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Quality and Economic Analysis of Green Coffee Beans Stored in Purdue Improved Crop Storage Bags

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QUALITY AND ECONOMIC ANALYSIS OF GREEN COFFEE BEANS STORED IN PURDUE IMPROVED CROP STORAGE BAGS

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ABSTRACT

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Coffee farmers and cooperatives in Colombia are plagued by the high humidity that engulfs the Central Andean Mountain Ranges, where the majority of the country's coffee farming presides. Farmers are forced to sell their yields immediately after harvests in order to mitigate quality loss due to the high moisture. Cooperatives are generally forced to store green coffee until enough volume is collected for export. Farmers and cooperatives are unable to utilize optimal storage methods to capitalize on price seasonality, leading to lower profits. Coffee is a luxury commodity and its price is almost entirely dependent on its quality, making it crucial to utilize storage solutions that maintain its quality over time.

Purdue Improved Crop Storage (PICS) bags are effective at maintaining crop quality during storage. The hermetically sealed bag system inhibits the transfer of moisture and oxygen between inside the bag and the atmosphere. This study utilizes PICS bags with green coffee to better understand the quality and economic implications of storing green coffee in hermetically sealed bags. PICS bags with the standard three layers (PICS3) were tested along with PICS bags with two layers (PICS2), and Traditional jute sacks. Moisture content, water activity, and cupping score were measured to understand the quality of green coffee during storage over a period of six months. Sample price, a New York Stock Exchange (NYSE) base price, and historical coffee prices were analyzed to understand the economic implications of storing green coffee beans in PICS bags.

The results of this study showed that PICS2 and PICS3 bags maintained overall green coffee quality over the experimental time frame. There was also no statistical difference between the quality of green coffee stored in PICS2 and PICS3 bags. Water activity was also found to be an important green coffee quality indicator. PICS bags were found to be economically successful, with a positive net present value return to storage over the three year lifespan of the PICS bags. PICS3 bags were the most successful over the three years, with an additional 4895 Colombian pesos (COP) ($1.79 USD) per 50 kilogram bag on average. A reduced cost PICS2 bag was the second most successful over three years and the most successful over two years of storage, with an additional 3427 COP per 50 kilogram bag ($1.25 USD). The cost of the PICS3 bag is ~$2.00 USD and an estimated cost of the reduced cost PICS2 bags is ~$1.33 USD. Sensitivity and elasticity analyses showed that bag success rate had the largest effect on return to storage and bag cost had the second largest effect, highlighting potential for further research.

Proving the PICS bags maintain green coffee quality during storage allows for continued research on the economic effects. Important implications derived from this research focus on a better understanding of the Colombian coffee market so that farmers and cooperatives can better navigate the industry. Storage without the threat of quality degradation allows farmers and cooperatives to be more autonomous in their market decisions, providing the incentive to overcome the risk of storage and raise overall income.

CHAPTER 1. INTRODUCTION

The rise in agricultural investment throughout developing countries allows for new technology adaption and opportunities for poverty mitigation according to the Food and Agriculture Organization (FAO) of the United Nations. Investment in agriculture has been proven to decrease poverty and raise overall food security and is twice as effective as non-agricultural investments (Miller et al. 2017). A country recently interested in investing in agriculture is Colombia. The years of violence between the Revolutionary Armed Forces of Colombia (FARC) and the government wreaked havoc on the country and its agriculture. This disorder eventually led farmers to seek solace in the stability of illegal crop production or flee their rural land, fueling the political struggle. Recently, the FARC rebels signed peace accords with the Colombian government, ending half a century of violence and uniting a war-torn country. Attached to these peace accords are rural and agriculture development measures including the following: roads, irrigation systems, agricultural subsidies, schools, rural credit schemes, seed distribution, and food and nutrition programs (Beeckmans and Emsden 2016).

However, even with the newfound interest in agricultural investment, Colombian farmers and cooperatives still face significant production, technological, and economic challenges. Colombian coffee farmers struggle with high humidity during the drying and storage processes and are forced to sell their green coffee beans immediately after harvest. Cooperatives must store the green coffee until enough volume is collected for export eligibility, which leaves them vulnerable to quality degradation. One of the largest problems for smallholder coffee farmers and cooperatives in Colombia is the inability to utilize market price seasonality through storage and raise their economic well-being due to inadequate knowledge and availability of storage techniques that can greatly raise net yield and increase market availability and price, all without decreasing quality. Colombian coffee production is closely linked to the international coffee market and has important implications for the industry's stability overall, due to high quality and demand for Colombian coffee. The ability for farmers and cooperatives to store coffee can lead to price premiums through potential seasonality and mitigating quality loss during storage. While problems still exist for Colombian agricultural development, the new increase in investment makes it the ideal time to focus on new innovations and technologies to solve crop storage and other agricultural issues.

The objective of this study was to enable smallholder farmers and cooperatives in Colombia to utilize market price patterns to receive higher prices for green coffee and raise overall income and thus economic sustainability. This study observed the economic effects of storing green coffee[1] beans in Purdue Improved Crop Storage (PICS) bags by studying the progression of green coffee bean quality and price over a time period of 6 months. Green coffee beans were also be stored in traditional jute bags over the same 6 months and the quality and value were compared to the beans stored in the PICS bags. PICS bags with two layers (PICS2) and PICS bags with three layers (PICS3) were also compared to determine whether two layers would be enough to maintain quality and thus reduce the cost of investment in the bags and raise overall revenue. Standard PICS (PICS3) bags contain one bag layer of woven polyethylene that is utilized as a label and two inner bag layers of high density polyethylene that provide the hermetic seal. PICS2 bags utilize one outer bag layer and one inner bag layer. The quality of the green coffee beans was determined by measuring moisture content (MC) and water activity (A_w) as well as a cupping score and price from the cooperatives that utilize certified coffee experts called cuppers. This allowed for conclusions about the steadiness of the green coffee bean quality and the potential for selling at a

[1] Green coffee refers to the middle stage of coffee production. Coffee cherries are picked, deskinned/depulped, washed or fermented, and then dried. Green coffee is dehulled and roasted to complete processing.

higher price when the market saturation is low. With the exception of an article on green coffee storage in the *Journal of Stored Products Research*, there is little evidence that coffee storage has been actively studied and certainly not well-linked to flavor preferences and prices. This study provides evidence of the effectiveness of PICS bags and other hermetic storage technologies for mitigation of poverty and social disorder among Colombia's rural population. The main hypotheses tested will be: a) PICS bags maintain superior quality relative to traditional storage, b) coffee stored in PICS bags receives a price premium above that of traditionally stored green coffee, c) time in PICS bag storage does not affect quality nor price premium other than normal seasonal price variation, d) water activity is an important indicator of coffee quality, e) PICS bags with two layers (PICS2) maintain equal coffee quality to PICS bags with three layers (PICS3), f) significant seasonal variation exists in Colombian green coffee prices, and g) green coffee storage in PICS bags can increase average net income for Colombian farmers and cooperatives both through storage quality maintenance and seasonal price patterns.

Smallholder farmers in Colombia face significant economic and storage problems with green coffee beans. The tropical climate of Colombia inhibits farmers from storing green coffee beans because the high humidity causes the moisture content to rise and thereby decreases bean quality. This forces farmers to sell green coffee beans immediately after drying and to accept harvest period traditionally lower prices. Farmers have limited methods to test the moisture content of the green coffee beans before selling them to the cooperative and mainly rely on years of experience and the feel of the beans. Asymmetric access to information can lead to issues of market power but the cooperatives function for generally for the well-being of the farmers and this is unlikely to be an issue in this case. Regardless, analyzing such is beyond the scope of this study. The Cooperativa de Caficultores de Manizales will only purchase green coffee beans if the moisture content is 10-14 percent. According to El Comité Nacional de Cafeteros, green coffee beans must not exceed 14 percent moisture content to be exported (Comité Nacional De Cafeteros 2002). In a climate that averages 85 percent humidity, it is difficult to achieve and maintain this optimal moisture content without advanced technologies, such as ventilated silos, which are typically beyond the financial means of smallholder farmers and the rural cooperatives that support them. To export on the international market, cooperatives must have a relatively large supply of various types of green coffee beans. However, because the average size of a Colombian coffee farm is only 5 hectares, it can take 1.5 to 2 months[2] to collect sufficient volume for export (Gilbert and Gomez 2016). At the cooperative, the green coffee beans are typically stored in jute bags (denoted as Traditional throughout the remainder of the paper) in open atmosphere warehouses and so are able to take on moisture, while other specialty and organic varieties are stored in large metal silos. Large cooperatives may have the capacity to store in warehouses in cooler and dryer conditions that would maintain quality during storage, such as the cooperative in Chinchiná, Colombia. However, costs would be high to transport large volumes to and from these warehouses. Colombian cooperatives without access to low humidity warehouses are buying coffee of higher quality than what they can sell it for later. If green coffee beans reach a moisture content of 14 percent or above, the beans are deemed to be of insufficient quality for export and must be redried either back at the farm or at the cooperative for a fee. The Cooperativa de Caficultores de Manizales in Chinchiná, Colombia claims that beans can easily gain 2 percent moisture during storage and can reach the 14 percent threshold. While drying the beans again is an option, the

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[2] According to the National Federation of Coffee Growers in Colombia, the 2016 average coffee productivity was 17.8 bags per hectare, or 2,225kg/ hectare. If average contract size is 37,500lbs or 17,010kg, along with two harvest periods that stretch over 3 months each and specific quality aspects demanded by buyers, it is feasible that it would take significant amounts of time to obtain enough volume for export (Rau and Gomez 2017; “Coffee C Futures | ICE” 2017).

quality of the redried beans is lowered significantly and is not an ideal solution. Due to the high humidity and ineffective methods, there is a clear opportunity for technological interventions that can preserve the green coffee's quality and price.

