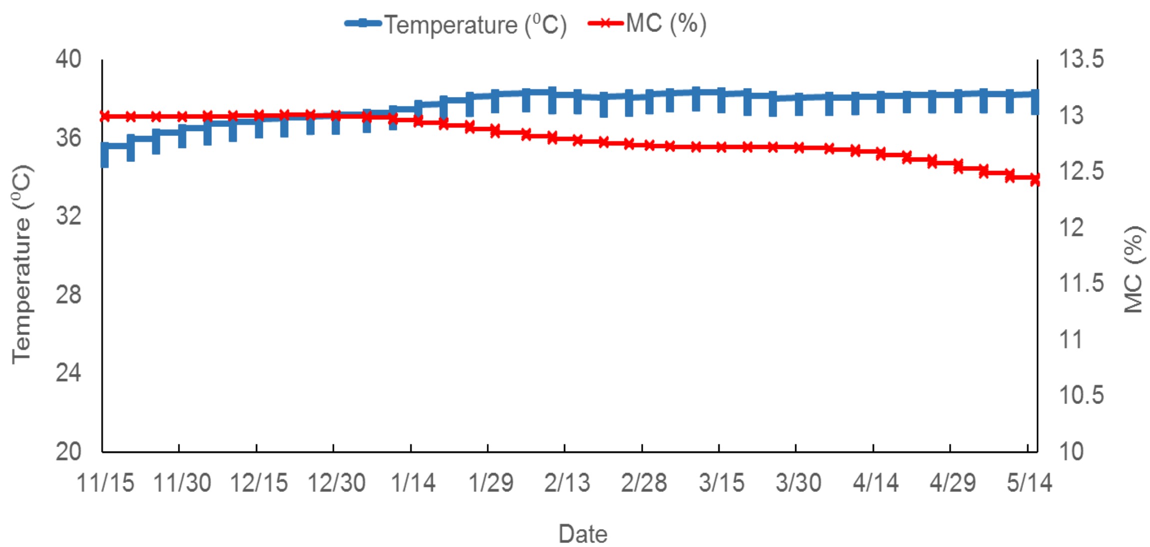

Figure 4.10. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 2 at 0.32 m^3/min/t only from Nov. to Jan.

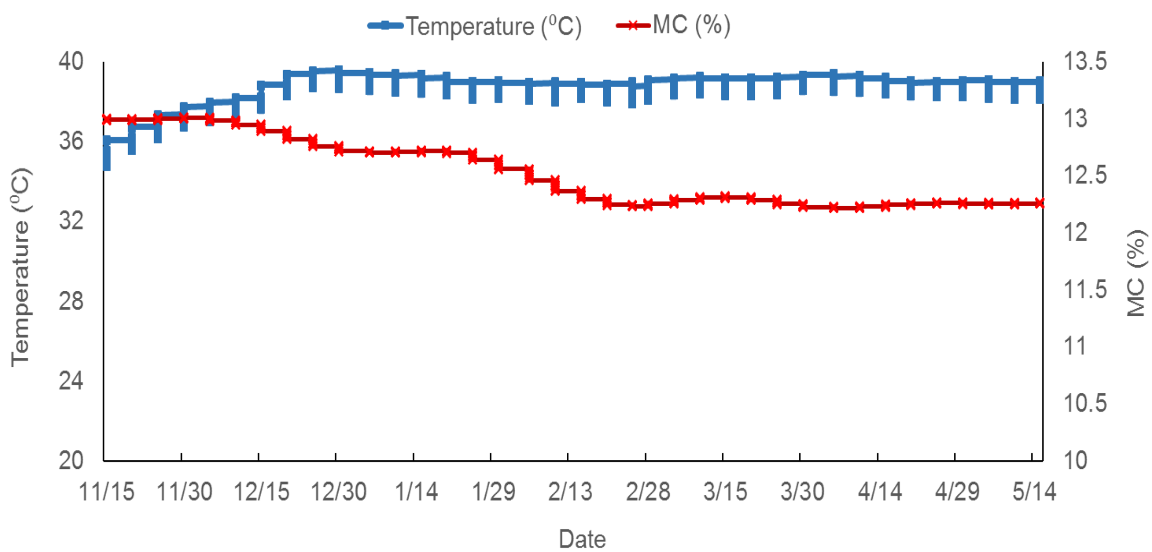

Figure 4.11. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 3 at 0.32 m^3/min/t only from Nov. to Jan.

The final average grain temperature for Strategy 4 was the highest because the 7.3°C fan warming always kept the grain and ambient temperature difference greater than 10°C (table 4.7). By May, the grain temperature was 41°C and the MC was 11.8% (fig. 4.12). As stated previously, modifying this strategy according to the fan warming effect could make this strategy more effective at this airflow rate. However, due to the high fan warming effect and the low availability of cooler air temperatures in this region, it would be difficult to lower the grain temperature below the level achieved using the 0.22 m^3/min/t airflow rate.

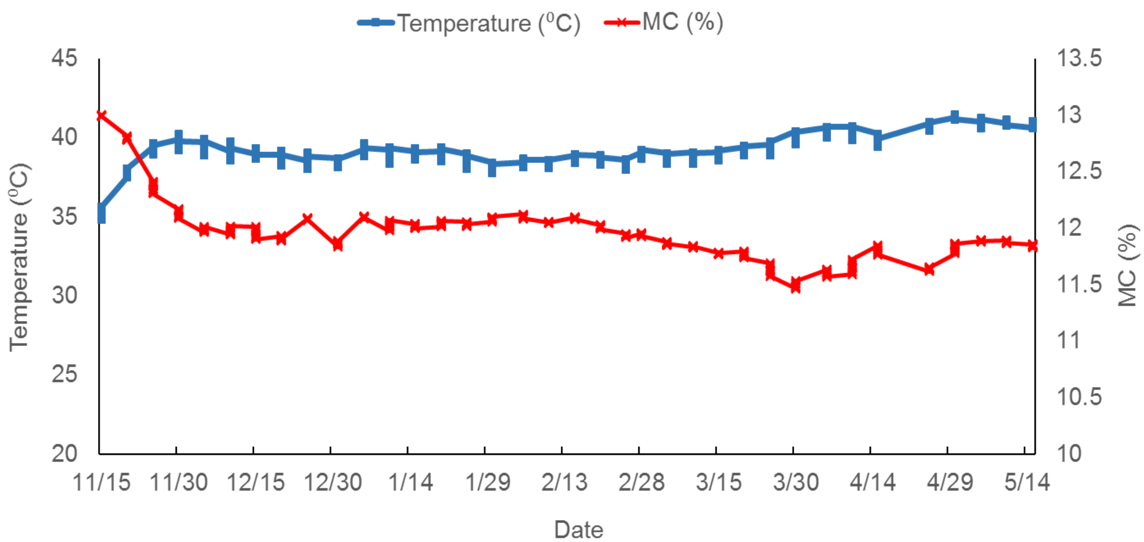

Figure 4.12. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 4 at 0.32 m^3/min/t.

4.3.2.3 Ambient aeration strategies with 0.13 m^3/min/t airflow rate

Although 0.13 m^3/min/t is not recommended in the literature for ambient aeration in tropical climates (Calderon, 1972), lower airflow rates would lower the fan warming effect. However, it would extend the time required to move the temperature front all the way to the top of the grain mass. Same as in the previous section, none of the conditions of the strategies were changed in order to make the comparison using the other airflow rates.

From table 4.8 it can be observed that with most of the strategies, except for Strategy 1, it is possible to decrease the grain temperature by 3°C to 4°C, compared to the temperatures achieved with an airflow rate of 0.22 m^3/min/t.

Table 4.8. Five-year average of average grain temperature, moisture content, total fan run hours and standard deviation of ambient aeration strategies at 0.13 m^3/min/t for paddy rice stored in Guanacaste, Costa Rica.

Ambient aeration strategy	Temperature, °C (SD)[a]			MC, % (SD)[a]			Total fan run hours (SD)[b]
	Dec. 1	Feb. 28	May 15	Dec. 1	Feb. 28	May 15	
1	35.5 (0.9)	34.6 (0.7)	34.2 (1.4)	13.0 (0.0)	13.0 (0.0)	13.0 (0.0)	11 (8)
2 - Aeration from Nov.15th to Jan 31st	33.0 (2.5)	29.3 (0.4)	29.5 (0.6)	13.0 (0.1)	13.1 (0.1)	13.1 (0.1)	312 (0)
3 - Aeration from Nov.15th to Jan 31st	31.2 (2.0)	29.3 (0.4)	29.4 (0.6)	13.0 (0.2)	13.3 (0.1)	13.3 (0.1)	624 (0)
4	29.3 (1.7)	29.0 (0.7)	29.2 (0.5)	13.2 (0.4)	13.2 (0.4)	13.2 (0.4)	156 (6)

SD= ± Standard deviation.
[a]Average of the grain bulk SD of each year.
[b] SD of the total fan hours from year to year.

The first strategy was the only one where the five-year average of the average grain temperature was higher than with the 0.22 m^3/min/t airflow rate by the end of the storage season (table 4.6). This is because the number of hours under 24°C ambient temperature (26.6°C at the plenum) with an ERH in equilibrium with the grain at 13% MC decreased noticeably due to less fan warming (table 4.5). Because of this, the 11 fan run hours were not enough to move the temperature front all the way through the grain mass. This left the grain at an average temperature of 34°C during most of the storage season (fig. 4.13).

In order to increase the number of fan run hours, the temperature upper limit would have to be increased to at least 26°C ambient temperature (28.6°C in the plenum). Due to the 2.6°C of fan warming, the temperature decrease of the grain would not be much different than that with 0.22 m^3/min/t airflow.

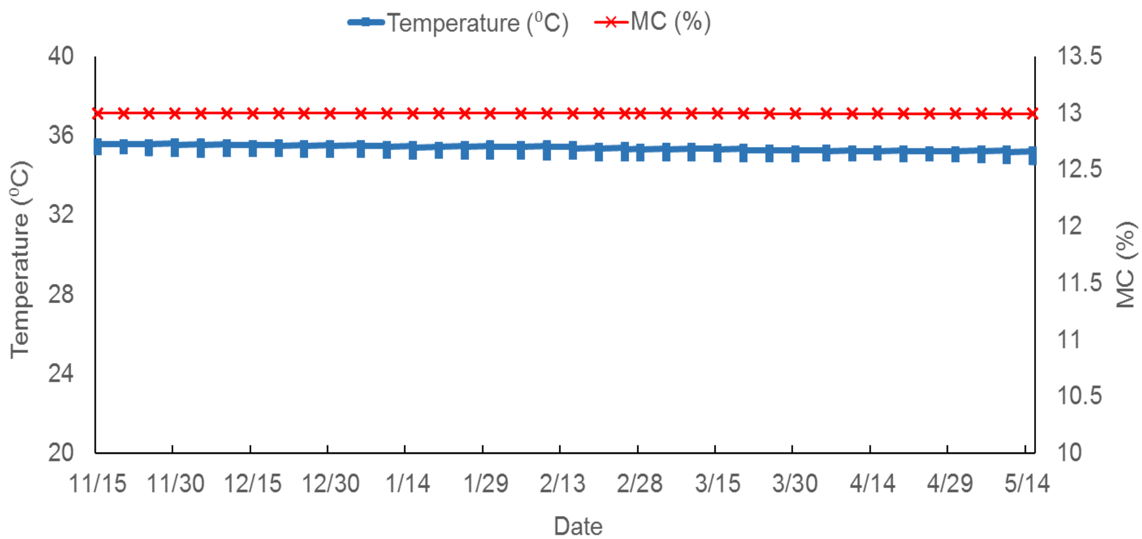

Figure 4.13. Five-year average of the average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 1 at 0.13 m^3/min/t.

Strategy 2 lowered the average grain temperature to 33°C by early December, which was slightly lower than the grain temperature at the same date using the 0.22 m^3/min/t airflow rate (table 4.3). By the end of December, the temperature front reached the top of the grain mass and from then on the temperature remained stable at approximately 29.5°C (fig. 4.14). This is approximately 3°C below the final average grain temperature of the 0.22 m^3/min/t airflow rate and similar to the difference in the fan warming effect due to 0.13 0.22 m^3/min/t versus 0.22 m^3/min/t. The average MC increased by 0.1% through the storage period.

Strategy 2 can be recommended if a lower airflow rate (0.13 m^3/min/t) was considered because it reduces the grain temperature by 5.5°C by the end of the storage period (1.3°C lower than the temperature achieved with Strategy 4 at 0.22 m^3/min/t on the same date) with a minimum increase of the average MC (0.1% increase) and with a reasonable number of fan run hours (312 h), considering that Strategy 4 at 0.22 m^3/min/t required 214 hours.

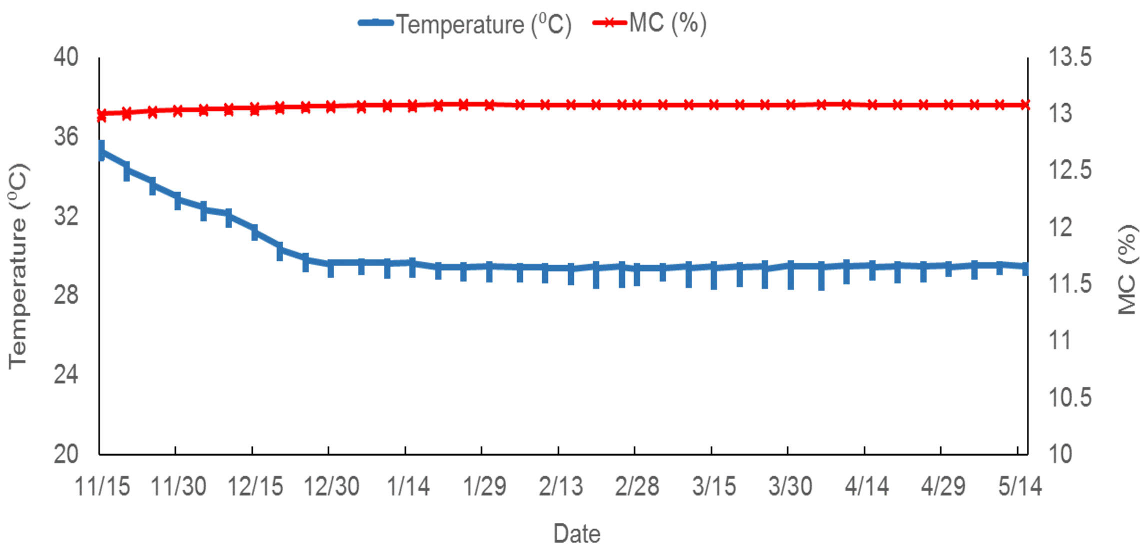

Figure 4.14. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 2 at 0.13 m^3/min/t only from Nov. to Jan.