Colombia is the third largest producer of coffee in the world and produces an estimated 13.6 million bags of coffee each year (Gilbert and Gomez 2016). The coffee industry in Colombia represents 16 percent of the nation's Gross Domestic Product (GDP) (Andrade et al. 2013). There are two main harvest periods for coffee. The first harvest period runs from October to December and accounts for 60 percent of the annual production, while the second harvest period is from April to June. There are an estimated 600,000 coffee farmers in Colombia and 95 percent of the farmers grow coffee on less than 5 hectares of land, and producing 69 percent of the coffee (Gilbert and Gomez 2016). Colombia exported 12.3 million bags of green coffee beans in 2016, with the largest importer of Colombian coffee beans being the United States (43 percent of exports). Colombian-grown coffee consistently reaches cupping and grading certifications that lead to much higher value adding aspects. According to the Intercontinental Exchange, Colombian coffee receives a 400 point[3] premium per pound, while other large coffee-producing countries such as Ethiopia and Brazil received par or zero discount points per pound ("Coffee C Futures | ICE" 2017). A deliberate shift to growing specialty and organic varieties has occurred to capture the added value of the already high quality of Colombian coffee (Gilbert and Gomez 2016).

[3] Points are indicated as deliverable growths and are the growths from a country, including new or yet unknown growths. Growths are separated into three categories; premium, par, and discount (100 points = US$ 0.01, i.e. 1 point= 1/100 cent). Contract size is 37,500 pounds. ("Deliveries, Delivery Months, Tenderable Growths and Differentials" 2013)

CHAPTER 2. LITERATURE REVIEW

Technically sound and culturally and economically appropriate storage methods are an effective solution for the quality degradation caused by moisture absorption. Hermetic storage technology inhibits the transfer of gasses and moisture from the atmosphere or product. This ensures product stability and preservation. Common types of hermetic storage options include metal silos and plastic bags. Metals silos are effective at minimizing post-harvest losses from moisture and pests. However, metal silos have a high investment cost and a high return to storage estimate. A study published in the *Journal of Development and Agricultural Economics* found that metal silos ranging from 100 to 300 kilograms cost $35-$375, respectively. The profitability of the metal silos is determined by size. Specifically, 1.8 ton silos have a cost benefit ratio of 3.25. Conversely, small silos with a capacity of 90 kilograms have a negative cost benefit ratio (George 2011). Metal silos are also cumbersome and heavy to move, which can limit access to the technology for women or farmers with disabilities. In addition, such structures are not scalable in real time. That is, to effectively utilize a metal silo, a farmer or cooperative must be able to completely fill the rigid structure with product, which displaces oxygen necessary for insects to live. This creates a binding limit in developing countries where yields are highly volatile from year to year; thus, the optimal size of the rigid structure changes annually or perhaps more often, leading it to be ineffective most of the time for smallholder farmers. While metal silos are effective and long-lasting at larger scale, the high cost of adoption and yield uncertainty make it an infeasible solution for most smallholder farmers. However, cooperatives that store larger amounts of crops, still have the potential to profit from metal silos of various sizes.

Other often used hermetic storage solutions include plastic bags. The SuperGrain bags by GrainPro are commercially available plastic bags in various sizes used throughout much of Africa, South America, and Southeast Asia (Borém et al. 2013). The bags consist of an outer polypropylene layer and an inner high-density polyethylene liner. Farmers may also use jute bags as an outer protective layer. SuperGrain bags were proven to be effective at mitigating insect damage of grains by inhibiting oxygen through hermetic sealing. However, large grain borers were still able to perforate the bags during artificial infestation. While the bags controlled pests adequately, insect morality was not complete (Ndegwa et al. 2016). An article in the *Journal of Stored Products Research* reported that GrainPro sacks effectively preserved the flavor and aroma of green coffee beans (Borém et al. 2013). Economic study of the SuperGrain bags found them effective when considering price, availability, and durability (Ndegwa et al. 2016).

Another type of hermetic storage option is the Purdue Improved Crop Storage (PICS) bag. The 3-layer hermetically sealed plastic bag system was developed for cowpeas in Western Africa and has evolved to storing other products such as maize, Bambara nuts, and rice (Ndegwa et al. 2016). The system consists of two inner layer bags made of high-density polyethylene that are the hermetic seal and an outer layer of woven plastic for protection (Williams, Murdock, and Baributsa 2017). PICS have proven to be effective and low cost way for smallholder farmers to safely store their products. In a 196-day study on maize, PICS bags retained 100 percent kernel weight and killed over 95 percent of insects (Williams, Murdock, and Baributsa 2017). While there were levels of aflatoxin detected, it was significantly lower when compared to traditional woven bags (Kumar and Kalita 2017). The lightweight and reusable bags cost approximately $1.80 for the 100kg bag, allowing access for low income farmers and women, relative to metal silos (Williams, Murdock, and Baributsa 2017). The median lifespan for the bags is 3 years and a study done in Niger found that 79 percent of the bags were being used at the end of the third year (Foy and Wafula 2016). A study of a side by side comparison of the PICS bags and GrainPro bags published in the Journal of Stored Products Research, found that while GrainPro bags and PICS bag both successfully preserved cowpea grain (Baoua et al. 2013). However, PICS bags possess the advantages of lower cost, wider accessibility, and greater durability over the GrainPro bags (Baoua et al. 2013). The versatility, effectiveness and reusability of the PICS bags make it a viable option for mitigating crop loss in developing countries.

Proving these storage methods to be economically appropriate for smallholder farmers is extremely important. Farmers who lack access to sufficient storage techniques are commonly forced to sell their crops right after harvest to avoid substantial losses to yield and value. Generally, this causes farmers to accept lower prices, which can leave farmers vulnerable until the next harvest period. However, the benefits of allowing farmers to store their crops must also outweigh the potential losses associated with storage. Upfront profits received after harvest can be invested either back into the farm and infrastructure or used to pay off debts associated with farm inputs. The return to storage ratio must be positive for farmers to justify the risk of storage, rather than selling upfront and taking the lower prices.

Limited research has been completed on the economics of green coffee storage at the farmer or cooperative level in the supply chain. Research has been done on the effectiveness of maintaining green coffee quality in various storage methods. A study completed in Brazil found that hermetic storage methods, such as GrainPro bags, maintained quality (Borém et al. 2013). The quality measurements included water content, color, electrical conductivity, potassium lixiviation, and sugar content. The experiment also studied the effects of a modified atmosphere by injecting a set of the hermetic big bags with 60 percent CO_2. The experiment showed that hermetic big bags were a viable option for storing green coffee beans for a 12-month period. There was also no significant difference between the quality of the bags with the injection of 60 percent CO_2 and the bags without. This study validates the hypothesis that hermetic storage technologies are a feasible solution for green coffee storage issues and demonstrates the need for studying the effect of water activity during storage.

CHAPTER 3. METHOD BACKGROUND AND THEORY

Before evaluating the economic possibilities of incorporating hermetic storage into the Colombian coffee industry, it must first be proven that green coffee quality is maintained. A study completed in Brazil showed that green coffee stored in hermetic GrainPro and big bags maintained their quality (Ribeiro et al. 2011). Quality was measured in this study using moisture content, color, electrical conductivity, potassium lixiviation, and sugar content as indicators. Researchers used jute bags as a control for the study. The researchers found that moisture content of the green coffee stored in the jute bags increased between 9.80 percent and 11.40 percent, remaining in equilibrium with temperature and relative humidity. They also found that green coffee beans that were stored in hermetic storage techniques steadily maintained their moisture content at around 10 percent. The green coffee beans were stored without the dried pod, which was noted to be common practice. However, in Colombia the green coffee is stored with the dried pod in order to protect the green bean. Ribeiro et al. (2011) concluded that it was technically feasible to use hermetic storage for maintaining coffee quality over prolonged storage times.