Strategy 3 also reduced the average grain temperature to 29.5°C, except that with this strategy the temperature front reached the top of the grain mass about a month before it did in Strategy 2 (fig. 4.15). The average MC increased by 0.3% points with this strategy.

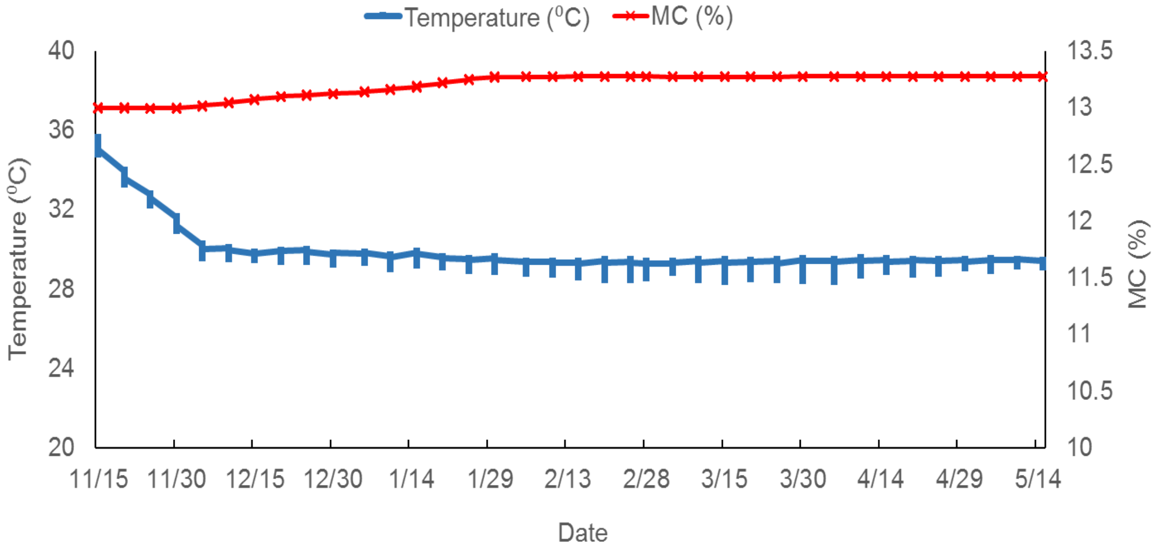

Figure 4.15. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 3 at 0.13 m^3/min/t only from Nov. to Jan.

Strategy 4 reduced the five-year average of the average grain temperature to 29.3°C by early December, approximately 3°C below the grain temperature compared to the same date at 0.22 m^3/min/t airflow rate, and similar to the difference in the fan warming effect. The grain mass remained at this temperature for the rest of storage season (fig. 4.16). The lower fan warming effect allowed for a lower average grain temperature to be achieved with less fan run hours than those required for the 0.22 m^3/min/t airflow rate. However, the lower fan warming effect did not decrease the ERH of the aeration air as much as the 0.22 m^3/min/t airflow rate. As a result, the MC of the lower grain layer increased by 0.7% points and caused an increase of 0.2% points of the average MC.

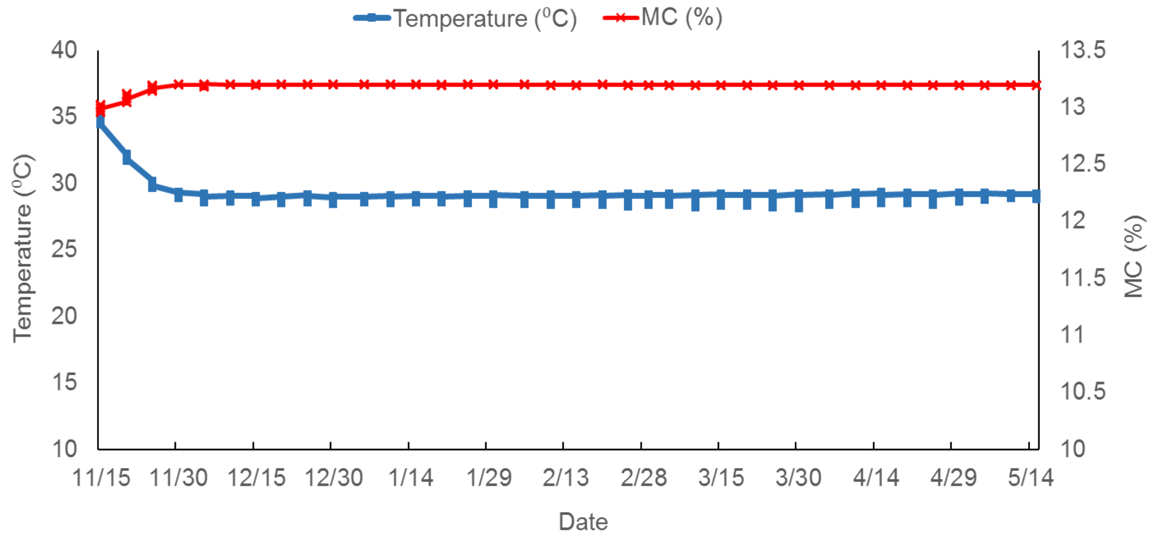

Figure 4.16. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and aerated using Strategy 4 at 0.13 m^3/min/t.

It is quite apparent from the analysis of these strategies that reducing the fan warming effect would help make these strategies more effective in lowering the average grain temperature. Nevertheless, these cooler temperatures achieved with the lower airflow rate of 0.13 m^3/min/t would still fall within the optimum development range of most insect pests (25°C - 33°C) (Fields, 1992). At these temperatures, the number of insects would quickly increase, which would then create another issue since heavily infested grain can warm up due to heat generated by the insects' metabolism and given that insect infestations are generally localized inside the grain bulk. This effect can generate temperature differentials inside the grain bulk that can cause moisture migration and consequently fungi development (Navarro et al., 2002). In this situation, the objective of the ambient aeration would be to maintain a minimum temperature differential within the grain bulk (ideally below 5°C) to avoid issues of moisture migration (Navarro et al., 2002).

Given that it is not possible to reduce the rice temperature below the optimum development range of insects using positive-pressure systems, as demonstrated by the results of the computer simulations under the conditions of the region under study, it is advisable to consider a negative-pressure suction aeration system, in which the aeration air is pulled instead of pushed through the grain mass, to eliminate the fan warming that positive-pressure systems cause (Noyes and Navarro, 2002). Nevertheless, using negative-pressure systems could have some disadvantages like the holes of the perforated floor could get clogged with fines or foreign material due to the suction, and the moisture of the rice in the surface of the grain bulk could increase given that there would be no fan warming effect that reduces the ERH of the air suctioned through the roof vents (Noyes and Navarro, 2002). If the negative-pressure were to be implemented, it would be necessary to look for the appropriate time of day to run the fans in order to avoid performing the aeration during hours when the ambient air RH is high and the surface of the grain mass could get rewetted.

4.3.3 Chilled aeration strategy

The results for ambient aeration demonstrated that it is not possible to reduce the average grain temperature below 30.8°C by the end of the six-month storage period using an airflow rate of 0.22 m^3/min/t, and below 37.2°C and 29.2°C using 0.32 m^3/min/t and 0.13 m^3/min/t, respectively. This makes it impossible to control stored-product insects without relying on chemical control.

The only way to cool paddy rice in this particular location below the optimum insect development range of 25°C to 33°C is through grain chilling. The results of the grain chilling simulation under the conditions of Guanacaste indicated that the GCH-20 would cool the rice to below 15°C in approximately 117 hours (table 4.9). Maier et al. (1992) reported about the same cooling time required to reduce the temperature of paddy rice below 15.5°C in Texas, U.S., under an average ambient temperature of 26.3°C and 75.5% RH, which are conditions slightly cooler and less humid than Guanacaste.

Table 4.9. Five-year average of average grain temperature, moisture content, total fan run hours and standard deviation of the grain chilling strategy at 0.17 m^3/min/t for paddy rice stored in Guanacaste, Costa Rica.

	Temperature, °C (SD)[a]			MC, % (SD)[a]			Total fan run hours (SD)[b]
	Dec. 1	Feb. 28	May 15	Dec. 1	Feb. 28	May 15	
Chilling strategy	12.3 (2.1)	14.3 (1.8)	15.5 (2.4)	13.2 (0.5)	13.2 (0.5)	13.2 (0.5)	117 (0)

SD= ± Standard deviation.
[a]Average SD of grain bulk from the five-year analysis.
[b]SD between the total fan hours of each year.

Chilling grain below 15°C in less than a week would reduce energy cost and avoid that most insect species complete even one life cycle because most of them take at least a month to develop from egg to adult at ideal temperatures between 30°C and 35°C (Rees, 2004).

According to these results, the cooling front reached the top of the grain mass in less than a week (fig. 4.17) resulting in a top layer rice temperature of 14.6°C. Subsequently, the stored paddy rice would start rewarming up to an average grain temperature of 15.5°C by the end of the storage period in May due to the high ambient temperature of the region.

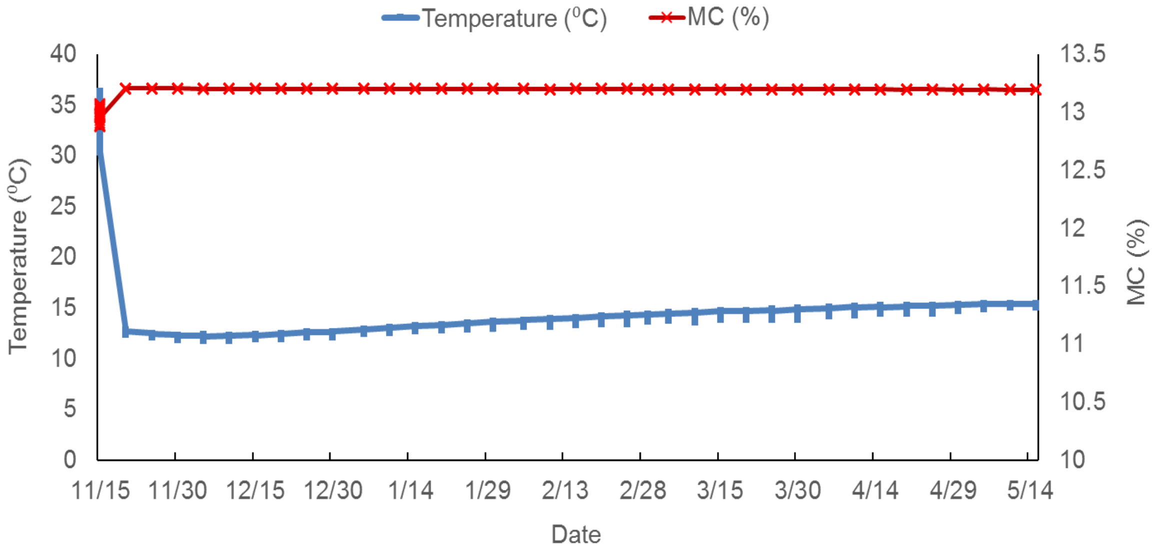

Figure 4.17. Five-year average of average grain temperature and moisture content (MC) profile of paddy rice stored from Nov. 15th to May 15th in Guanacaste, Costa Rica and chilled at 0.17 m^3/min/t.

Even though the average grain temperature increased by approximately 3°C after six months of storage, mainly due to rewarming of the top layer due to high headspace temperatures, the bottom grain layer above the plenum and the grain along the sidewall, the average grain temperature remained within the range in which insect development would stop (Fields, 1992). This would reduce or eliminate completely the need of chemical control of stored-product insects. Lazzari et al. (2006) observed that temperatures below 15°C effectively controlled populations of major stored-product pests like *R. dominica* and *Sitophilus* spp. for a period of 60 days.

The grain chilling strategy was also effective in maintaining a uniform MC throughout the grain bulk and minimize shrink loss (table 4.6). The MC of the bottom grain layer increased to 13.8% during the grain chilling process, while the rest of the grain bulk basically remained at 13% MC during the storage season. The reason for the MC increase in the bottom layer was because the ERH of the chilled air was on average 80% which is equivalent to a rice EMC of 15.8%, which is 2.8 percentage points higher than the initial MC of 13%. This calculated value was based on the data recollected during the 2015 and 2016 trials in Kansas (Chapter 3). This data showed values of up to 80% RH (Appendix E), which explains why the MC of the lower level of grain increased.

4.4 Conclusions

This study analyzed four ambient aeration strategies and three aeration airflow rates for paddy rice stored under the tropical weather conditions of the North Pacific coast of Costa Rica and compare results against chilled aeration using an existing computer simulation model developed by Lawrence and Maier (2011). The specific conclusions of this research are:

- Ambient temperatures below 24°C with relative humidity up to 90% can be used for aeration of paddy rice in Guanacaste, Costa Rica, because the fan warming effect due to the heat of compression will reduce ERH by an average of 20% at an airflow rate of 0.22 m^3/min/t.
- Using ambient air and an airflow rate of 0.22 m^3/min/t it is not possible to reduce the average grain temperature by more than 4°C (initial grain temperature of 35°C) due to the climatic conditions of Guanacaste and the high fan warming effect.
- The best ambient aeration strategy tested to lower the average grain temperature with the least amount of fan run hours for the weather conditions of Guanacaste would be to run the fan when the ambient temperature is 10°C lower than the grain temperature in the top section of the center core 1.5 m below the grain surface. This strategy increased the average grain MC minimally (by 0.1%).

- Applying ambient aeration by early morning (6:00 a.m. to 8:00 a.m.) and late evening (5:00 p.m. to 7:00 p.m.) is only effective from November to January, when the average ambient temperature is the lowest (approximately 25°C).
- Increasing the airflow rate to 0.32 m^3/min/t increases fan warming to approximately 7°C which causes warming of the paddy rice using any of the four ambient aeration strategies evaluated. Thus, a higher airflow rate did not achieve the intended effect and is not recommended.
- Applying ambient aeration by early morning (6:00 a.m. to 8:00 a.m.) and late evening (5:00 p.m. to 7:00 p.m.) from November to January, with a lower airflow rate of 0.1 m^3/min/t reduced the average grain temperature by 5.5°C and slightly increased the average MC by 0.1%. Thus, this alternative would be recommended to achieve lower grain temperatures.
- Chilled aeration lowered the average grain temperature to 15.5°C in 117 hours while the average MC increased slightly by 0.2%. Chilled aeration is the only technically feasible strategy to achieve average grain temperatures sufficiently low to reduce or eliminate the need for chemicals to control stored product insects.