Water activity is another important quality indicator for green coffee beans that has not been fully explored by the literature. Water activity is the ratio of the vapor pressure of the water within a material to the vapor pressure of pure water at the same temperature (Fontana, Jr 2001). However, water activity can be more commonly explained as the amount of water that is available for chemical or biological reactions within a food product. Some water molecules within green coffee beans are bound within other molecules, such as sugars, and are unavailable to be used by enzymes, chemical reactions, bacteria, or molds. Moisture content alone tells little of a product's composition or the likelihood of quality degradation. A food product can have a high moisture content, but still have a water activity that is low enough to inhibit chemical and biological reactions. Products such as honey, candies or soda are examples of foods with water molecules bound to the sugar molecules, leaving the product shelf-stable. Water activity is especially important in green coffee beans for enzymatic, oxidative, and browning reactions. Water is essential for these reactions to occur and specific water activities are optimal for limiting unwanted reactions and promoting positive reactions. As seen by figure 3.1, the optimal level of oxidation, enzyme activity and browning reactions is around 0.55 and is the ideal water activity level for green coffee beans according a study published in *Roast Magazine*. Research completed on hermetic storage options has not included measured water activity levels over time. Water activity is an important aspect when considering the quality of the cupping score. Because water activity has a direct effect on the chemical reactions within the green coffee, it is an important aspect in the formation of key flavor compounds during roasting, which can be favorable or unfavorable depending on the water activity during storage. Further research on the effect of water activity on cupping score would be an important aspect of understanding water activity's implications for the coffee industry.

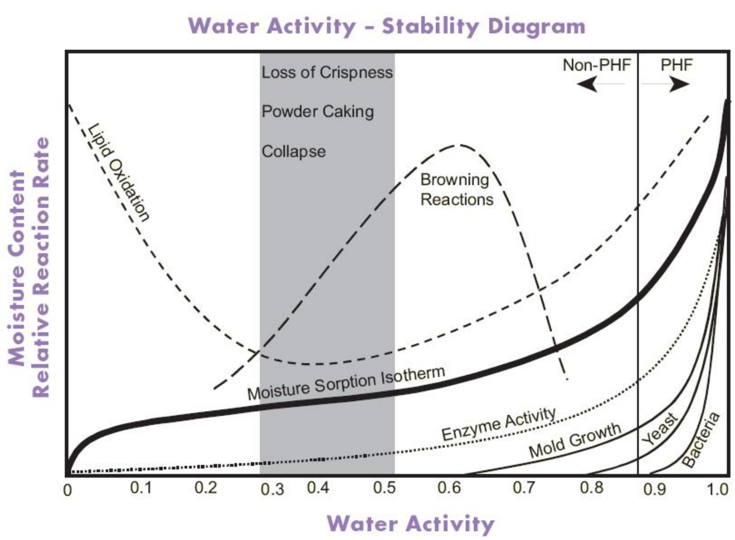

Figure 3.1 Water activity stability diagram[4]

[4]Source: AQUALAB ("Water Activity for Product Safety and Quality." 2017)

3.1 Sample preparation and experimental procedures

The experiment was conducted at the Universidad de Caldas in Manizales, Colombia. The 700 kg of coffee used in the experiment was purchased from the Cooperativa de Caficultores de Manizales in Manizales, Colombia. Manizales lies within the Caldas region and is part of the "coffee axis" of Colombia, known for its high coffee production. The steady weather conditions, volcanic soils, and Andean Rainforest climate provide an ideal environment for growing high quality coffee ("Our Coffee Regions | Café de Colombia" 2017). This region is also known for its hands-on approach to planting, harvesting, and processing the coffee beans, which gives farmers and cooperatives more incentive to use technologies that coincide with these farming practices. The green coffee beans were purchased during the secondary harvest season. The latitude of the Caldas region causes two dry and two wet seasons, which allow for two harvest periods with almost identical weather conditions ("Our Coffee Regions | Café de Colombia" 2017; Rau and Gomez 2017).

Coffee was bagged in 50-kg quantities in traditional jute bags, PICS bags with 2 layers, and PICS bags with three layers. Each type of bag had nine replicates, totaling 27 bags. The PICS bags are a three-layer hermetic system composed of two bag layers of high-density polyethylene and a final bag layer of woven plastic to protect the inner layers from mechanical damage and act as a label. The traditional jute bags (referred to as "Traditional bags") acted as a control for the experiment since they are commonly used to store green coffee beans at farms, cooperatives, and during distribution. The traditional bags leave green coffee exposed to moisture and oxygen atmospherically and do not protect the beans from physical, chemical, and microbiological damage. The PICS bags are impermeable to gasses, such as oxygen and carbon dioxide, and moisture once closed. The three-layer system protects the beans from mechanical, microbiological, and chemical damage. Mechanical damage during movement and shipping of the bags can cause bean breakage. Physical damage can also be done by insects that bore into the beans during production. Insects are suffocated after bag closure and are inhibited from causing further damage. During the physical examination that determines price, the number of broken/insect ridden beans subtract from overall bean score. Chemical damage is caused by the exposure to moisture. The color of the green coffee bean is an important quality standard; beans that are too light or dark are deducted from the score. Exposure to moisture can cause green coffee beans to discolor. Finally, microbiological damage can be caused by molds. However, without access to enough moisture and oxygen, mold growth is inhibited.

Hermetic storage options such as the Purdue Improved Crop Storage (PICS) bags are a potentially viable solution for mitigating the detrimental effects moisture exposure has during green coffee storage in Colombia. Coffee is a luxury commodity whose price is almost completely dependent on its quality, which makes maintaining coffee quality throughout all stages of production and processing extremely important. Decreases in quality have large economic impacts for farmers and cooperatives in Colombia. However, the current practice of selling yields immediately after harvest is not an ideal solution since it leaves farmers' and cooperatives' vulnerable and dependent upon current market prices.

This study focuses on two main areas of green coffee storage. First, green coffee quality is observed and measured during storage, focusing on moisture content, water activity, and cupping score to measure quality. Because PICS bags have never been used with green coffee, this study must first determine if PICS bags maintain overall quality and viable storage option. Second, the economics of green coffee storage are examined. Utilizing sample prices assigned by the cooperative, New York Stock Exchange (NYSE) base prices, and historical price data, seasonality and a net present value return to storage were calculated to understand PICS bags economic viability as a solution for green coffee storage. Incorporating PICS bags into the Colombian coffee industry will not solve all economic and quality issues. However, by mitigating the risks of storage by diminishing the detrimental effects of moisture exposure, farmers and cooperatives can gain more control of their operations and become more independent in their market decisions. The remainder of this thesis is divided into three chapters and one appendix. The second chapter is focused on the quality and sensory analysis of green coffee stored in PICS2 and PICS3 bags. The third chapter analyzes the economic effects of storing green coffee in PICS2, PICS3, and Traditional bags. The final chapter provides a summary of the study's conclusions. Supplemental materials can be found in the appendix.

CHAPTER 4. ANALYIS OF GREEN COFFEE QUALITY DURING STORAGE

4.1 Introduction

The price for coffee beans is almost completely dependent on quality. Few agricultural commodities are so tied to their quality indicators. While dependency on quality may seem like a burden to coffee farmers and cooperatives, the relationship also poses a unique opportunity for direct increases in price due to increases in quality. This creates an environment where investments in new technologies and innovations are more likely to generate economic benefits for adopters and stakeholders who are willing to take more risks in order to achieve higher quality and prices.

Coffee quality is highly determined by the chemical and physiochemical composition of green coffee beans (Borém et al. 2013). During roasting, key flavor compounds are formed through browning reactions that are determined during the green coffee[5] state (Borém et al. 2013). Therefore, focusing on green coffee is the key to increasing the quality and price of the final product. Green coffee quality is determined through physical and chemical analysis as well as a cupping score, which involves trained and certified coffee experts called cuppers. Cuppers assign sensory scores on key quality attributes including flavor, aroma, residual flavor, sweetness, acidity, cleanness of cup, balance, and uniformity. Initial quality testing is generally completed in origin country by green coffee buyers or cooperatives. One of the largest indicators that cuppers use to quickly determine quality is moisture content. This is especially important for coffee production in countries such as Colombia. Due to the high humidity in the Central Mountain Range of Colombia (where the majority of Colombian coffee is grown), it is difficult to control the moisture

[5] Green coffee is in the middle stage of coffee production. Coffee cherries are picked, deskinned/depulped, washed or fermented, and then dried, resulting in green coffee. Green coffee is dehulled and roasted to complete processing.

content of green coffee beans, especially during storage. Green coffee beans are traditionally stored in woven jute bags that do little to protect the beans from physical, chemical, or microbiological damage. It is readily known in the Colombian coffee culture that high moisture content poses threats of mold, discoloring, and off flavors. This forces Colombian farmers and cooperatives to sell the green coffee harvest immediately after the drying step[6]. However, cooperatives must collect enough volume of green coffee to qualify for export, and therefore must store for up to 2 months. Due to these market and environmental constraints, the storage phase of the coffee supply chain is an ideal place for technological interventions to raise overall quality and price.

To secure green coffee's overall quality, various quality indicators need to be controlled during storage. While moisture content is a key factor, water activity is also important for understanding the chemical composition of green coffee. Water activity is the ratio between vapor pressure of the food product and the vapor pressure of pure water in a closed system (Fontana, Jr 2001). That is, water activity is equal to the relative humidity of the air when in equilibrium with the food and is a better overall quality indicator than moisture content (Fontana, Jr 2001). Moisture migration between the green coffee beans and the atmosphere is a major cause of quality deterioration, causing sucrose molecules to polymerize into glucose, which has been associated with the "past crop" taste (Kornman 2016). Water activity is also important for understanding the non-enzymatic browning reactions that occur during the roasting process (Kornman 2016). However, water activity has not been fully explored for its long-term effect on quality for green coffee during storage. One article in *Roast Magazine* examined the relationship between water activity and moisture content in green coffee beans and found that moisture content only predicted the corresponding water activity 51 percent of the time, while water activity predicted coffee

[6] Coffee cherries are picked, deskinned/depulped, and a sticky layer of sugars is washed or fermented off. Once dried the product is known as green coffee.

quality and stability quite accurately with an optimal water activity range between 0.5 and 0.59 (Fretheim 2008). Technological innovations, such as hermetic storage bags, have the potential to maintain green coffee quality during storage. Purdue Improved Crop Storage (PICS) bags have proven to be an effective way to mitigate post-harvest loss by limiting quality damage in crops, such as maize and cowpeas, during storage (Williams, Murdock, and Baributsa 2017). The three-layer hermetically sealed bag system provides an affordable and accessible solution for decreasing crop damage by limiting moisture and oxygen exposure.

By studying the effects of hermetic storage on green coffee bean quality, steps toward increasing the overall quality of coffee and its prices can proceed. Technological interventions such as the PICS bags are opportunities to mitigate quality degradation during storage. This study also focused on determining whether all three layers of the PICS bags were needed to maintain green coffee bean quality over time and whether two layers were just as effective. PICS2 represents PICS bags with one outer layer of woven plastic used as protection and for a label and one inner bag layer made of high-density polyethylene (HDPE) that acts as the hermetic seal. PICS3 represents the standard PICS bags with one outer layer bag of woven plastic and two inner layer bags made of HDPE. The outcome of this study will reveal the effectiveness of PICS bags with two layers (PICS2) and PICS bags with three layers (PICS3) at maintaining green coffee bean quality and the importance of water activity as a green coffee bean quality indicator.

4.2 Materials and Methods

4.2.1 Sample preparation and experimental procedures

The experiment was conducted at the Universidad de Caldas in Manizales, Colombia from March to October 2017. Seven hundred kilograms of green coffee were purchased from the Cooperativa de Caficultores de Manizales in Manizales, Colombia. The green coffee (*Coffea arabica L*.) used in this experiment was taken from a lot harvested and dried in March 2017. The green coffee beans were bagged in 9 traditional bags, 9 PICS2, and 9 PICS3, totaling 27 bags. Each bag was filled with 50 kilograms of green coffee beans. The bags were labeled with a code which corresponded to sample codes written on bags taken to the cooperative for further testing. This was to ensure blind testing from the cuppers at the cooperative. Three bags from each technology were tested monthly. Three samples were taken out of each bag, totaling 27 samples per month. Bags were opened every three months so that the beans could acclimate to the hermetic seal before resampling. One set of bags was tested on month 1, 4, and 7. The second set of bags were tested on month 2 and 5. The third set of bags were tested on month 3 and 6. At the end of the six month experimental timeframe there was a total of 162 potential observations. The sample size of this experiment was determined based on the maximum amount of samples the cooperative agreed to analyze each month and not according to any estimates of power of statistical tests. Each sample taken from the bags was 500 grams. The sample probe used was designed to sample the entire depth of the bag and the samples were taken from the middle and both sides of the bags, all to obtain a representative sample of the entire bag. Samples were placed in ziplock bags and labeled with the corresponding bag code. Samples were taken to the Cooperativa de Caficultores de Manizales in Chinchiná, Colombia for further testing on moisture content and cupping score.

4.2.2 Analytical procedures

All analyses performed used the 500 gram samples taken from the various bag types. The variables measured during the experiment were moisture content (MC), water activity (A_w), rendimiento, and cupping score. Water activity was measured at the Universidad de Caldas and moisture content, rendimiento, and cupping score were all measured at the Cooperativa de Caficultores de Manizales in Chinchiná, Colombia. All methods, other than water activity measurements, are in accords with standards of the National Federation of Coffee Growers in Colombia.

Water activity was measured using an AQUALAB Pawkit water activity meter, which utilizes capacitance by converting a measured humidity value into a specific capacitance by electronic measurement using the circuit (METER 2017). Moisture content was measured using a Grain Moisture Tester PM-410 that also utilizes a measuring principle of capacitance by dielectric constant (Kett 2018).

Rendimiento, which translates to “yield,” is a physical analysis of the green coffee beans. It is scored by taking 100 grams of green coffee beans, dehulling the beans, and performing a visual inspection for health, size, broken beans, and insect damage. The weight of the unacceptable green coffee beans and hulls is subtracted from the overall 100 gram sample, with 94 being the highest possible score. Rendimiento is also used to calculate the price farmer’s receive when selling their green coffee beans to cooperatives.

The sensory analysis was performed by cuppers at the cooperative who have national certifications from the National Coffee Growers Federation. Green coffee beans are dehulled, roasted, ground, and brewed to strict specifications outlined by the Federation. Ten sensory attributes are graded out of 10 for each sample. The attributes include aroma, flavor, residual flavor, acidity, body, uniformity, balance, cleanness of cup, sweetness, and a cupper's score. These attributes are then tallied up to form a sensory score out of 100. This cupping score is used to differentiate samples based on flavor profiles and is only used for the export market. This sensory analysis does not affect the price the farmer's receive for their green coffee beans.

4.2.3 Statistical analysis

Missing sensory score observations were a significant issue when performing statistical analysis. Moisture content and water activity had complete observations. The Cooperative has various standards in place to protect the health and safety of the cuppers and integrity of equipment. One of these measures involves the potential presence of toxin and off-flavor producing molds. Thus, no samples with moisture content greater than 14 percent are ever assessed at the cooperative.

Samples taken from traditional bags were over the 14 percent moisture content threshold in the first month and never went below 14 percent in the following months. Five PICS bags (two PICS2 bags and three PICS3 bags) contained coffee over 14 percent moisture content at month 0. This is due to the high humidity on the bagging day (moisture content was within 10-14 percent range when the green coffee beans were purchased hours before at the cooperative). Because there were no sensory score observations for the traditional bags after month 0, traditional bags were excluded from the statistical analysis of sensory score. The five bags that were over 14 percent moisture content at the beginning were controlled for by including a dummy variable for observations sampled from the high moisture content bags. Analyses including these bags were also completed and compared. Also, month 1 observations had to be excluded due to sampling error. Statistical analysis was performed over months 2-7. This may indeed have been a benefit because it provided more opportunity for moisture and water activity in the bags to equilibrate.

Various methods were used to control for the remaining missing sensory score observations. Excluding all missing observations was not an option due to a lack of statistical precision with such low numbers of observations (insufficient degrees of freedom). Using a fixed score for all missing sensory score observations was also not ideal. The relationship between moisture content and sensory score is not linear and a high moisture content would not necessarily indicate a low sensory score, which would skew the results of the analysis by exaggerating the relationship between moisture content and sensory score. Regressions were completed by replacing missing sensory score observations with 50, 70, 80, and 90. Results of these analyses are in the appendix for readers who may be interested in reviewing the outcomes.

Imputation methods were eventually utilized to manage the remaining missing variables. Out of the initial 162 observations, 54 were excluded as traditional bags. Out of the 108 observations left, 46 were missing data for the sensory score. Thirty of the missing sensory score observations had initial moisture contents over 14 percent at month 0. Analysis with and without these high initial moisture observations was performed and compared. The Classification and Regression Trees (CART) imputation method was used to impute the missing sensory score observations. The machine-learning method models are obtained by recursively partitioning[7] the data space of predictor variables (moisture content and water activity) and fitting a simple prediction model within each partition (Loh 2017). The CART model approximates the conditional distribution of a univariate outcome using multiple predictors, in this case moisture content, ratio of moisture content, water activity, and ratio of water activity[8]. The predictors are partitioned so that subsets of units formed by the predictors have relatively homogenous outcomes (Burgette and

[7] Repeatedly split the records into two parts to achieve maximum homogeneity within the new parts.
[8] Ratio of moisture content and ratio of water activity were calculated by dividing the observation at month x by the observation at month 0.