4.5 Future research

Based on the evaluation of the chilled and ambient aeration strategies for paddy rice stored in a tropical climate using the computer simulation model, the following research work should potentially be pursued in the future:

- Develop similar analysis of grain chilling and ambient aeration strategies in different commodities and tropical locations in order to be able to recommend better grain management strategies to companies that store other commodities.
- Expand the research on the effect of fan warming on the results of ambient aeration.
- Develop a further analysis on the advantages and disadvantages of using negative-pressure systems for aeration and grain chilling in tropical climates.
- Analyze further the possibility of using lower airflow rates (0.13 m^3/min/t) in tropical climates, in order to reduce the fan warming effect and achieve lower grain temperatures.

Chapter 5- Economic analysis of ambient and chilled aeration strategies developed for paddy rice stored in a tropical climate using a Net Present Cost (NPC) economic model.

5.1 Introduction

The implementation of any new project or project investment has to be accompanied by an economic analysis that determines the feasibility and financial benefit that may come from making the initial investment. Most of the aeration and grain chilling economic analysis that are available in the literature are based primarily on the initial cost of the grain chilling unit, shrink loss, and the electrical cost of running the aeration system (Calderon, 1972; Hellemar, 1993; Maier and Navarro, 2002; Sutherland et al., 1970; Volk and Afonso, 2009).

To make an accurate evaluation of the investment cost, the cost-benefit ratio should be evaluated over a reasonable length of time, which is something that few grain chilling projects have done so far, and that is one of the reasons this technology is still not considered as feasible in some parts of the world.

The first research that made an effort to determine the cost-benefit ration of grain chilling over a reasonable period of time was developed by Maier et al. (1989). It analyzed the savings accrued using grain chilling to preserve and maintain the quality of damp maize in the United States. They observed that the savings obtained by drying maize to 16.5% MC instead of 14% MC and then selling it at 15.5%, either by blending or due to the weight-loss caused by evaporative cooling during grain chilling aeration (threes cycles), would result in a positive after-tax cash flow every year for a 10-year life-time of the grain chiller.

Evaluating future cash-flows that a present investment will generate is not easy to determine and requires having at least a basic understanding of concepts like time-value-of-money and opportunity cost (James and Eberle, 2000). In common terms, the time-value-of-money refers to the idea that a dollar today is worth more than a dollar tomorrow, because the dollar tied to an investment today can generate a future return (Rulon, 1996). The opportunity cost refers to a benefit that a person or business could have received if an alternate course of action had been taken (Investopedia, 2017). For example, compare the benefit of investing in pest control based on chemicals vs. grain chilling.

Since little research has been done on the return of investment in grain chilling, this technology is still seen as a too high of an initial investment in many parts of the world, including Central America. Nevertheless, the benefits that this technology can bring over time can well be worth it. Among those many benefits, the most mentioned is the control of pests. Since temperatures in the tropics are within the optimum range of development for stored-product insects (25°C to 33°C) year-around (Fields, 1992), it is almost impossible to control pests just by using ambient aeration. This makes it necessary to use chemical control. By reducing the temperature of grain below 15°C using grain chilling, not only would it diminish or eliminate the need of chemical control, but would also reduce the added health and environmental issues that may also have economic repercussions (Rulon et al., 1999).

To the best of our knowledge, the only research project that has taken into account the time-value-of-money and opportunity cost for the analysis of economic viability of investing in grain chilling was Rulon et al. (1999). They used a Net Present Cost (NPC) methodology to determine the cost of a grain chilling prototype developed by Purdue University. The NPC is a variation of the Net Present Value (NPV), which is a tool used commonly to evaluate the profitability of an investment or project based on the calculation of the present net cash inflow that the project is expected to generate minus the initial required investment (Investopedia, 2017). Since grain storage is only one step in the long processing chain of grain, it is difficult to calculate the cash inflow associated strictly to grain storage practices, that's why NPC is a more accurate evaluation of cash flows associated solely to grain storage (Rulon et al., 1999). Due to the fact that this method calculates expenses, instead of income like the NPV does, the NPC is evaluated on the basis of a minimum discount rate (Rulon et al., 1999). The discount rate refers to the interest rate used to discount future cash flow to determine present value, or in this case, present cost (Investopedia, 2017). So, when looking at the results of the NPC model, lower the NPC the better.

For this research, the NPC approach was considered the most accurate method to appraise the investment in the grain chilling technology because it takes into consideration fixed costs like depreciation, taxes, insurance and interest rate; and variable costs like conditioning and sampling, shrink loss, repairs and marketing (Rulon, 1996).

Rulon et al. (1999) also took into account factors that are less quantifiable like worker safety, environmental issues, end-product value, among others, to compare chilling technology against the cost of ambient aeration and fumigation. Based on these factors, they observed that the annual operating cost and NPC of chilled aeration was highly competitive against fumigation and ambient aeration in wheat and popcorn, due to the high cost of chemicals back in the decade of the 1990s (Rulon et al., 1999). Chilling cost in popcorn were even more competitive when a premium price of less than one cent per retail bag was added for a post-harvest pesticide-free product. The base price of the 455 g retail bag in 1999 was $0.99.

As a country conscientious of the environment, Costa Rica is encouraging the use of environment-friendly technologies for the production of rice (Arias, 2016). Given that, a post-harvest pesticide-free product would give an extra incentive to the grain chilling investment in this country.

The objective of this study was to compare the costs of the ambient and chilled aeration strategies developed for the tropical weather conditions of the North Pacific coast of Costa Rica and analyze them using a Net Present Cost (NPC) economic model, so that farmers and grain handling, storage, and processing companies can objectively evaluate their options and determine what is best for them.

5.2 Materials and methods

A Net Present Cost (NPC) economic model developed by Rulon et al. (1999) was utilized in this study to determine the economic viability of the ambient and chilled aeration strategies analyzed in Chapter 4 based on operating costs and time-value-of-money.

The format in which this model was developed is compatible with Excel and was set-up in a way that is easily understood and modifiable, so that it can be adapted to the parameters of this study.

The model uses amortization to annualize the total NPC because this value is presented as the sum of the discounted cost over a 10–year period. The amortized NPC is equated to ten equal annual payments which, given the time-value-of-money, are equivalent to the total NPC (Rulon, 1996).

5.2.1 Model parameters and equations

The input parameters for this study were based on a standard rice milling company located in Guanacaste, Costa Rica (10°26'N, 85°24'W).

The information was collected from several sources including rice milling companies, banks, other financial entities, and agrochemical companies, among others. The name of the sources and information they provided is listed in Appendix G. The operational parameters in the ambient and chilled aeration sheets were determined based on the results of Chapter of 4.

This model makes the calculation of annual operating costs and NPC of chilled aeration over a period of 10 years. Given the major drawback of the grain chilling technology is the high initial cost, a lease option and other economically viable options are also considered in this model. For the base case scenario, the results from Chapter 4 of final grain temperature, MC and fan run hours from the grain chilling strategy were input into the calculations and then modified in the alternative scenarios.

The typical pest management and conditioning techniques used in the grain industry like ambient aeration and fumigation were also analyzed over a period of 10 years. For fumigation, the in-house and contract options were evaluated, even though contract fumigation is not common in the rice industry of Costa Rica. However, both are considered in order to expand the array of possibilities that may be economically feasible. In the same way, as with the grain chilling information, the final grain temperature, MC and fan run hours for the ambient aeration in the base case scenario were taken from the results of Chapter 4. This information made reference to the ambient aeration strategy # 4 that was determined to be most suitable for the region and consisted of turning on the aeration fan when the ambient temperature was 10°C lower than the grain temperature in the top section of the center core of the grain mass.

The input data of the model was separated into spreadsheets and coded alphabetically. The outputs of the model were also separated in spreadsheets with a summary in the last sheet for better comparison of the different strategies (table 5.1).

Table 5.1. Economic model sheet titles.

Sheet code	Sheet title
A	Facility description
B	Ambient conditioning and aeration worksheet
C	In house fumigation worksheet
D	Contract fumigation worksheet
E	Chilled aeration worksheet
F	Primary operating cost summary table
G	Net present cost - in house fumigation
H	Net present cost - contract fumigation
I	Net present cost - chilled aeration
J	Net present cost - chilled aeration with lease option
K	Net present cost summary

5.2.1.1 Sheet A: Facility description sheet

In Sheet A (table 5.2) the facility to be modeled is described. In this case the location of the storage silos is in the province of Guanacaste, Costa Rica (North Pacific coast). The standard 1,500 t (14.58 m in diameter and 14.57 m of side wall height) long-term storage silos for the region were used to make the calculations per ton throughout the model. To have results that are closer related to reality, actual ton stored in these silos were calculated by taking into account the compaction factor and the fact that the silos are not usually filled all the way to the roof in order to leave some accessibility for inventory, sampling, and fumigation purposes.

Table 5.2. Facility description

Location description	Guanacaste, Costa Rica
Grain type	Paddy rice
Silo size (t)	1,478
Grain price[1] ($/t)	536.41
Fan horsepower (HP)	20
Hourly labor cost[1] ($/h)	2.98
Electrical cost[1] ($/kWh)	0.141
Percent of business financed by debt (%)	40.00
Rate of return on equity (ROE, %**)**	15.00
Annual interest rate (%)	14.23
Tax rate (%)	58.20
Discount rate (%)	11.38
Base inflation rate (%)	0.80
Fumigation inflation rate (%)	6.00

[1] Exchange rate from colones (₡) to U.S. dollars ($): ₡560.74/$. Source: Costa Rica Central Bank

The grain price parameter is exclusively used for the calculation of shrink charges for the different aeration strategies, for this reason the price utilized is the one paid to the farmer by the rice industry. This price is defined by law for the local market in Costa Rica and has a baseline of $39.48 per sack of 73.6 kg of dry (13% MC) and clean (1.5% dockage) paddy rice (Conarroz, 2016), which would be equal to $536.41/t.

The average fan horsepower commonly used by rice companies in this region is a 20 HP (15 kWh) centrifugal fan. The hourly labor cost utilized was based on the minimum salary of a worker with minimum qualifications plus an addition of 24.83% of the salary to account for the social charges paid by employer, according to the latest report of the Department of Labor of Costa Rica (MTSS, 2015).

The electrical cost was based on the cost per kWh of the region (ICE, 2017) and the records shared by the rice companies.

The percent of business financed by debt and rate of return on equity (ROE) was set at 40% and 15%, respectively, which are considered acceptable levels for a profitable business (Loth, n.d.; Rulon, 1996). These parameters are used for the calculation of the discount rate.

The annual interest rate, total tax rate, and base inflation rate of non-fumigant parameters (electricity, labor, insurance, etc.) were determined as 14.23%, 58.20% and 0.80%, respectively, based on data from Costa Rica from the World Bank databse (2016).

The fumigation inflation rate was determined as 6.00% based on information provided by fumigation companies based on the change of prices of agrochemicals and labor costs.

The discount rate was determined at 11.38% based on the following equation:

(eq.1) *Discount rate (%) = (ROE*(1-% of business financed by debt)) + (Interest rate* (1-tax rate)*% of business financed by debt)*

5.2.1.2 Sheet B: Ambient aeration and conditioning sheet

Sheet B (table 5.3) shows all the costs related to the ambient aeration and conditioning labor for a six month storage period.

Table 5.3. Ambient aeration and conditioning

Moisture samples (samples/silo)	12
Sampling labor (h/sample)	3
Conditioning Labor (h/silo)	90
Fan hours (h/silo)	214
Shrink loss (%)	0.0
Sampling labor charge ($/t)	$\frac{moisture\ samples * sampling\ labor * hourly\ labor\ cost}{(silo\ size)}$
Conditioning labor charge ($/t)	$\frac{conditioning\ labor * hourly\ labor\ cost}{silo\ size}$
Electrical cost ($/t)	$\frac{fan\ hours * fan\ HP * electrical\ cost}{(silo\ size)}$

Shrink loss ($/t)	$shrink\ loss\ \% * grain\ price$

The number of moisture content samples taken per storage period were determined according to data shared by the rice companies. They sample every 15 days approximately, over a period of six months. The number of hours per sample was calculated according to the time it takes to go into the silos, sample, process the samples in the laboratory, and get the results.

Conditioning labor refers to the amount of time spent monitoring moisture sample results, ambient conditions, and supervise operation of the aeration systems. It was set to 90 hours per silo, taking into account an average of half-hour per day spent on conditioning labor over a period of six months.

Based on the aeration model results of Chapter 4, the fan run time over the six-month period were determined at 214 h, and given that the average final MC of this same strategy was 13.1%, it was determined that there was no MC reduction using this ambient aeration strategy, which means that there was no shrink loss. The calculations for sampling, conditioning, and shrink loss and electrical costs are shown in table 5.3.

5.2.1.3 Sheet C: In-house fumigation

In Sheet C (table 5.4) all the costs related to fumigation labor done by the rice mill with their own labor and equipment over the six-month storage period is shown.

Table 5.4. In-house fumigation

Number of in-season fumigations (fumigations/silo)	1
Application of insecticide to surroundings (applications/silo)	24
Fumigant cost ($/t)	0.63
Employees per fumigation crew (employees/crew)	4
Silos fumigated per crew (silos/crew)	6
Training per employee (h/yr/employee)	4
Man hours per fumigation (h)	12
Man hours per application (h)	1
Aeration time per fumigation (h)	0
Initial equipment cost ($)	3,350.00
Expected equipment life (years)	5
Equipment maintenance (% of initial cost)	10.00
Equipment insurance (% of initial cost)	0.0
Liability insurance ($/t)	0.0200
Grain protectant ($/t)	0.900
Chemical of additional application ($/t)	0.004

Labor charge ($/t)	$\frac{((man\ hours/fum * hourly\ labor\ cost * \#\ of\ fum) + (man\ hours/appl * hourly\ labor\ cost * of\ appl)}{(silo\ size)}$
Fumigation training charge ($/t)	$\frac{training/employee * hourly\ labor\ cost * employees/crew}{(silo\ size * silos\ fumigated/crew)}$
Aeration charge ($/t)	$\frac{aera.time/fum * fanHP * electric\ cost * \#\ of\ fum}{(silo\ size)}$
Fumigant cost ($/t)	$fumigant\ cost/fum * \#\ of\ fum$
Annual operating cost of fumigation equipment ($/t)	$\frac{initial\ equip.cost * (maintenance + insurance)}{(silo\ size * silo\ fumigated/crew)}$
Cost of applications to surroundings ($/t)	$chemical\ of\ additional\ appl. * \#\ of\ appl.to\ sorroundings$

The first parameter in this sheet is the number of fumigations per storage period. According to the rice companies, they base their fumigations on the amount of insects resulting from monitoring so this is rather variable, but at least they do one fumigation per six-month storage period. Due to the high infestation pressure they have to handle, they usually have to make applications of insecticides in the surroundings of the silos throughout the storage period. To take into consideration this factor, an additional parameter was included in this spreadsheet. For this specific case, it was considered that an additional application per week over the six-month period would be reasonable according to information of DEMASA S.A. In the case of the grain protectant, deltamethrin is a commonly used active ingredient, according to information of Coopeliberia R.L., and the dosage is about 10 mL/t (K-Obiol 25 EC). The local cost is about 90 $/L, according to information provided by DEMASA R.L. The dosage of this same chemical applied to the surroundings is about 0.5 mL/m^2 (K-Obiol 25 EC). Assuming that the area to be applied would be about the size of the base of the silo (165 m^2), this would be about 82.5 mL per application or 0.05 mL/t, based on the same units.