Reiter 2010). The partitions are found by recursive binary splits of the predictors, which can be represented by a tree structure, as seen in figure 4.1, with leaves corresponding to the subsequent splits (Burgette and Reiter 2010). The leaves represent the conditional distribution of the outcome for units in the data with predictors that fulfill the criteria that define the leaf (Burgette and Reiter 2010). Impurity in the prediction model is measured by the sum of squared deviations and the performance is measured by root mean squared error (RMSE) (Shmueli, Patel, and Bruce 2017). The regression tree is then "pruned" to avoid overfitting by finding the point at which the validation error begins to rise (Shmueli, Patel, and Bruce 2017). Once the CART model is built, it can be used for imputation. CART models can be used for categorical and continuous variables and for both independent and dependent variables (Burgette and Reiter 2010). The CART method was compared to various other methods of data prediction modeling and was found to have closest distribution to experimental data observations.

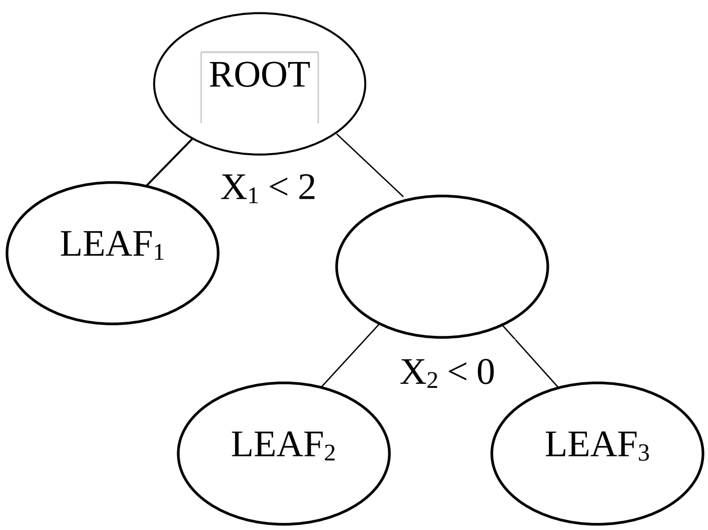

Figure 4.1. Example of CART tree structure[9]

[9] (Burgette and Reiter 2010)

Histograms in figures 4.2 and 4.3 show the distributional differences of absolute sensory score for all data and between bag type (PICS2 vs. PICS3) for the imputed data set and the raw dataset with all missing variables excluded. The distributions for sensory score between the two datasets are very similar. Also, the average sensory scores by bag type are very similar. This indicates that the imputation method seemed to capture important aspects of the true distribution. When analyzing the distributions by month, the sensory score remained consistent until months 6 and 7, as seen in figures 4.4 and 4.5. The distributions for the imputed dataset and the raw dataset on the sensory scores were also very similar over time. This indicates that the sensory scores, and therefore quality, were maintained over time in both PICS2 and PICS3 bags until month 7 and that both the imputed dataset and raw dataset were similar[10].

[10] As a reminder, bags were only opened every three months. Months 2 and 5, months 3 and 6, and months 4 and 7 are the same bag sets and should be compared accordingly.