The average number of employees needed for fumigation labor like laying down the tarp on the top of the grain mass, calculating dosage, doing the application, aerating the silo afterwards, etc., is for four employees according to the information of the rice companies (Appendix G).

The average number of 1,500 t silos per industry is of approximately six according to information of the National Rice Bureau. Considering that each silo may have to be fumigated at some point during the storage period, it was considered that a crew of four employees could fumigate all of them throughout the storage season.

According to internal policy of some rice companies, an average of four hours of training and continuing education per year are required per employee on a fumigation crew, based on data provided by the rice companies (Appendix G).

Another parameter takes into account the number of man hours per fumigation, which is determined based on the time it takes to make the fumigation from beginning to end, multiplied by the number of employees in the crew. According to the rice companies it takes about two hours to make a fumigation and about one hour to remove the tarp and aerate, multiplied by the number of crew members, the required man hours are about 12. The man hours required per additional application is one on average.

Since the rice mills just retrieve the tarp and uncover fans and exhausts when fumigation is over and do not use fan assisted aeration to dissipate the fumigant, this cost was not included in the sheet.

The cost of the personal protection equipment was calculated at an average of $3,350 based on the local market price of safety gear for the whole crew and chemical protection for the applicator. A summary of the protection equipment and costs of each part of the equipment are shown in Appendix H. The equipment useful life was set at five years in the original model by Rulon (1999) and cannot be modified.

Equipment maintenance was set at 10% in the original model by Rulon (1999), which is about average of what is spent on maintenance and replacements according to comments of the rice companies (Appendix G). The equipment insurance cost is not included in this case because rice companies do not usually insure this kind of equipment.

To determine the cost of the liability insurance the Costa Rican National Institute of Insurance in 2017 was contacted to get a quote on the cost of the insurance related to handling chemicals. This cost was related to the $/t based on the average number of ton fumigated per storage season which equated into 0.04 $/t.

The calculations for labor charge and training charge, chemical and grain protectant cost; and annual cost of fumigation equipment are shown in table 5.4.

5.2.1.4 Sheet D: Contract fumigation sheet

The contract fumigation Sheet (table 5.5) is the shortest one of all the calculation sheets since is basically made up of the fumigation and protectant application costs of the fumigator.

Table 5.5. Contract fumigation

Number of fumigations per silo (fumigations/silo)	1
Applications of insecticide to surroundings (applications/silo)	24
Aeration time per fumigation (h)	0
Contract fumigation (materials and application) ($/t)	0.650
Grain protectant ($/t)	1.800
Contract application (materials and application) ($/t)	0.06
Aeration charge ($/t)	$\frac{aera.time/fum * fanHP * electric\ cost * \#\ of\ fum}{(silo\ size)}$
Fumigation charge ($/t)	$contract\ fum\ charge * \#\ of\ fum$
Cost of applications to surroundings ($/t)	$contract\ application\ charge * \#\ of\ appl$

The first parameter in the sheet is the number of fumigations per silo, which will be the same as the number of fumigations per season in the in-house fumigation sheet. The additional applications to surroundings and the aeration time per fumigation was also the same as it was for the in-house fumigation sheet.

The contract fumigation and grain protectant cost were determined based on the information shared by the U.S. based fumigation company Fumigation Service & Supply, Inc. in 2017, since it was not possible to get response from the attempts to contact local fumigation contractors in Costa Rica. The cost per unit of fumigant application was calculated at 0.650 $/t, the grain protectant was determined at 1.8 $/t and the applications to surroundings at 0.06 $/t, which are assumed to be performed by the fumigation contractor also. These are baseline costs related to the parameters of the current study and they include sealing and material costs. The calculations for aeration and fumigation charges are shown in table 5.5.

5.2.1.5 Sheet E: Chilled aeration sheet

All the chilled aeration costs are broken down in Sheet E (table 5.6). This include chilling cycles per silo and number of hours per cycle, number of chilled silos, initial chiller costs, among others.

Table 5.6. Chilled aeration

Chilling cycles (cycles/silo)	1
Number of silos chilled	6
Chiller hours (h/cycle)	117
Average power load (kWh)	28
Labor per chilling cycle (h)	2
Initial chiller cost ($)	74,700.00
Salvage value (% of initial cost)	35.00
Expected life of chiller (years)	10
Maintenance cost (% of initial cost)	1.00
Equipment insurance (% of initial cost)	0.73
Moisture samples (samples/silo)	12
Shrink loss (%)	0.0
Premium ($/t)	0.000
Annual lease payment ($)	10,926.57
Chilling labor charge ($/t)	$\frac{chilling\ cycles * labor/chilling\ cycle * hourly\ labor\ cost}{(silo\ size)}$
Electrical cost ($/t)	$\frac{elect.cost * avg.connected\ load * h/chilling\ cycle * \#\ of\ cycles}{(silo\ size)}$
Sampling labor charge ($/t)	$\frac{moisture\ samples * sampling\ labor * hourly\ labor\ cost}{(silo\ size)}$
Operating cost of Chiller ($/t)	$\frac{initial\ chiller\ cost * (insurance\% + maintenance\%)}{(number\ of\ silos * silo\ size)}$
Shrink cost ($/t)	$shrink\% * grain\ price/unit$
Leasing cost ($/t)	$\frac{annual\ lease\ payment}{(\#\ of\ silos\ chilled * silo\ size)}$

The number of cycles per silo and the fan run hours per cycle was determined at 1 and 117, based on the number of hours and cycles required to chill the grain temperature to an average of 15.5°C, according to the results of the aeration model (Chapter 4). In the same way as the calculation of the number of silos to be fumigated, an average of six silos to be chilled was considered.

The average power load of the GCH-20 grain chiller was 28 kWh and the initial chiller purchasing cost at $74,700 (price utilized in Mexico) was provided by the manufacturer (Coolseed, 2016).

The number of labor hours per chilling cycle was estimated at two, based on the number of hours it took to set up the chiller in the 2015 and 2016 wheat chilling trials (Chapter 3).

The salvage value, which refers to the estimated value of the grain chiller at the end of the expected life, was determined at 35% of initial chiller cost based on the ASABE tables of salvage values of farm machinery (Edwards, 2015). The expected economic life of the grain chiller was determined at 10 years based on the suggestions of Edwards (2015).

The maintenance cost was determined at 1.00% of initial grain chiller cost based on the 2015 and 2016 field experiments and the observations made by Rulon et al. (1999).

For the calculation of the annual equipment insurance, the Costa Rican National Institute of Insurance was contacted in January, 2017. They provided a quote that was equal to a 0.73% of initial grain chiller cost.

The number of moisture samples required for the six month storage period is the same as the number of moisture samples for the ambient aeration sheet. Since the average final MC of the chilling strategy in the aeration model (Chapter 4) was 13.2%, it was determined that there was no shrink loss due to chilled aeration.

The premium refers to the additional amount gained ($/t) due to the associated improved quality or other advantages as non-chemical treatment during storage. Since this is not currently implemented in Costa Rica it was not possible to determine an exact premium amount based on chemical-free treatment during storage, nevertheless, this could be a potential plus for to the grain chilling technology since there is already a demand in the market for organic rice (Arias, 2016).

The annual lease payment is analyzed as an option to purchasing the chiller and the effect it has on the NPC. It was determined based on information provided by local financial entities that provides leasing services (Appendix G). They provided a passive interest rate of 8.5% + 4.5% prime at a 10-year term. This calculation equated to an annual payment of $10,926.57 with one advanced payment of $10,926.57. The calculations for chilling labor, electricity, sampling labor, and chiller operation charges are shown in table 5.6, as well as shrink loss and leasing charges.

5.2.1.6 Sheet F: Analysis of annual operating costs of chilled aeration vs. ambient aeration and fumigation

The summary of annual operating costs from ambient aeration and conditioning, in-house and contract fumigation, and chilled aeration are presented in Sheet F. This sheet is divided in two sections, the first presents a summary of the annual operating costs (table 5.7) and the second one makes a comparison between the costs of chilled aeration vs. ambient aeration plus fumigation (table 5.8). Since it is likely that silos aerated with ambient air under the climatic conditions analyzed will require chemical control at some point, these two items were added up.

Table 5.7. Summary of annual operating costs

Ambient aeration and conditioning ($/t)	$Sum\ of\ all\ costs\ of\ ambient\ aeration\ and\ conditioning$
In house fumigation ($/t)	$Sum\ of\ all\ cost\ of\ in-house\ fumigation$
Contract fumigation ($/t)	$Sum\ of\ all\ costs\ of\ contract\ fumigation$
Chilled aeration ($/t)	$Sum\ of\ all\ costs\ of\ chilling\ aeration$
Chilled aeration with lease option ($/t)	$Sum\ of\ all\ costs\ of\ chilling\ aeration + leasing\ cost$

Table 5.8. Annual operating costs of chilled aeration vs. ambient aeration and fumigation

Chilled aeration vs. In house fumigation + Ambient aeration ($/t)	$Chilled\ aeration - (ambient\ conditioning + in - house\ fumigation)$
Chilled aeration vs. Contract fumigation + Ambient aeration ($/t)	$Chilled\ aeration - (ambient\ conditioning + contract\ fumigation)$
Chilled aeration with lease vs. In house fumigation + Ambient aeration ($/t)	$Chilled\ aeration\ with\ lease\ option - (ambient\ conditioning + in - house\ fumigation)$
Chilled aeration with lease vs. Contract fumigation + Ambient aeration ($/t)	$Chilled\ aeration\ with\ lease\ option - (ambient\ conditioning + contract\ fumigation$

5.2.1.7 Sheet G: NPC analysis of in-house fumigation

The NPC calculation of in-house fumigation is made in Sheet G. Additional to annual operating costs, the NPC spreadsheets also take into account after-tax charges, inflation, and depreciation of equipment over a 10-year period, which is one life-cycle for the grain chiller and two life-cycles for the fumigation equipment. These costs are rated back to their value in today's dollars by using the discount rate.

In the case of the in-house fumigation, the NPC in Year 0 was calculated as shown in table 5.9. The year 0 refers to the year in which the fumigation equipment is purchased.

Table 5.9. NPC of in-house fumigation in year 0

Expenses ($/t)	$\frac{\boldsymbol{initial\ equipment\ cost}}{(\boldsymbol{silos\ fumigated/crew * silo\ size})}$
Discount factor	$\boldsymbol{Discount\ for\ year\ 0\ is\ one}$
NPC	$\boldsymbol{Expense * discount\ rate}$

From Year 1 to Year 10 the NPC of each year is calculated as shown in table 5.10. The first part of this sheet adds the pre-defined inflation factor to the expenses. After that, an after-tax expense is calculated based on the premise that all expenses would offset a portion of income and thus reduce the company's taxable earnings. The after-tax is the actual expense to the business after deducting the expenses from taxable income (Rulon, 1996). The taxation method over the income of the company is applicable for the U.S. as well as for the Costa Rican taxation system (MH, 2017).

Table 5.10. NPC of in-house fumigation from Year 1 to 10

Expenses ($/t)	$((\boldsymbol{ambient\ aeration\ and\ conditioning}) * (\mathbf{1} + (\boldsymbol{base\ inflation\ rate} * \boldsymbol{year})))) + ((\boldsymbol{labor\ charge} + \boldsymbol{training\ charge} + \boldsymbol{chemical\ charge} + \boldsymbol{grain\ protectant\ charge} + \boldsymbol{annual\ operating\ cost\ of\ equipment}) * (\mathbf{1} + (\boldsymbol{fum\ inflation\ rate} * \boldsymbol{year})))$
After-tax ($/t)	$\boldsymbol{Expenses} - (\boldsymbol{tax\ rate} * \boldsymbol{expenses})$
Discount factor	$(\mathbf{1} + \boldsymbol{discount\ rate})^{-\boldsymbol{year}}$
NPC ($/t)	$(\boldsymbol{after\ tax} - \boldsymbol{tax\ shield}) * \boldsymbol{discount}$
Total NPC ($/t)	$\boldsymbol{Sum\ of\ NPC\ for\ years}\ \mathbf{0}\ \boldsymbol{to}\ \mathbf{10}$
Amortized NPC ($/t)	$\boldsymbol{Total\ NPC} * (\frac{\boldsymbol{discount\ rate}}{\mathbf{1} - (\mathbf{1} + \boldsymbol{discount})^{-\mathbf{10}}})$

After the discounted NPC is calculated for each year, the total NPC is calculated and finally the amortized NPC for each year is calculated.

5.2.1.8 Sheet H: NPC analysis of contract fumigation

The NPC calculation of contract fumigation is made in Sheet G. This sheet does not include the calculation of Year 0 since there are no expenses for purchase of fumigation equipment. From Year 1 to 10 the NPC is calculated as shown in table 5.11.

Table 5.11. NPC of contract fumigation from Year 1 to 10

Expenses ($/t)	$((\boldsymbol{ambient\ aeration\ and\ conditioning}) * (\mathbf{1} + (\boldsymbol{base\ inflation\ rate} * \boldsymbol{year}))) + ((\boldsymbol{chemical\ charge} + \boldsymbol{grain\ protectant\ charge}) * (\mathbf{1} + (\boldsymbol{fum\ inflation\ rate} * \boldsymbol{year})))$
After-tax ($/t)	$\boldsymbol{Expenses} - (\boldsymbol{tax\ rate} * \boldsymbol{expenses})$
Discount factor	$(\mathbf{1} + \boldsymbol{discount\ rate})^{-year}$
NPC ($/t)	$\boldsymbol{After\ tax} * \boldsymbol{discount}$
Total NPC ($/t)	$\boldsymbol{Sum\ of\ NPC\ for\ years}\ \mathbf{1}\ \boldsymbol{to}\ \mathbf{10}$
Amortized NPC ($/t)	$\boldsymbol{Total\ NPC} * (\frac{\boldsymbol{discount\ rate}}{\mathbf{1} - (\mathbf{1} + \boldsymbol{discount})^{-\mathbf{10}}})$

5.2.1.9 Sheet I: NPC analysis of chilled aeration

The NPC calculation of chilled aeration is made in Sheet I. This sheet is very similar to the NPC in-house fumigation sheet, except that includes the salvage value of the grain chiller at the end of the life cycle.

Year 0 in this sheet is exactly the same as the one in-house fumigation except for the parameter of number of silos fumigated, which is actually the same as the number of silos chilled in this study (table 5.12).

Table 5.12. NPC of chilled aeration on Year 0

Expenses ($/t)	$\frac{\boldsymbol{initial\ equipment\ cost}}{(\boldsymbol{silos\ chilled} * \boldsymbol{silo\ size})}$
Discount factor	$\boldsymbol{Discount\ for\ year}\ \mathbf{0}\ \boldsymbol{is\ one}$
NPC ($/t)	$\boldsymbol{Expense} * \boldsymbol{discount\ rate}$

From Year 1 to 10 the NPC of chilled aeration is calculated as shown in table 5.13.

Table 5.13. NPC of chilled aeration from Year 1 to 10

Expenses ($/t)	$((\boldsymbol{labor\ charge} + \boldsymbol{electricity\ charge} + \boldsymbol{sampling\ charge} + \boldsymbol{annual\ operating\ cost} + \boldsymbol{shrink\ loss\ chrage} - \boldsymbol{premium}) * ((\boldsymbol{1} + (\boldsymbol{base\ inflation} * \boldsymbol{year})))$
After-tax ($/t)	$\boldsymbol{Expenses} - (\boldsymbol{tax\ rate} * \boldsymbol{expenses})$
Discount factor	$(\boldsymbol{1} + \boldsymbol{discount\ rate})^{-\boldsymbol{year}}$
NPC ($/t)	$\boldsymbol{after\ tax} * \boldsymbol{discount}$
Salvage ($/t)	$\frac{(\boldsymbol{initial\ cost} * \boldsymbol{salvage\ value})}{\boldsymbol{silos\ chilled} * \boldsymbol{silo\ size}}$
Total NPC ($/t)	$\boldsymbol{Sum\ of\ NPC\ for\ years\ 0\ to\ 10} - \boldsymbol{NPC\ of\ salvage}$
Amortized NPC ($/t)	$\boldsymbol{Total\ NPC} * (\frac{\boldsymbol{discount\ rate}}{\boldsymbol{1} - (\boldsymbol{1} + \boldsymbol{discount})^{-\boldsymbol{10}}})$

5.2.1.10 Sheet J: NPC analysis of chilled aeration with lease option

The NPC calculation of chilled aeration with lease option is made in Sheet J. Although this option does not include the purchase of equipment, it was stated that an advance payment was made for the leasing which is the only parameter included for Year 0 (table 14).

Table 5.14. NPC of chilled aeration with lease option on Year 0

Expenses ($/t)	$\frac{\boldsymbol{annual\ lease\ payment}}{(\boldsymbol{silos\ chilled} * \boldsymbol{silo\ size})}$
Discount factor	$\boldsymbol{Discount\ for\ year\ 0\ is\ one}$
NPC ($/t)	$\boldsymbol{Expense} * \boldsymbol{discount\ rate}$

From Year 1 to 9 the NPC calculation of chilled aeration with lease option is presented in table 5.15. The expenses of Year 10 is calculated separately because on the last year the leasing cost is not included since by the end of the leasing contract the lessee is given the option to buy, exchange or return the unit.

Table 5.15. NPC of chilled aeration with lease option from year 1 to 10

Expenses from year 1 to 9 ($/t)	$((labor\ charge + electricity\ charge + sampling\ charge + annual\ operating\ cost + shrink\ loss\ charge - premium + leasing\ charge) * ((1 + (base\ inflation * year)))$
Expenses on year 10 ($/t)	$((labor\ charge + electricity\ charge + sampling\ charge + annual\ operating\ cost + shrink\ loss\ charge - premium) * ((1 + (base\ inflation * year)))$
After-tax ($/t)	$Expenses - (tax\ rate * expenses)$
Discount factor	$(1 + discount\ rate)^{-year}$
NPC ($/t)	$after\ tax * discount$
Total NPC ($/t)	$Sum\ of\ NPC\ for\ years\ 0\ to\ 10 - NPC\ of\ salvage$
Amortized NPC ($/t)	$Total\ NPC * (\frac{discount\ rate}{1 - (1 + discount)^{-10}})$

The final sheet of the economic model is Sheet K which shows the summary of total and amortized NPC of each of the strategies, which makes it easier to make the comparison between them.

5.3 Results and discussion

5.3.1 Base case scenario

5.3.1.1 Operational cost analysis of base case scenario

The annual operational cost analysis of the base case scenario evaluates the operational costs of the current pest management practices of the rice companies in the region of Guanacaste, Costa Rica, including ambient aeration, and makes a comparison with the operational costs of a potential strategy based on the grain chilling technology. It is noted that the initial cost of the grain chiller, as well as the initial cost of the fumigation and protection equipment in the in-house fumigation sheet, are not part of the operational costs, but they are included in the NPC analysis in section 5.3.1.2. The operational costs are analyzed separately to demonstrate that in case the grain chiller option shows not to be competitive against the other grain management strategies, it would be due to the initial cost of the grain chiller.

In table 5.16, the results of final grain temperature, MC and fan run hours of the ambient aeration and grain chilling strategy from the aeration model used in Chapter 4 are shown in order to remind the reader where these inputs are coming from.

Table 5.16. Final grain temperature, moisture content, and fan run hours of the ambient aeration and grain chilling strategies determined from the aeration computer model.

Aeration strategies	Grain temperature (°C)	MC (%)	Fan run hours
Ambient aeration[a]	30.8	13.1	214
Chilled aeration[b]	15.5	13.2	117

[a]Based on an airflow rate of 0.22 m^3/min/t.
[b]Based on an airflow rate of 0.17 m^3/min/t.

According to these inputs, the economic model determined the grain chilling, ambient aeration and fumigation costs which are shown in table 5.17.

Table 5.17. Summary of annual operational costs ($/t) for ambient aeration, in-house fumigation, contract fumigation, and chiller with purchase option and lease option.

Parameter	Ambient Aeration	In House Fumigation	Contract Fumigation	Chiller Purchase	Chiller Lease
Sampling labor	0.07	-	-	0.07	0.07
Conditioning labor	0.18	-	-	-	-
Electrical cost	0.41	-	-	0.31	0.31
Shrink cost	0.00	-	-	0.00	0.00
Operating chiller cost	-	-	-	0.15	0.15
Labor cost	-	0.07	-	0.01	0.01
Training cost	-	0.01	-	-	-
Aeration cost	-	0.00	0.00	-	-
Fumigant cost	-	0.63	0.65	-	-
Grain protectant cost	-	0.90	1.80	-	-
Additional appl. cost	-	0.09	1.44	-	-
Leasing cost	-	-	-	-	1.23
TOTAL	0.66	1.70	3.89	0.53	1.77

It was observed that the parameter that had more influence on the total operational cost of ambient aeration was the electrical cost caused by the extended number of fan hours, even though this strategy required much less fan run hours than the other four ambient aeration strategies analyzed in Chapter 4 (table 5.17). For in-house and contract fumigation the most influential operational cost was the grain protectant cost, which was even higher for the contract fumigation because it includes labor and material costs (table 5.17). In regards to the fumigant cost, it is noticeable that the cost of the fumigant used with the in-house fumigation strategy is almost identical to the cost in the contract fumigation strategy, which includes labor and material costs (table 5.17). This is due to the fact that the rice companies are using the high dosage of the fumigant, which, according to their comments, is to compensate for the fumigant loss and to make sure that they get a good degree of pest control. It has to be remembered that the data for the contract fumigation came from a U.S. based fumigation company given that the Costa Rican fumigation companies never responded to the phone calls, so these costs may be somewhat different for Costa Rica.

The parameter that had more influence on the chilling operational costs was the electrical consumption (table 5.17), given that the grain chiller power requirement is approximately 28 kWh. This is about double the power requirement of the ambient aeration fan. Nevertheless, since the ambient aeration strategy requires more fan hours (table 5.16), the electricity cost is still 0.10 $/t cheaper than the ambient aeration strategy.

Even though the grain chilling leasing option is not analyzed in this section, the operational costs are shown in table 5.17 for comparison and for the development of the optional scenario in section 5.3.2.1. The analysis shows that the most influential cost for this financial option was the annual leasing payment which increases the total operational cost to more than triple the cost of the grain chiller purchase option. Nevertheless this option has other economic benefits that will be discussed in section 5.3.2.1.

The comparison of the operational costs of the grain management strategies is made in table 5.18. In this table the negative sign indicates that the grain chiller strategy would be 1.89 $/t cheaper per ton than ambient aeration plus in-house fumigation. It also indicates that the grain chiller strategy would be 4.02 $/t cheaper than ambient aeration plus contract fumigation. This shows that the grain chiller would lower the operational costs of the paddy rice storage compared to any of the traditional pest management options. Those depend mainly on a chemical control which increases the cost of these strategies. The same economic analysis made in popcorn stored during the summer in the Midwestern region of the U.S. showed that savings in fumigant and labor costs would make the grain chilling strategy about 0.96 $/t and 1.11 $/t lower than in-house and contract fumigation, respectively (Rulon et al., 1999).

Table 5.18. Comparison of annual operational costs ($/t) of chilled aeration vs. ambient aeration + in-house fumigation or contract fumigation in the base case scenario.

Chilled aeration - (In-house fumigation + Ambient aeration)	-1.89
Chilled aeration - (Contract fumigation + Ambient aeration)	-4.02

5.3.1.2 NPC analysis of base case scenario

This section makes a comparison of the NPC of each of the grain management strategies in order to make an accurate evaluation of the true value of investing in strategies based on chemical control or in the grain chilling technology. This evaluation considers fixed costs like tax rate and initial equipment cost, and variable operational costs like equipment maintenance and sampling over a ten-year period. To consider costs further in the future, these costs were inflated based on the predefined inflation rates and then they were discounted back to present cost through the discount rate. Finally, for easy comparison among the strategies, an annual amortized NPC was calculated. The complete calculation of the total and amortized NPC of the base case scenario can be found in Appendix I.

From this analysis, it was observed that due to the high purchase price of the grain chiller, the amortized NPC of the grain chilling strategy would be higher than the in-house fumigation plus ambient aeration option (fig 5.1). This is mainly due to the low initial investment required to purchase the fumigation and protection equipment compared to the high initial cost of the grain chiller. Nevertheless, the grain chiller strategy would still be a better financial option compared to the contract fumigation plus ambient aeration option due to the high operational costs of the contract fumigation (fig. 5.1).

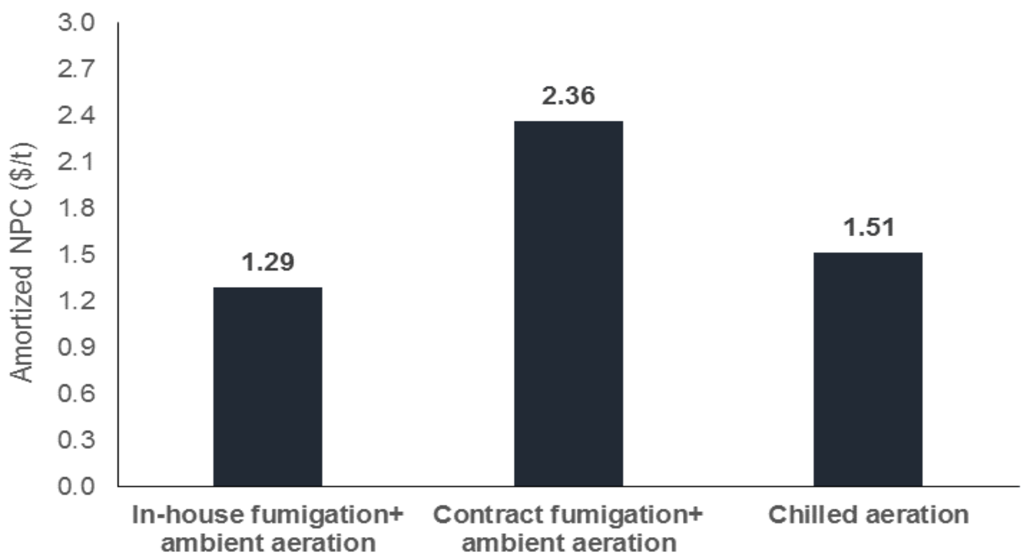

Figure 5.1. Annual amortized NPC ($/t) of in-house fumigation, contract fumigation and chilled aeration in the base case scenario.

In order to make the grain chilling technology feasible for the rice companies in Guanacaste, it is necessary to find ways to finance the initial cost of the grain chilling unit, which is the reason why the leasing option and other viable options will be analyzed in section 5.3.2.

5.3.2 Optional scenarios for financing of the grain chiller

5.3.2.1 Leasing option

The leasing option is a financial tool that would help the rice companies finance the initial cost of the grain chiller so that it could be paid over a period of time, in this case in ten years, instead of making the whole payment in the first year. A summary of the total and amortized NPC of the leasing option is shown in table 5.19 and the complete calculation is shown in table H.4 of Appendix I.

Table 5.19. Total and amortized NPC of chilled aeration with lease option

Total NPC	5.38
Amortized NPC	0.93

The leasing option adds the annual leasing payment to the annual operational costs, which increases the operational costs of the company (table 5.17). Even so, the grain chilling costs are still 0.66 $/t lower than the in-house fumigation plus ambient aeration option and 2.79 $/t lower than the contract fumigation plus ambient aeration option (table 5.20).

Table 5.20. Comparison of annual operational costs ($/t) of chilled aeration with leasing option vs. ambient aeration plus in-house fumigation or contract fumigation.

Chilled aeration with lease - (In-house fumigation + Ambient aeration)	-0.66
Chilled aeration with lease - (Contract fumigation + Ambient aeration)	-2.79

Although the leasing option increases the operational costs of the company, it gives the opportunity to the rice milling company to dilute the initial cost of the grain chiller over the ten-year period, instead of paying the whole cost on day one (Year 0), which in the long run represents a lower cost for the company (fig. 5.2).