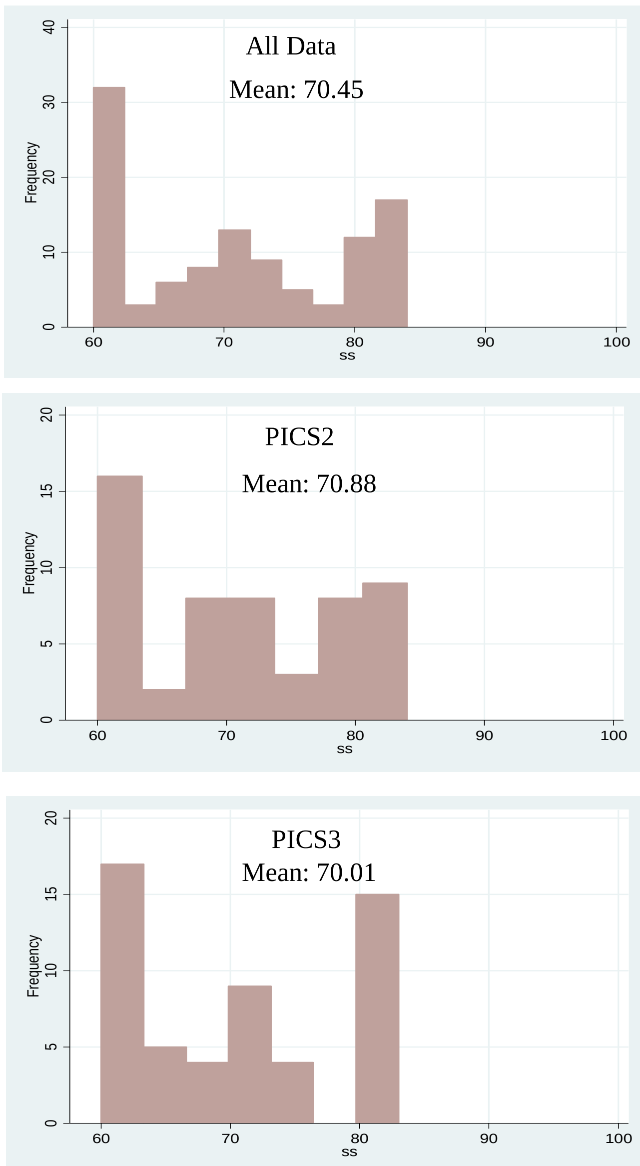

Figure 4.2. Distribution of absolute sensory score by bag type on imputed data

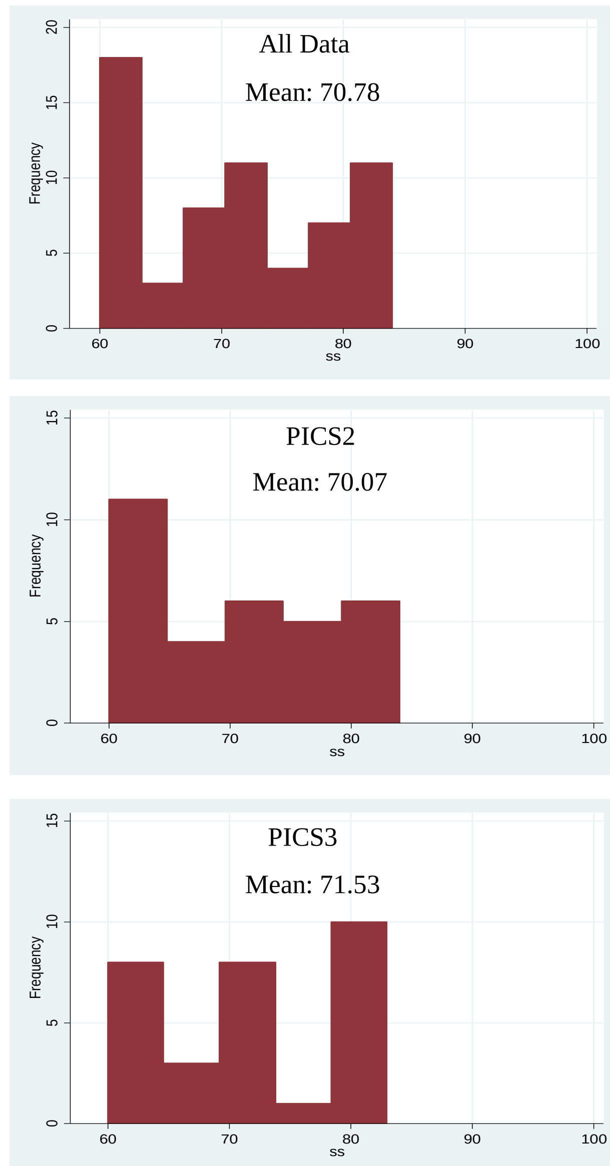

Figure 4.3. Distribution of absolute sensory score by bag type on raw data

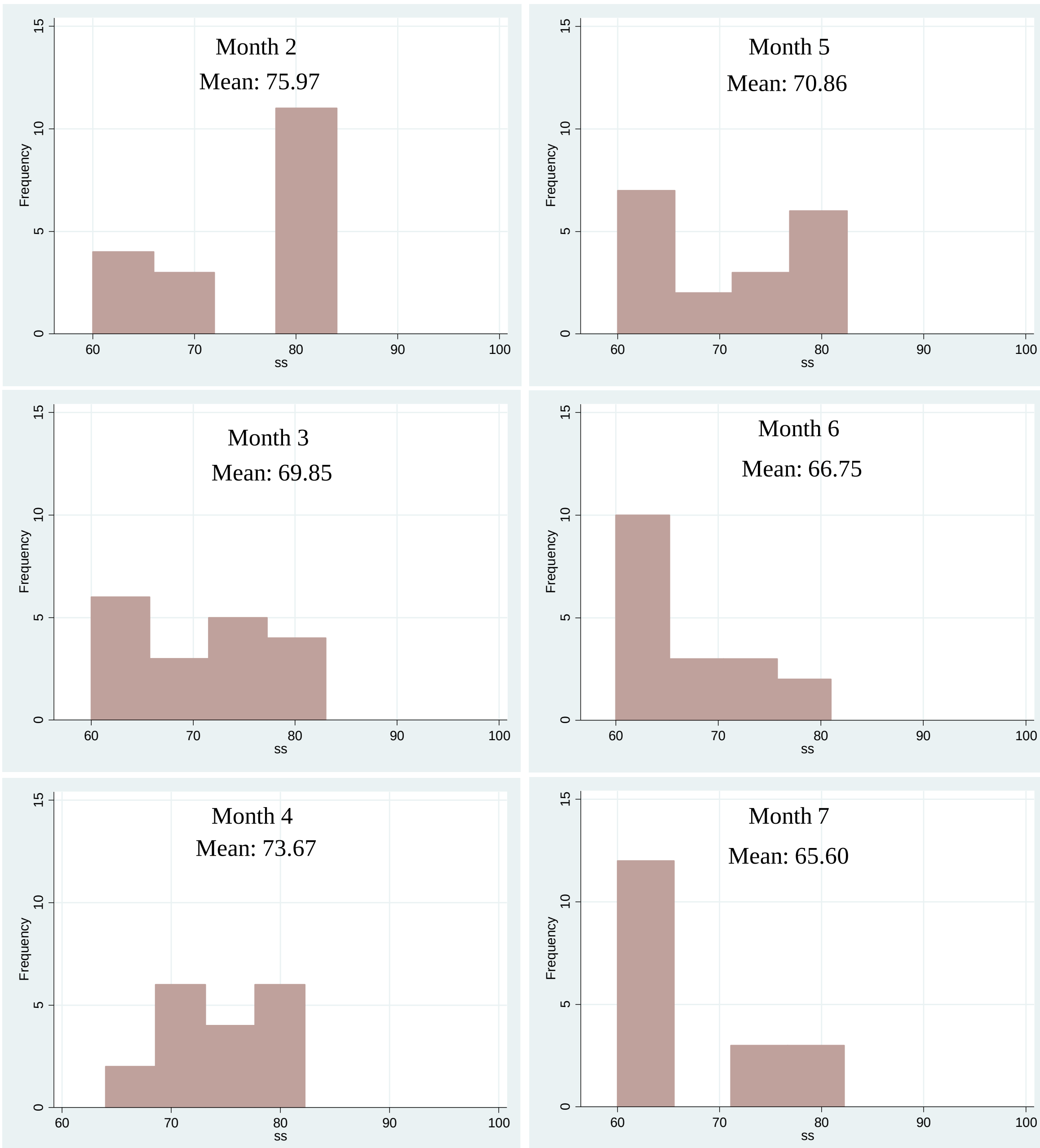

Figure 4.4. Distribution of absolute sensory score by month on imputed data

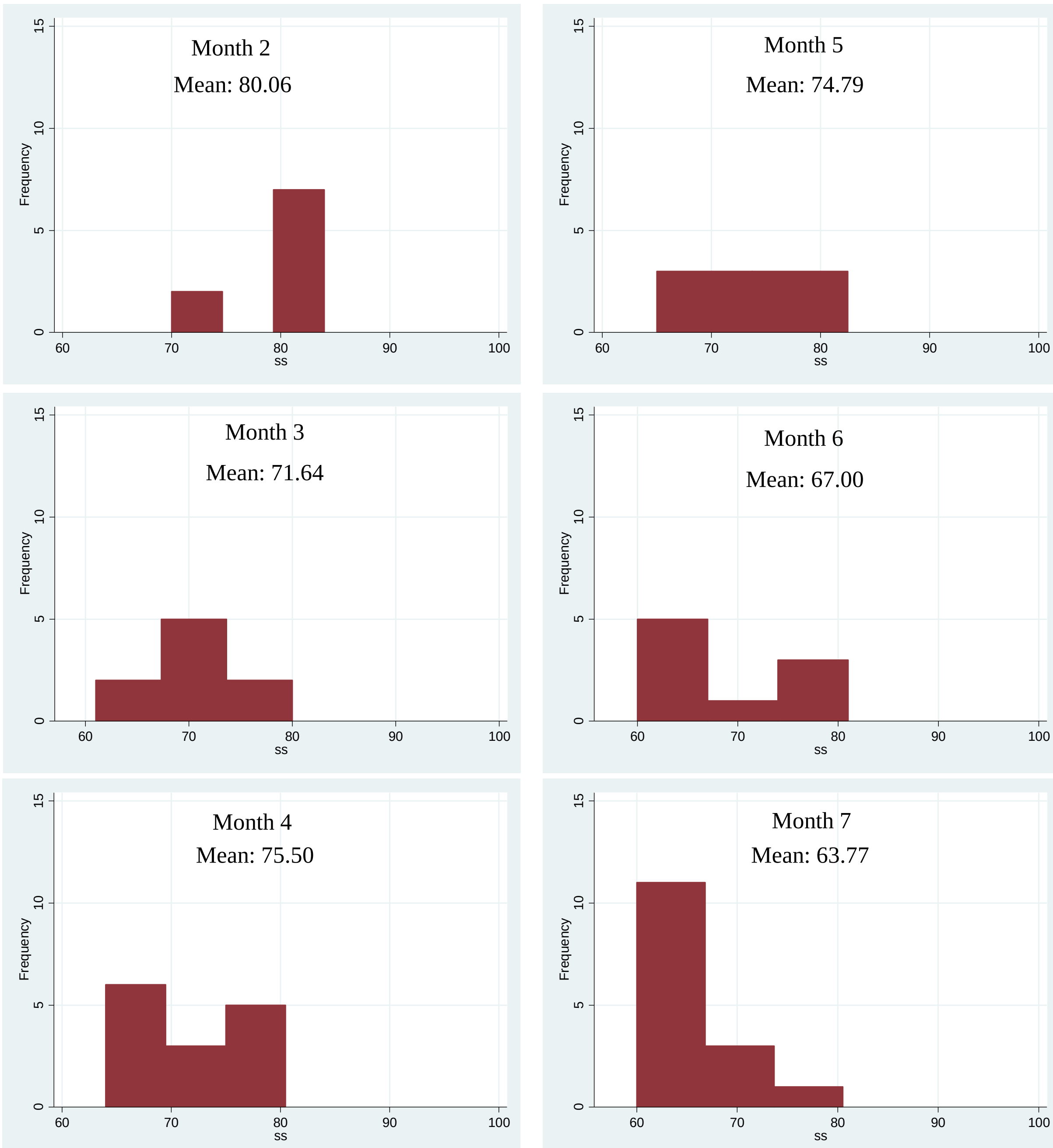

Figure 4.5. Distribution of sensory score by month on raw data

4.2.3.1 Sensory score analysis

Linear regression models were used to analyze the relationship between sensory score (with imputed values substituted for missing values), PICS bags, moisture content, water activity, and time. The logarithm of the ratio in sensory score (lnrss), the logarithm of the ratio in water activity (lnraw), and the logarithm of the ratio in moisture content (lnrmc) were used to examine how quality indicators, such as moisture content and water activity, changed over time and if so, how those changes affected the sensory score in each bag technology. These variables can equivalently be interpreted as the logarithm of ratios or differences in logarithms from two time periods. They were calculated by taking the natural logarithm of the measurement at month x over the measurement at month 0 of the same sample. Regression analysis was also conducted excluding moisture content to determine if moisture content had an effect on the water activity's significance. That is, to analyze to what extent water activity and moisture content provide unique verses common information in explaining sensory score and sensory score change over time and storage method.