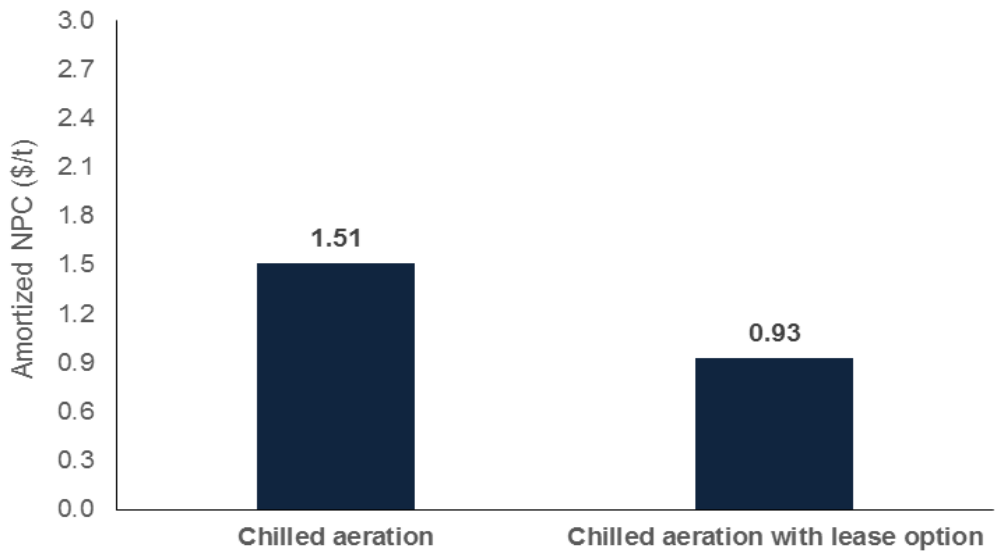

Figure 5.2. Comparison of annual amortized NPC ($/t) of chilled aeration with purchase option vs. leasing option.

Given that this financing option would considerably reduce the amortized NPC of the grain chiller, this would become a feasible option even against the amortized NPC of 1.29 $/t of the in-house fumigation plus aeration option

5.3.2.2 Purchase price optimization

The objective of the analysis of this option is not only to show the rice company what would be an appropriate purchasing price to make the grain chilling technology viable, but also to give a reference to the grain chilling manufacturer of what would be a reasonable purchase price for this market.

To determine a viable purchase price for the grain chiller, based on the amortized NPC, this price was reduced, without modifying any other parameter, until the amortized NPC of the grain chiller was equal to the amortized NPC of the in-house fumigation plus ambient aeration option (1.29 $/t).

According to this analysis it was determined that the purchase price of the grain chiller would have to be equal to $62,600 in order to make this option viable (table 5.21). This is equal to a discount of approximately 16% of the original purchase price, which seems more than what the manufacturer may be willing to offer, unless a special deal can be negotiated or the rice company can find a way to subsidize the grain chiller initial cost. On the other hand, this result may inform what the target price of the grain chilling should be if it were introduced into the Costa Rican rice industry.

Given the significant price discount required to make this option feasible, this may be the less probable option of all the ones considered in this analysis for financing the grain chiller.

Table 5.21. Grain chiller purchase price optimization based on reduction of amortized NPC ($/t) to the level of amortized NPC of in-house fumigation plus aeration in base case scenario.

	Base case scenario	Purchase price optimization option
Chiller purchase price ($)	74,700	62,600
Amortized NPC ($/t) of in-house fumigation + ambient aeration	1.29	1.29
Amortized NPC ($/t) of chilled aeration	1.51	1.29

5.3.2.3 Grain chiller capacity optimized

For this scenario, the number of silos treated with the grain chilling technology were increased, without modifying any other parameter, until the amortized NPC of the grain chiller was equal to that of the ambient aeration plus in-house fumigation option (1.29 $/t). The purpose of making this modification is to determine the minimum number of silos or minimum quantity of grain that the grain chiller would have to be used on to make this technology viable for the rice companies in this region of the country.

This analysis showed that the number of silos treated with the grain chilling technology would have to increase from 6 to less than 8 silos (7.2 silos) in order to make the amortized NPC of the grain chiller equal the amortized NPC of the ambient aeration plus in-house fumigation option. When the number of silos is rounded up to 8 the amortized NPC of the chilled aeration decreases below the level of the in-house fumigation option (table 5.22). In terms of quantity of grain, this means that the total number of tons treated would have to increase from 8,868 t to a minimum of 10,641 t in order to make the chilled aeration option feasible. This amount seems an achievable quantity, even for the smaller rice companies, considering that additional to the Guanacaste harvest, most of them receive paddy rice from harvests of other parts of the country, which usually comes in during different times of the year. This means that the rice companies are receiving paddy rice basically all year, which would justify the purchase of the grain chiller given that it would be required throughout the year, which would lower its net cost.

Table 5.22. Grain chiller capacity optimized based on reduction of amortized NPC ($/t) to the level of amortized NPC of in-house fumigation plus aeration in base case scenario.

	Base case scenario	Grain chiller capacity optimization option
Number of silos treated with grain chilling	6	8
Amortized NPC ($/t) of in-house fumigation + ambient aeration	1.29	1.29
Amortized NPC ($/t) of chilled aeration	1.51	1.18

5.3.2.4 Premium price option

If a premium sell price could be applied to the paddy rice treated with the grain chiller, this could reduce the cost per ton of this preservation method and make it a viable option for the rice millers.

Given that rice, and especially milled rice, is extremely sensitive to fissuring when it is exposed to high or low relative air humidity, an added value of grain chilling could be that it can maintain stable RH conditions of the air that comes in contact with the rice kernels. Therefore reducing the possibility of fissuring and allowing an increase of head yield (whole kernels), which has a direct impact on the final sell price of rice since fractured kernels are worth about half of whole kernels (Maier and Navarro, 2002). In California, a group of scientists from Purdue University, in joint efforts with AAG Manufacturing Co. (Milwaukee, WI) chilled 175 t of milled rice and observed that grain chilling reduced fissuring by 90% (Maier and Navarro (2002). For this reason, rice treated with chilled aeration was commercialized with a premium price given its higher quality.

Another added benefit of chilled aeration that can justify a premium price is the chemical-free product that can be commercialized as "post-harvest pesticide free". According to recent reports by Arias (2016), there are already initiatives that are coming into the market in Costa Rica for organic rice, which means that there could be a potential market that would pay for the post-harvest pesticide-free option.

For the analysis of this option, the procedure was changed from previous scenarios. In this case, the base case amortized NPC (0.00 $/t premium) was compared with 0.10 $/t, 0.50 $/t and 1.00 $/t premium price in order to determine the effect of a hypothetical premium price paid for an added-value chilled rice. Since the premium price would also reduce annual operational costs, this analysis also shows the variation of this factor due to the premium price (fig. 5.3)

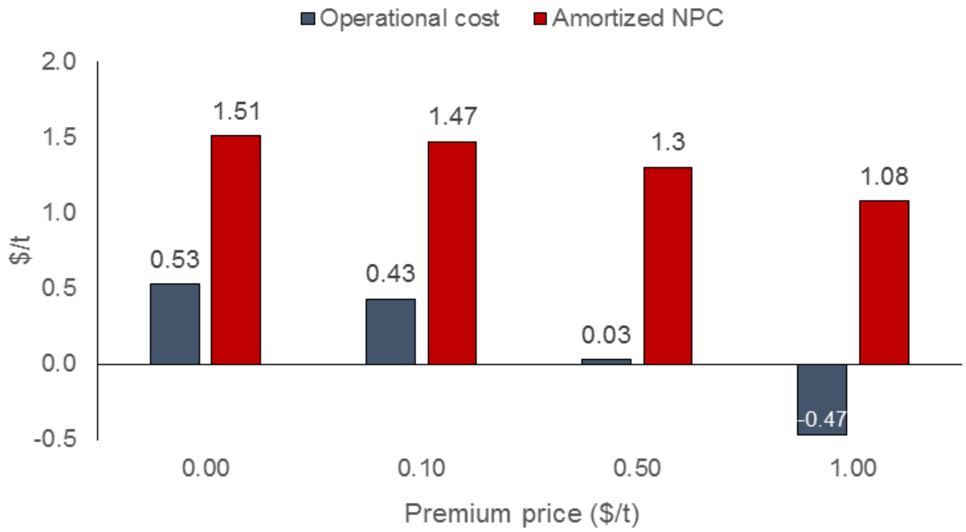

Figure 5.3. Comparison of base case scenario annual operational cost ($/t) and amortized NPC ($/t) with no premium price vs. premium price of 0.10 $/t, 0.50 $/t and 1.00 $/t.

This analysis shows that just a 0.10 $/t premium price would lower the amortized NPC by 0.04 $/t and the operational costs by 0.10 $/t. At a 0.50 $/t premium, the decrease would be even more substantial (fig. 5.3), especially for the operational costs that would lower by 0.50 $/t compared to the base case operational costs, making the annual operational costs almost zero, while the amortized NPC would almost be equal to the amortized NPC of 1.29 $/t of the in-house fumigation plus ambient aeration option. A 1.00 $/t premium price actually makes the operational costs negative, which means that the grain chilling unit would pay for itself starting from the first year given that the income generated by this added benefit would be higher than the annual costs of the grain chiller as shown by the negative values in table 5.23. The 1.00 $/t premium would also have the benefit that it would reduce the amortized NPC to 1.08 $/t, which means that it would even be lower than the 1.29 $/t amortized NPC of the in-house fumigation option.

Table 5.23. Ten-year calculation of total and amortized NPC of chilled aeration with a 1.00 $/t premium sell price.

Year	Expenses	After Tax	Discount	NPC
0	8.424	8.424	1.000	8.424
1	-0.469	-0.196	0.898	-0.176
2	-0.473	-0.198	0.806	-0.159
3	-0.476	-0.199	0.724	-0.144
4	-0.480	-0.201	0.650	-0.130
5	-0.484	-0.202	0.583	-0.118
6	-0.487	-0.204	0.524	-0.107
7	-0.491	-0.205	0.470	-0.097
8	-0.495	-0.207	0.422	-0.087
9	-0.499	-0.208	0.379	-0.079
10	-0.502	-0.210	0.340	-0.071
SALVAGE	2.948		0.340	1.004

Total NPC	6.251
Amortized NPC	1.078

A 1.00 $/t premium price seems like a real possibility given that it would not represent a significant price increment for the retail buyer, especially if this increment is analyzed per retail bag. For example, in Costa Rica the common presentation of the retail bag of white rice is 1.8 kg. If it is considered that one ton of paddy rice would be equal to 650 kg of commercial rice (whole kernel plus broken kernel), considering a milling yield of approximately 65% (Conarroz, 2007), one ton of paddy rice would generate approximately 361 bags of commercial rice, which means that the price increment per retail bag would be $0.003, or ₡1.49 (in local currency).

5.4 Conclusions

Overall, it was possible to determine the feasibility of the ambient and chilled aeration strategies developed for the tropical weather conditions of the North Pacific coast of Costa Rica through the Net Present Cost (NPC) economic model and viable economic options to finance the grain chiller. The specific conclusions of this section are:

- The analysis of the base case scenario showed that the annual operational costs of the grain chilling technology would be 1.89 $/t and 4.02 $/t lower than the operational costs of the ambient aeration plus in-house fumigation and contract fumigation options, respectively.
- The NPC analysis of the base case scenario showed that the annual amortized NPC of the grain chilling technology would be 0.22 $/t higher than the ambient aeration plus in-house fumigation option, but it would be 0.85 $/t lower than the amortized NPC of the ambient aeration plus contract fumigation option.
- The leasing option for the grain chilling technology would increase the operational costs of the grain chiller due to addition of the annual leasing cost, but would reduce the annual amortized NPC by 0.58 $/t compared to the purchase option. This would make the amortized NPC for this technology 0.36 $/t and 1.43 $/t lower than the ambient aeration plus in-house fumigation and contract fumigation option, respectively.
- The purchase price of the grain chiller would have to be lowered from the initial cost of $74,700 to $62,600 in order to make this technology economically viable for the rice milling companies under the base case scenario.
- The minimum amount of paddy rice that would have to be treated with the grain chilling technology in order to make it cost effective under the base case scenario would be 10,641 t.

- A 1 $/t premium sell price for paddy rice treated with the grain chilling technology would generate economic benefit that would surpass the operational costs and reduce the amortized NPC below any traditional grain management option.

5.5 Future research

Based on the evaluation of the economic advantages and limitations of the ambient and grain chilling strategies for paddy rice stored under tropical weather conditions, the following research is suggested for future work:

- Expand the NPC economic analysis of grain chilling vs. fumigation plus ambient aeration for other commodities and tropical climate locations in order to be able to recommend the most economical grain quality management strategies to companies that utilize other commodities.
- Investigate the potential economic savings of using the grain chiller as a complement of the drying process.

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Appendix

Appendix A- The response of stored-product insects to temperature (Fields, 1992)

Zone	Temperature (°C)	Effect
Lethal	50-60	Death in minutes
	45-50	Death in hours
Supraoptimal	35	Development stops
	33-35	Development slows
Optimal	25-33	Maximum rate of development
Suboptimal	13-24	Development slows
	13-20	Development stops
	5-13	Death in weeks to months
Lethal	0-5	Death in weeks

Appendix B- Basic function of GCH-20 grain chiller

The operation of the GCH-20 grain chiller consists of a pair of cooling circuits that work independently, which means that they can work together when the ambient temperature is high (over 25°C) to achieve set temperature or alternating when temperature drops, in order to save energy. When the unit is turned on, the cooling gas moves into a liquid state by means of exchanging heat with the ambient air around the cooling coils. Around the evaporator coils, the ambient air yields heat and the cooling gas moves from the liquid to the gaseous state, by removing sensitive and latent heat (moisture) from the ambient air. The rpm of the centrifugal fan adjusts itself according to the ambient temperature to achieve the set point temperature of approximately 10°C.