Moisture content and water activity are potentially endogenous variables[11] and therefore an instrumental variable (IV)[12] regression framework was used to test the exogeneity of these two regressors. Two-Stage Least Squares (2SLS)[13] regression methods were used to control for

[11] Water activity and moisture content are potentially endogenous because the same underlying atmospheric factors such as humidity, exposure to moisture, and storage method affect them as affect the sensory score. That is, water activity, moisture content, and sensory score are jointly determined by the same data generating process. Ignoring this endogeneity in statistical analyses would result in biased and inefficient estimates of the impact of water activity and moisture content on sensory score due to correlation between these variables and the regression error term.
[12] Instrumental Variables (IV) method utilize variables (z) that are correlated with changes in the endogenous independent variables (water activity and moisture content), but not correlated with regression error term.
[13] Two-Stage Least Squares (an IV method) is used in a single equation setting when there are one or more endogenous variables on the right-hand side of a regression equation. 2SLS analysis uses instruments (see earlier footnote) to estimate a first stage regression and generate predicted values of the right-hand side endogenous variables. With good instruments, these predicted values are proxies for the underlying variables but not correlated with the error term. The 2SLS estimator is consistent in all cases and finite sample properties depend on the model being over identified and the quality of the instruments.

potential endogeneity between water activity, moisture content, and sensory score. The Durbin and Wu-Hausman tests for endogeneity were used to test a null hypothesis that both were exogenous against an alternative hypothesis that they are endogenous. If the null cannot be rejected then it is generally assumed that Ordinary Least Squares (OLS) methods would be unbiased and more efficient than IV methods. The Durbin and Wu-Hausman endogeneity tests differ in that the former uses an estimate of the error term's variance based on the assumption the variables are exogenous, while the latter uses an estimate of the error term's variance based on the assumption the variables are endogenous. The results of the both endogeneity tests were insignificant, indicating that the null hypothesis (H0: variables are exogenous) could not be rejected and there was no significant endogeneity in these variables. Results for the endogeneity tests are in table 4.1 below. Sensory Endogeneity Tests 1 and 2 analyzed the logarithm of the change in sensory score and Sensory Endogeneity Tests 3 and 4 analyzed the logarithm of absolute sensory score. Sensory Endogeneity Tests 2 and 4 excluded moisture content variables. For readers interested in the 2SLS model and results, please refer to the appendix.

Table 4.1. Endogeneity test results for sensory score analysis

	Sensory Endogeneity Test 1 (lnraw)	Sensory Endogeneity Test 2 (lnraw)	Sensory Endogeneity Test 3 (lnaw)	Sensory Endogeneity Test 4 (lnaw)
	Score (p-value)	*Score (p-value)*	*Score (p-value)*	*Score (p-value)*
Durbin	2.015 (0.3651)	2.0973 (0.3504)	1.736 (0.1877)	0.05110 (0.8212)
Wu-Hausman	0.9223 (0.4011)	0.9605 (0.3863)	1.617 (0.2065)	0.04687 (0.8291)

The tests for endogeneity indicated that OLS regression methods were appropriate. The OLS regression equations for sensory score analysis are as follows:

$$lnrss_{it} = \beta_0 + \beta_1 lnraw_{it} + \beta_2 lnrmc_{it} + x2_t + x3_t + x4_t + x6_t + x7_t + PICS2_{it} + u_{it} \quad (4.1)$$

Where x2, x3, x4, x6, x7 are months in storage dummy variables, PICS2 is a bag technology dummy variable, u is the error term, and the *i* and *t* subscripts respectively denote the bag type and month of each sample variable.

The regression model for the absolute level of sensory scores follows the same equational structure but substitutes the logarithms of the sensory score, water activity, and moisture content for their logarithmic changes and is as follows:

$$lnss_{it} = \gamma_0 + \gamma_1 lnaw_{it} + \gamma_2 lnmc_{it} + x2_t + x3_t + x4_t + x6_t + x7_t + PICS2_{it} + \varepsilon_{it} \qquad (4.2)$$

Where x2, x3, 4, x6, and x7 are months in storage dummy variables, PICS2 is a bag technology dummy variable, and ε is the error term. The subscripts are as defined earlier.

4.2.3.2 Water activity analysis

Analysis was also completed on the water activity observations to better understand the relationship between water activity, time, and PICS bags. Along with sensory score analysis above, understanding water activity's role in quality and how water activity changes when green coffee is stored in PICS bags is important for understanding PICS bags' effectiveness. The entire dataset, including traditional bag scores, was used because there were no missing observations for water activity. Ordinary Least Squares (OLS) regression methods were used to analyze water activity as the dependent variable with PICS2, PICS3, month variables, and bag dummy variables to represent the bags that were not over 14 percent moisture content at month 0[14].

Histograms were also completed on the water activity data (all data observations) to better understand the distribution of observations. As seen in figure 4.6, PICS2 and PICS3 bags have

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[14] Bag dummy variables for bags that were not over 14 percent moisture content at month 0 were used because moisture content is endogenous to water activity and was used as the reason for exclusion (creating a pattern of all over 14 percent moisture content). Using the excluded bag dummy variables created bias in the regression results.

similar distributions, with average water activities at 0.7041 and 0.7109, respectively. Traditional bags had a higher water activity, with an average of 0.7604. All water activity observations were above the optimal range as stated in the article in *Roast Magazine*. However, due to consistently high humidity in the production regions in Colombia, it is possible that the ideal water activity range stated could be infeasible for areas with higher average humidity and are not necessarily representative of Colombian coffee production.

Figure 4.7 presents the distributions of water activity over six months. Visual interpretation of the distributions presents little change over time in the water activity. The average water activities between month 2 (0.7229) and month 7 (0.7267) were very nearly equal. This indicates that PICS2 and PICS3 bags were effective at maintaining the water activity of the green coffee beans.