Appendix C- Figures and illustrations of grain chilling trials developed in 2015 and 2016 in Wakefield, Kansas

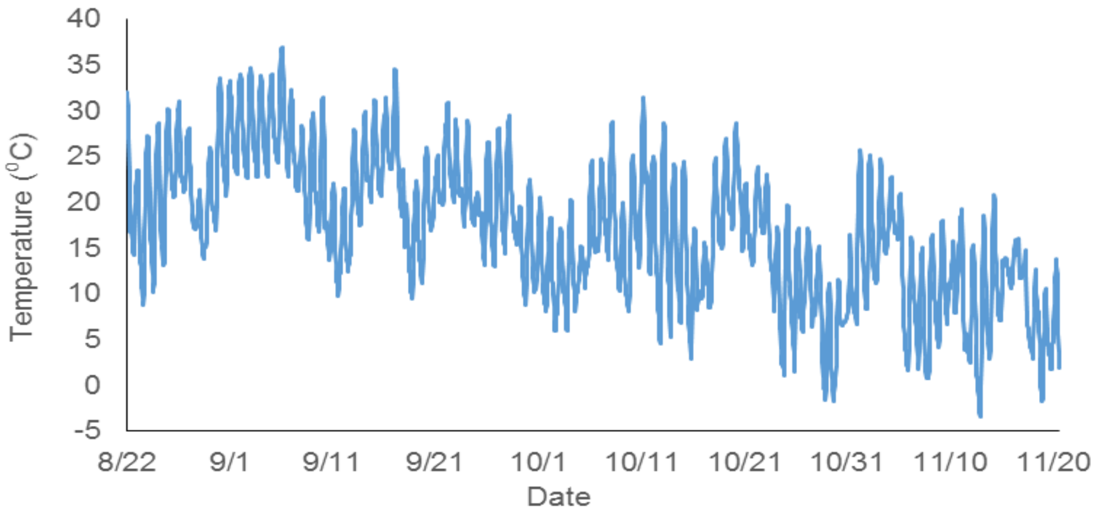

Figure C.1. Ambient temperature (°C) from Aug. 22nd to Nov. 20th, 2015 in Wakefield Cooperative, Clay County, KS.

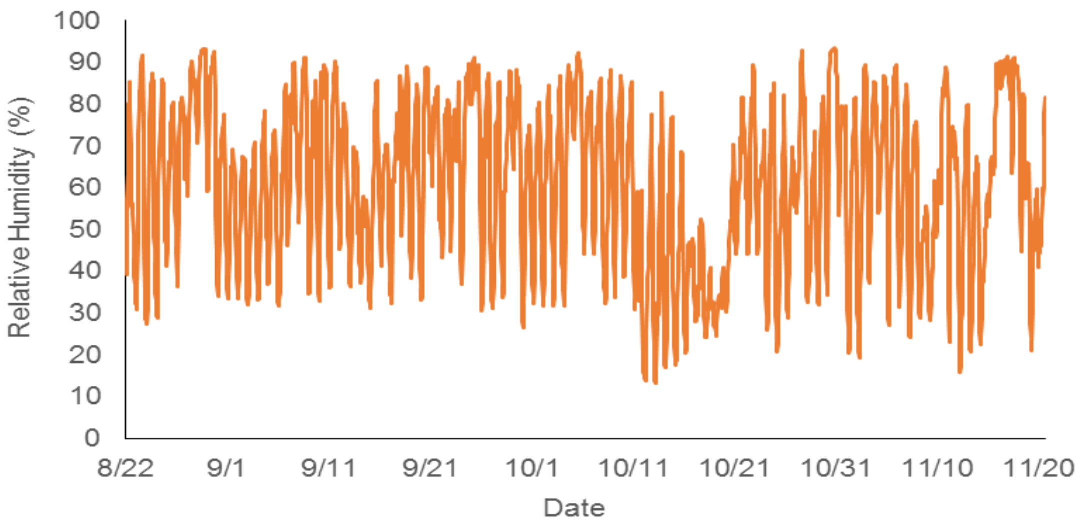

Figure C.2. Ambient relative humidity (%) from Aug. 22nd to Nov. 20th, 2015 in Wakefield Cooperative, Clay County, KS.

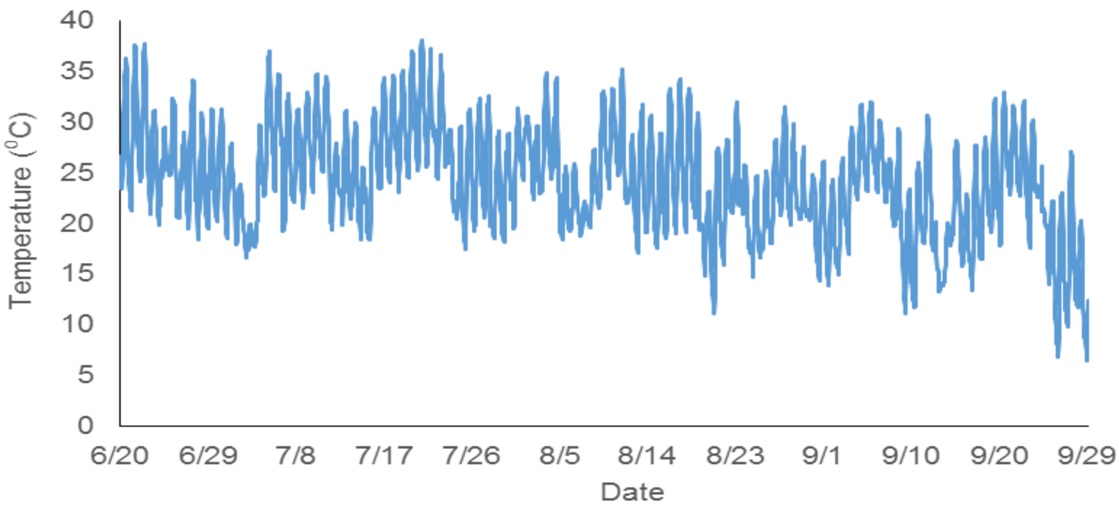

Figure C.3. Ambient temperature (°C) from June 20th to Sep. 29th, 2016 in Wakefield Cooperative, Clay County, KS.

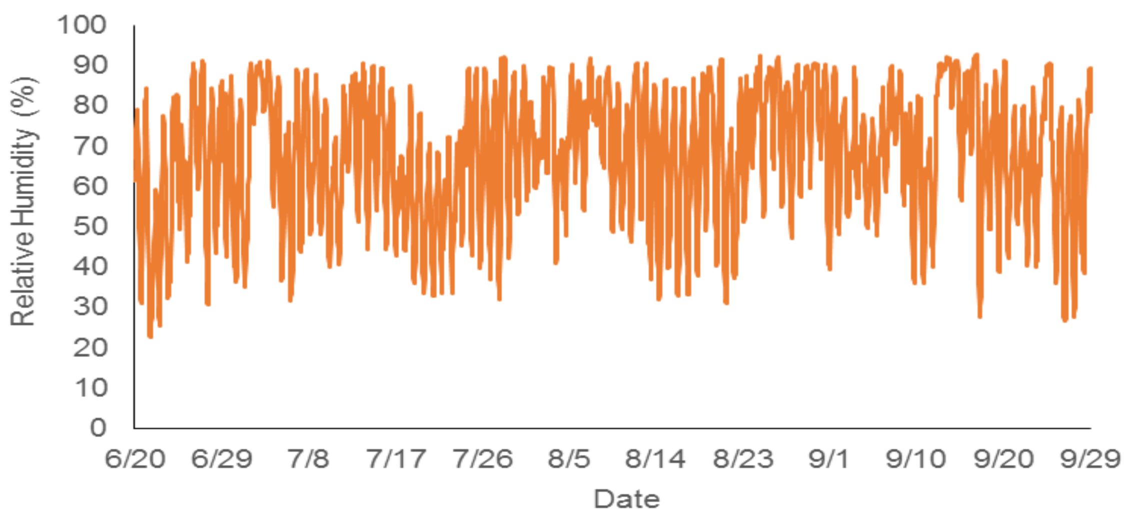

Figure C.4. Ambient relative humidity (%) from June 20th to Sep. 29th, 2016 in Wakefield Cooperative, Clay County, KS.

Figure C.5. Wheat spilled from the Chilled silo due to eave that cracked during the night of Sep. 29th, 2016 in Wakefield Cooperative, Clay County, KS.

Appendix D- Calculation of fan warm

Airflow rate (m^3/min/t)	Static pressure (in. w.c.)	Temperature increase[a] (°F)	Temperature increase[b] (°C)
0.32	13.1	13.1	13.1/1.8= 7.3
0.22	8.3	8.3	8.3/1.8= 4.6
0.13	4.7	4.7	4.7/1.8= 2.6

[a] Rule of thumb: For every 1 in. w.c. of SP the temperature of the air passing through the aeration fan increases by 1°F.
[b] The Fahrenheit to Celsius ratio is 1.8:1. This means that for every degree that the temperature changes on the Fahrenheit scale, temperature will change 1 degree on the Celsius scale.

Appendix E- Data from the 2015-2016 grain chilling trials in Wakefield, Kansas, used for the elaboration of the multiple linear regression equations for the grain chilling simulation in Guanacaste, Costa Rica

Ambient temperature and relative humidity		Temperature (≤ 15°C) and relative humidity of chilled air measured in transition parts	
Temperature (°C)	**RH (%)**	**Temperature (°C)**	**RH (%)**
17.5	69.9	11.6343	80.44
22.6	35	13.761	53.81
17	64.5	11.34296	75.14
22.6	45.4	13.08657	68.87

24.3	34.8	14.81573	73.18
20.8	54.7	14.52884	62.73
21	61.5	12.41103	64.55
18.7	68.1	11.44026	73.79
20.5	67.4	12.02239	74.36
23.5	56.5	13.08657	71.93
23.4	64	14.81573	74.54
22.6	66	14.43265	76.12
21.8	69.8	14.1452	76.57
21.6	72.3	14.1452	77.22
21.4	75.5	14.24138	78.39
21.4	30	14.62447	78.11
20.9	77.6	14.1452	77.91
20.5	79.6	13.95338	77.93
20.6	80.6	13.56862	77.96
21.2	78.7	12.99038	78.5
22.2	75.1	13.56862	78.2
23.5	69.4	13.95338	75.58
21.6	79.6	14.24138	77.67
21.1	81.7	14.33646	79.15
21.2	79.1	13.95338	78.66
21.4	77.7	14.24138	78.9
21.3	78	14.04901	78.66
22.1	76.8	13.85719	78.93
23.4	73.8	14.81573	79.38
23.7	72	13.2795	75.85
22.6	70.9	12.79745	77.57
20.8	76.5	12.60396	77.15
19.6	81.7	13.761	79.46
18.7	85.2	12.99038	80.64
17.7	84	12.11969	80.13
18.2	81.7	12.21699	79.84
18.8	79.8	12.50722	79.03
19.4	77.8	12.60396	78.77
20.3	73.9	13.2795	75.85
20.6	73.2	13.18332	77.09
21.4	70.7	12.50722	75.36
20.5	75.5	12.11969	76.57
19	81.1	12.31373	75.95
19	89.3	12.60396	79.82
21.5	77.3	13.2795	81.55

22.8	70.1	12.70015	75.91
24.3	65.3	14.62447	79.67
25.3	61.5	14.04901	71.64
26	59.1	14.81573	68.78
26	59.7	14.72066	68.8
25.5	63.7	14.1452	71.08
21.7	80.4	12.70015	77.14
20.2	85.7	12.50722	78.06
19.3	86.7	12.41103	78.3
19.2	88	12.31373	79.05
19.4	87.8	12.11969	79.06
19	88.9	12.02239	79.33
18.6	89.4	11.82834	78.59
17.9	90.5	12.31373	81.29
19.7	91.1	12.99038	81.89
22.9	82.8	12.79745	78.03
25.8	71.6	13.761	75.22
28.1	61.6	14.62447	70.87
29.3	46.7	14.33646	68.22
26.9	55.9	13.47188	73.52
24.5	66.9	13.08657	75.29
25.1	64.5	13.761	70.37
24.2	67.9	12.89308	76.29
24	69.3	13.08657	75.87
23.6	71.6	12.89308	76.49
22.9	73.7	14.72066	84.84
22.4	74.4	12.70015	76.93
21.9	73.9	12.50722	77.38
21.2	76.1	12.21699	77.85
20.6	77.4	12.21699	78.32
20.7	77.7	13.08657	79.25
22	73.1	13.37569	77.98
24.8	63.5	13.08657	75.87
27.6	54.7	13.85719	72.09
29.7	43.3	14.43265	67.09
27.2	53.6	13.47188	72.89
26.3	60.6	13.37569	74.36
25.9	63.6	13.2795	75.09
25.5	65.3	13.2795	75.46
25.1	65.3	13.66481	72.41
24.3	67.9	12.99038	75.88

23.8	69.3	12.89308	76.08
23.6	68.8	12.79745	76.1
23.6	65.6	14.62447	81.16
23.3	65.7	12.60396	76.73
23.1	66	12.31373	77.62
24.5	62.5	12.31373	77.18
26.6	55.1	13.2795	74.2
28.8	48.7	14.24138	68.45
30.7	42.7	14.62447	67.55
23.2	67.1	14.91192	76.49
22.7	67.1	14.43265	76.54
22.6	66.7	14.04901	76.37
23.8	62.3	14.24138	76.14
22.8	70.9	14.43265	77.65
22.7	70.2	14.24138	78.14
24.1	65.2	14.72066	77.39
30.5	41.4	14.72066	65.84
28.5	48.9	13.66481	71.98
27.8	53.4	13.56862	72.43
27	55.8	13.2795	74.04
26	60.2	13.18332	74.74
25.1	66.9	13.08657	75.87
24.3	72.4	12.99038	76.27
23.9	73.6	12.99038	76.27
23.4	75.6	12.79745	77.13
23.1	77.1	12.79745	77.13
22.7	78.4	12.79745	77.35
22.9	78	12.70015	77.36
24.9	69.8	12.99038	76.27
27.9	58.3	13.56862	73.83
29	53.4	13.85719	71.81
28	57.1	13.56862	73.19
27.1	61.5	13.47188	74.18
26.4	67.4	13.66481	73.99
26	69.3	13.47188	75.25
25.5	71.1	13.37569	75.64
25.1	72.3	13.2795	75.85
24.6	73.3	13.18332	76.25
24.3	73.8	13.08657	76.68
24.5	73.5	13.08657	76.68
28.3	58.6	13.95338	72.52

30.8	50.5	14.72066	68.36
31.5	45.9	14.43265	68.41
30.6	49.3	14.04901	70.33
27.6	60.9	14.04901	72.07
27.3	63.2	13.66481	73.99
27	64	13.37569	75.64
25.7	68.8	13.18332	76.25
24.2	76	12.99038	77.33
23.8	79.3	12.99038	77.56
23.1	83.1	12.89308	77.79
22.7	84.9	14.24138	71.07
24	80.7	13.08657	76.89
26.7	70.9	13.85719	73.96
28.7	61.9	14.43265	70.39
31.3	51.1	14.72066	68.91
29.6	59.4	14.52884	68.83
26.3	76.6	13.85719	73.31
25.1	81.1	13.761	74.14
24.4	82.6	13.2795	75.65
23.9	77	12.79745	76.71
23.5	75.2	12.70015	77.14
22.6	80.1	12.60396	78.05
21.6	88.8	13.47188	73.52
21.5	89.6	12.41103	79.04
21.2	90.1	12.21699	79.06
21.2	90.1	13.47188	90.92
21.7	78.6	13.85719	80.01
22.1	77.6	13.85719	79.46
23.8	73.7	14.91192	78.84
20.4	78.3	14.62447	78.87
18.8	87.4	12.02239	80.41
20.9	80.9	13.2795	78.23
23.3	57.7	14.33646	72.17
21.2	69.4	14.1452	75.17
21.1	67.2	14.1452	76.15
20.7	71.1	13.761	77.48
20	76.7	13.2795	78.23
19.5	80.8	12.99038	78.74
19.9	74.4	13.2795	78.97
19.4	77.7	12.31373	79.84
22.2	70.7	14.24138	77.44

20.7	38.8	14.62447	62.37
20.6	47.7	14.62447	64.23
21.5	46.6	14.81573	64.34
19.8	53.6	14.1452	68.47
23.2	52.9	14.04901	69.14
22.3	55.7	13.66481	71.29
21.3	58.9	13.37569	72.16
20.3	62.2	13.18332	73.4
19.3	67.6	12.70015	75.34
18.7	69.8	12.60396	75.92
18.7	68.3	12.60396	75.73
18.5	66.9	12.70015	75.34
18.3	66.7	12.60396	75.17
18.5	64.6	12.41103	76.34
20.7	58.8	12.99038	74.07
24.1	54.4	14.91192	66.885
24.3	57.1	14.52856	69.86
24.5	59.2	14.76847	68.035
25.6	57.8	14.67228	70.12
26.2	68.8	14.62475	72.365
25.1	73.8	14.33702	73.805
24.2	77.4	14.24083	74.335
23.8	75.2	14.1452	74.785
22.7	70.5	14.04929	74.46
21.6	66.6	13.52025	76.82
20.9	67.9	13.13494	76.95
21.1	63.9	13.03848	77.92
22.1	56.5	13.52025	75.77
23.3	51.5	13.61672	73.125
24.9	47.6	14.57665	71.425
28.9	36.9	14.95946	69.05
27.4	41.9	14.67256	71.85
25.3	50.4	14.19273	73.85
24.5	58.7	14.1452	73.22
23.1	71.7	13.2795	76.67
21.9	78.5	13.23141	76.48
20.7	80.9	13.13494	76.49
19.7	82.3	12.84527	77.605
20.1	81	12.89308	77.155
21.4	74.2	13.13494	76.38
21.8	73.4	13.13494	76.82

22.9	71.6	13.85719	78.465
24.5	68.4	13.80909	75.04
25.3	67.7	14.43265	72.615
24.5	82.8	14.04929	74.825
25.4	82.2	14.67228	73.945
26.5	68.5	14.67228	71.63
25.6	68.9	14.48046	72.525
25.2	69.8	14.38483	73.56
25.4	66.9	14.14492	74.18
25.3	66.2	14.24111	73.415
24.7	66.3	13.85691	74.57
24.8	65.1	13.80909	74.845
25.8	62.6	14.00119	73.775
24.2	63.2	14.62475	70.965
21.3	81.9	12.5075	78.91
20.7	86.3	12.45913	80.695
20.8	86.6	12.45913	80.99
20.6	88.7	12.26536	80.86
20.4	89.9	12.41048	80.255
20.5	90.4	12.02267	81.16
20.9	89.2	12.21671	80.555
21.6	88.5	12.31401	80.69
23.5	79.7	13.37597	76.755
23.4	80	13.47216	77.19
23.5	79.6	13.56835	76.855
25	73	13.761	75.61
27.6	63.5	14.48074	73.995
27.9	64.4	14.24083	75
28.3	62.3	14.96001	71.125
27	68.3	14.48074	73.19
25.3	75.6	14.33702	74.175
24.7	77.9	14.24083	74.98
24.2	80.1	13.61672	78.35
23.1	84.6	13.47216	78.235
22.2	87.7	13.08657	79.415
20.5	90.7	12.31373	81.96
20	91.2	12.31373	81.495
20	90.9	12.16834	81.315
19.5	90.2	11.97402	81.635
21.7	82.2	12.07104	81.315
23.7	77.9	12.7488	80.245
26	72.5	13.80909	76.935
24	65.3	13.37569	75.76
22.8	67.1	13.08657	77.375

22.1	72.3	12.98983	75.505
22.9	68.3	13.13494	77.685
22.2	75.1	13.03848	77.57
22.1	78	12.98983	78.04
22.4	81.3	12.98983	78.635
20.6	84.3	12.84527	79.155
28.1	50.5	14.62475	70.08
24.6	64.7	13.80909	74.355
22.9	72.3	13.56862	75.66
21.3	79.4	13.37569	77.125
21.2	78.4	13.18332	77.365
20.8	80.6	12.99038	77.365
20.8	80.7	12.70015	78.585
20.2	84.9	12.55559	78.595
20.2	83.9	12.41103	78.72
19.6	86.1	14.00119	82.41
19.4	86.3	12.26536	78.87
21.1	80.5	12.26536	78.405
23.2	69.4	12.60369	77.6
24.7	66	13.52025	75.425
25.1	66.3	14.28892	73.065
23.4	76.4	14.81629	70.1
23.4	83.2	14.67256	70.415
25	68.1	14.04929	73.065
25	73	13.761	75.61
22	74.1	13.08657	77.73
20.8	80.1	13.03848	77.735
20.6	81.5	12.94173	78.455
20.6	82.4	12.84527	78.96
20.4	84.6	12.89308	78.68
20.2	87.6	12.31401	80.195
20.4	87	12.7488	77.535
21.3	85.2	12.5075	78.88
24.8	64.9	13.761	73.46
27.7	49.8	13.66481	74.79
29.6	42.3	14.96001	66.985
29.6	37.9	14.81629	67.545
27.9	44.9	14.1452	71.97
25.5	54.9	13.56835	73.405
24.4	60.5	13.47216	75.025
23.2	63.3	13.2795	76.065
22	74.1	13.08657	77.73
20.8	80.1	13.03848	77.735
20.6	81.5	12.94173	78.455
20.6	82.4	12.84527	78.96
20.4	84.6	12.89308	78.68
20.2	87.6	12.31401	80.195

20.4	87	12.7488	77.535
21.3	85.2	12.5075	78.88
24.8	64.9	13.761	73.46
27.7	49.8	13.66481	74.79
29.6	42.3	14.96001	66.985
29.6	37.9	14.81629	67.545
27.9	44.9	14.1452	71.97
25.5	54.9	13.56835	73.405
24.4	60.5	13.47216	75.025
23.2	63.3	13.2795	76.065
18.1	86.9	12.70015	82.76
17.8	89.4	12.50722	81.13
17.7	90.8	12.45913	80.42
17.7	91.2	12.41103	83.4
17.7	91	12.36238	82.95
17.8	90.6	12.36238	81.6
17.8	90.4	12.65206	84.525
18.2	89.1	12.45913	82.25
18.9	85.7	12.55559	82.715
20.1	81.1	13.03848	79.93
22	74.1	13.08657	77.73
20.8	80.1	13.03848	77.735
23.2	76.1	13.85691	72.78
24.4	70.2	13.9531	72.095
27.2	58.4	14.38483	68.87
28.8	53.2	14.76819	69.92
19.3	88.9	13.9531	85.54
19.4	88.1	14.72038	82.325
19.6	82	14.48102	81.17
19.7	82.3	14.33702	80.895
20.3	80.2	14.38483	80.57
22.4	71.9	14.86355	76.52
24.7	79.3	14.14464	71.225
24.1	81.2	14.14492	72.2
23.2	85.6	13.56835	73.67
22.8	87	12.98955	74.09
22.5	88	13.3276	71.145
22.5	87.9	12.65206	73.16
22.3	88.6	12.2648	76.055
25.7	60.7	13.42323	69.625
27.4	67.9	14.48074	68.685
27.4	70.1	14.86438	70.355
27	73.7	14.91192	72.04
26.1	77.1	14.24083	71.915
25.2	77.7	14.72038	62.825
24.4	76.2	12.7488	72.7
27.9	61.7	14.52856	67.67

27.4	64.2	14.38455	67.645
26.9	64.8	13.80854	68.48
26.5	64.7	13.37541	68.695
26	64.9	13.18248	69.225
25.2	70.3	13.08629	70.52
25	72	12.89336	70.92
25.3	72.4	13.18248	70.425
21.9	85	13.2795	75
20.1	81.5	11.19589	76.875
19.9	83.6	13.905	81.86
20.5	78.3	14.48046	78.76
19.3	82.8	14.04873	79.715
20.1	82.6	13.37569	81.885
22.8	71.8	13.9531	81.86

Appendix F- Properties of the paddy rice used for the aeration model (bulk density, porosity, and thermal properties) retrieved from the ASABE standards D241.4 and D243.4.

Physical properties	Values	Source
Bulk density (kg/m^3)	579	ASAE 241.4
Specific heat (J/kg/K)	1.110 + 44.8 MC[a]	ASAE 243.4
Thermal conductivity (W/(m*K)	0.0866 + 0.0013 MC[a]	ASAE 243.3
Porosity (decimal)	0.504	ASAE 241.4

[a] MC= moisture content (w.b. %)

Appendix G- Entities that provided information for economic analysis of ambient aeration and grain chilling NPC

Type of company	Original name of company	Information provided
Rice milling companies	• Coopeliberia R.L. • Compañía Arrocera Industrial, S.A. • Derivados de Maíz Alimenticio S.A.	Silo size, storage time, fan horsepower, man hours for sampling, conditioning and fumigation, training hours, number of fumigations and applications of chemicals, type of fumigant used, type and cost of insecticides and protectant used
Financial entities	• Banco Nacional de Costa Rica • Mutual Alajuela	Interest rate for the 10-year lease of grain chiller.
	• Banco Central de Costa Rica	Currency exchange rate, passive interest rate.
	• The World Bank (International entity)	Annual interest rate, total tax rate, and base inflation rate of non-fumigant parameters.
Insurance entities	• Instituto Nacional de Seguros	Liability insurance and grain chiller insurance.
Agrochemical companies	• United Phosphorus Ltd. (Costa Rica branch)	Phosphine cost and dosage.
	• Fumigation Service and Supply, Inc. (U.S. based)	Contract fumigation costs, fumigation inflation rate.
Public government entities	• Ministerio de Trabajo y Seguridad Social	Hourly labor cost
	• Instituto Costarricense de Electricidad	Electrical cost
Public non-government entities	• Corporación Arrocera Nacional	Paddy rice price, general paddy rice storage information.

Appendix H- List of safety and chemical protection gear used for fumigations and chemical applications in rice industries of Guanacaste, Costa Rica

The fumigation crews are usually made up of four members, which have one member that takes the responsibility of serving as a guard in the ground and three members that would climb the silo for the installation of the tarp, close vents, and apply the dosage. These three crew members require fumigation masks, safety gear, and gloves to handle the phosphine tablets.

For the application of insecticides the applicator requires rubber-type gloves, body protection, and the backpack sprayer.

Equipment	Unit price ($)	Units	Total price ($)	Source
Full-face fumigation mask[a]	180	3	540	Drägerwerk AG & Co.
Phosphine cartridge[a]	65	3	195	
Safety gear for work in heights (helmet, harness, rope, diamonds)	800	3	2400	National Rice Bureau
Cotton gloves	10	3	30	3M Co.
Rubber-type gloves	10	1	10	
Chemical applicator body protection	15	1	15	DuPont Co.
4.5 gal. backpack sprayer	160	1	160	Stihl Co.
Total			3350	

[a]Price for the U.S.

Appendix I- Total and amortized NPC calculation of ambient aeration+ in-house fumigation and contract fumigation, and chilled aeration with purchase and leasing option

Table I.1. Ten-year calculation of total and amortized NPC of ambient aeration plus in-house fumigation in base case scenario.

Year	Expenses	After Tax	Discount	NPC
0	0.378	0.378	1.000	0.378
1	2.533	1.059	0.898	0.951
2	2.644	1.105	0.806	0.891
3	2.755	1.152	0.724	0.833
4	2.866	1.198	0.650	0.778
5	2.977	1.244	0.583	0.726
6	3.088	1.291	0.524	0.676
7	3.199	1.337	0.470	0.629
8	3.309	1.383	0.422	0.584
9	3.420	1.430	0.379	0.542
10	3.531	1.476	0.340	0.502
		Total NPC		7.491
		Amortized NPC		1.292

Table I.2. Ten-year calculation of total and amortized NPC of ambient aeration+ contract fumigation in base case scenario.

Year	Expenses	After Tax	Discount	NPC
1	4.791	2.003	0.898	1.798
2	5.030	2.102	0.806	1.695
3	5.268	2.202	0.724	1.594
4	5.507	2.302	0.650	1.496
5	5.746	2.402	0.583	1.401
6	5.985	2.502	0.524	1.310
7	6.223	2.601	0.470	1.223
8	6.462	2.701	0.422	1.141
9	6.701	2.801	0.379	1.062
10	6.939	2.901	0.340	0.987
		Total NPC		13.707
		Amortized NPC		2.365

Table I.3. Ten-year calculation of total and amortized NPC of chilled aeration in base case scenario.

Year	Expenses	After Tax	Discount	NPC
0	8.424	8.424	1.000	8.424
1	0.539	0.225	0.898	0.202
2	0.543	0.227	0.806	0.183
3	0.548	0.229	0.724	0.166
4	0.552	0.231	0.650	0.150
5	0.556	0.233	0.583	0.136
6	0.561	0.234	0.524	0.123
7	0.565	0.236	0.470	0.111
8	0.569	0.238	0.422	0.100
9	0.573	0.240	0.379	0.091
10	0.578	0.241	0.340	0.082
SALVAGE	2.948	-	0.340	1.004
		Total NPC		8.764
		Amortized NPC		1.512

Table I.4. Ten-year calculation of total and amortized NPC of chilled aeration with lease option.

Year	Expenses	After Tax	Discount	NPC
0	1.232	1.232	1.000	1.232
1	1.771	0.740	0.898	0.665
2	1.776	0.742	0.806	0.598
3	1.780	0.744	0.724	0.538
4	1.784	0.746	0.650	0.485
5	1.788	0.748	0.583	0.436
6	1.793	0.749	0.524	0.393
7	1.797	0.751	0.470	0.353
8	1.801	0.753	0.422	0.318
9	1.806	0.755	0.379	0.286
10	0.578	0.241	0.340	0.082
		Total NPC		5.386
		Amortized NPC		0.929