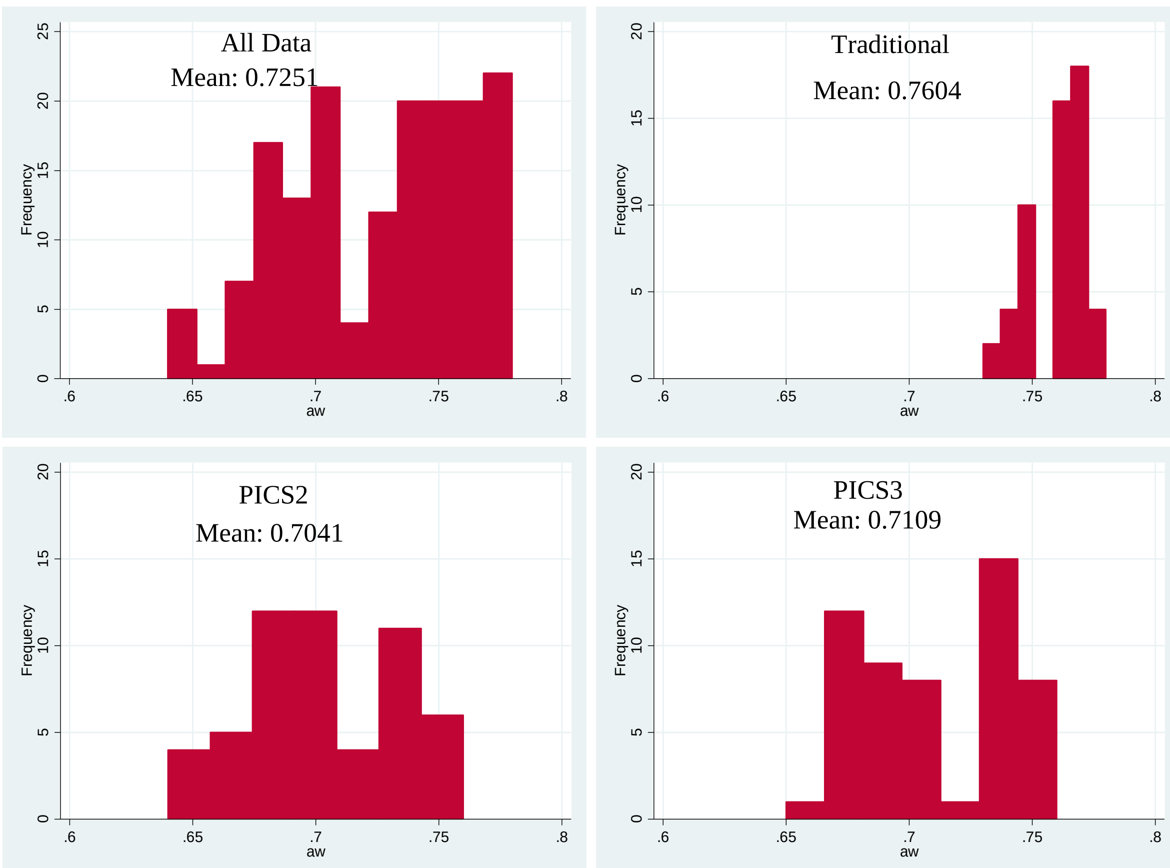

Figure 4.6. Water activity distribution by bag type

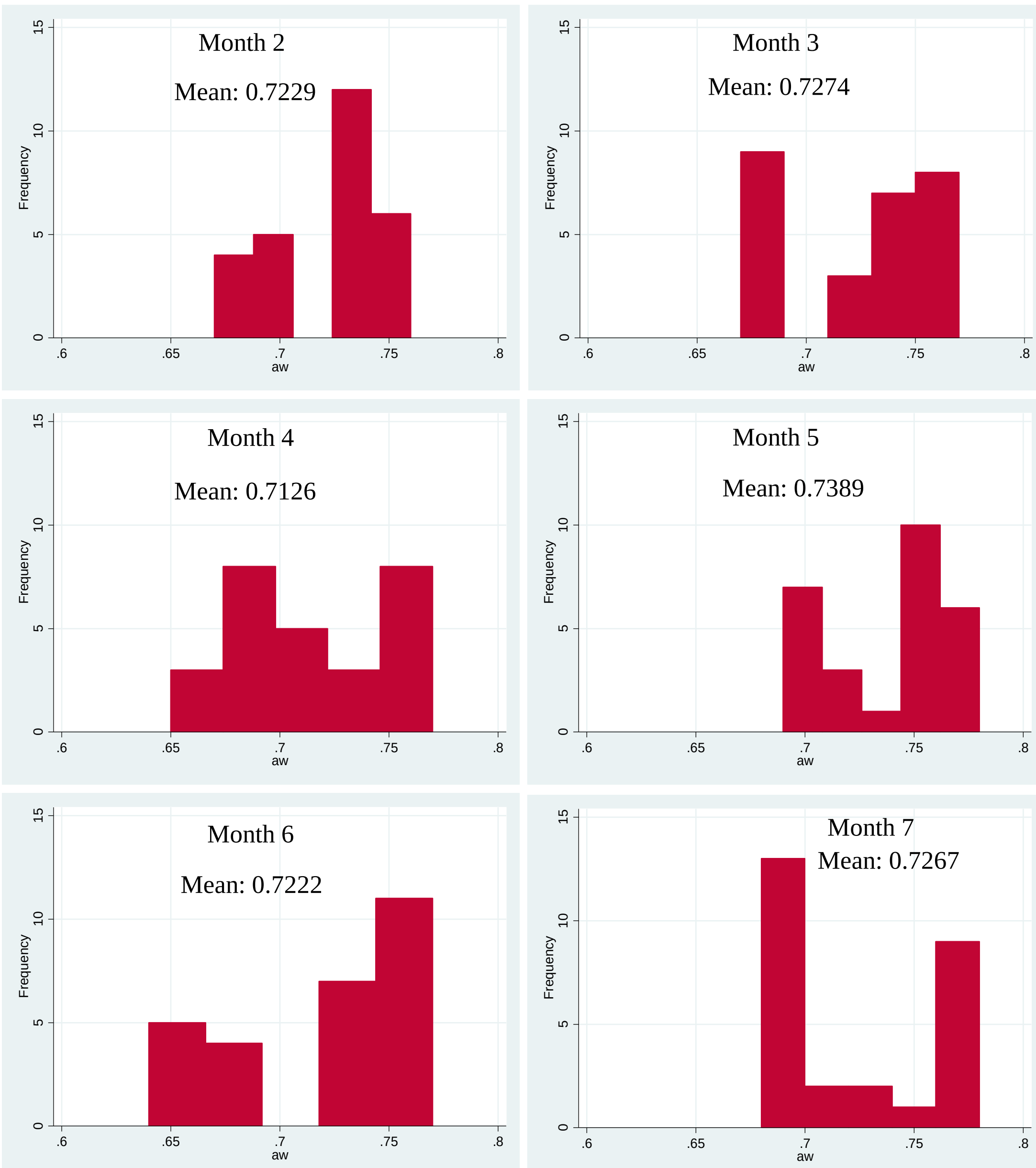

Figure 4.7. Water activity distribution by month in storage

4.3 Results

4.3.1 Sensory Score

4.3.1.1 CART Imputation Method

Figure 4.8 presents the regression tree for the CART imputation method to better visualize the decision rules for predicting the missing sensory score missing. Water activity, ratio of water activity, and moisture content were used to determine the regression tree. Each root node contains a single input x variable (raw, mc, or aw) and a split point on that variable. Ratio of moisture content was included in the imputation method but was not utilized by the program. The number associated with the x variable on the root node denotes the values of the x variable in the partition. The left branch is the average of the y variable when the statement on the node is true. The leaf node associated with the root node represents the average sensory score corresponding with the inequality in the root node. For example, in the first partition, the average sensory score was 63.23 for observations that had a ratio of water activity observation that was greater than or equal to 0.9935.

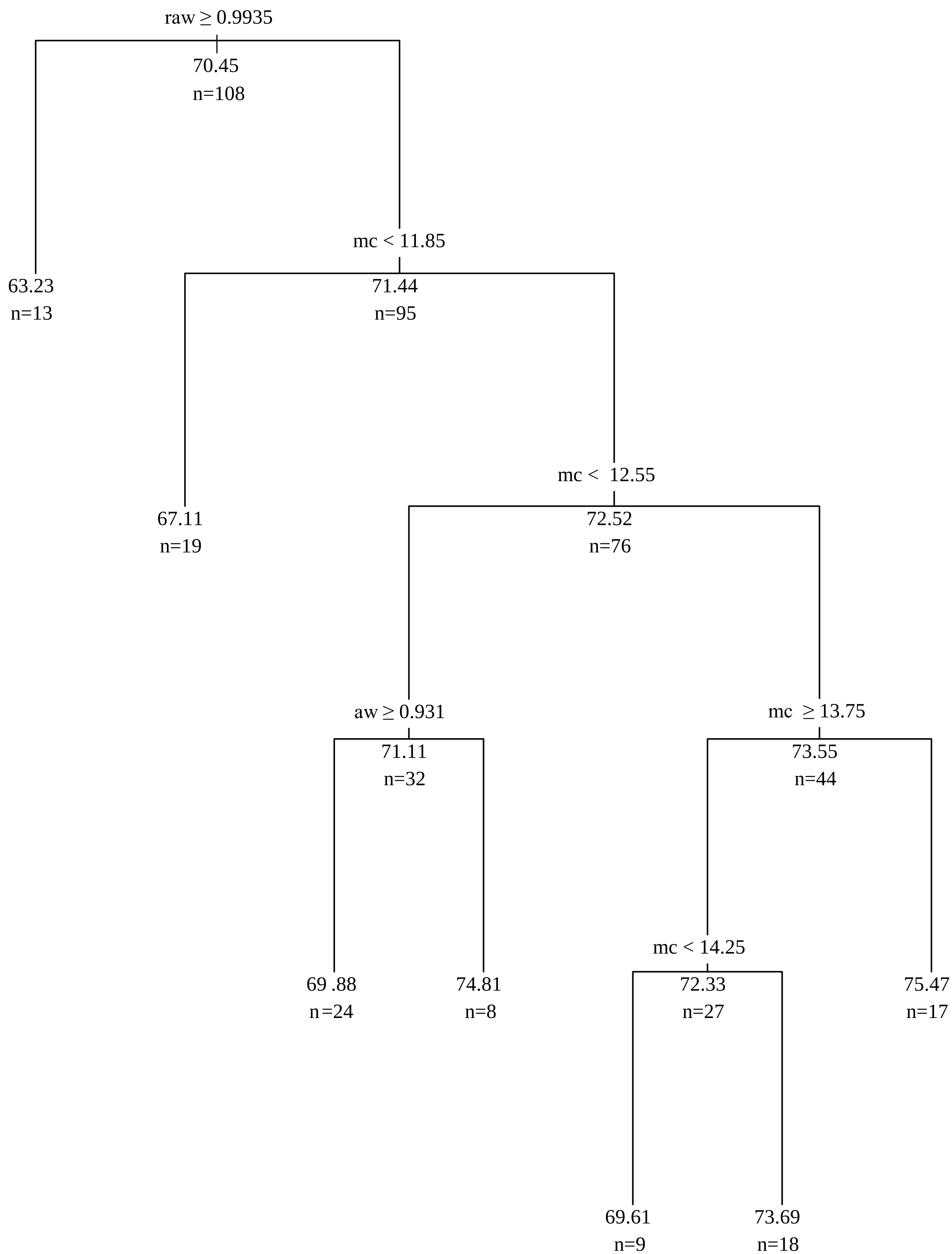

Figure 4.8. CART imputation method decision tree

4.3.1.2 Logarithm of the Ratio of Sensory Score

Table 4.2 presents the results for the sensory score regression utilizing the imputed data for missing sensory score observations. As seen in table 4.2, Sensory Regression 1 included a full set of variables hypothesized to impact sensory scores, while Sensory Regression 2 excludes the logarithmic change of moisture content (lnrmc). The logarithmic change in water activity (lnraw) was statistically significant with and without lnrmc included in the regression. The logarithmic change of moisture content was not statistically significant as seen in the results for Sensory Regression 1 presented in table 4.2.

There was a statistically significant negative effect on the logarithm of the ratio of sensory score (lnrss) from lnraw, indicating that a 1.00 percent decrease in the lnraw leads to a -1.32 percent increase in the lnrss. The negative effect of lnraw on lnrss is because water activity ranges from 0 to 1 and the optimal water activity ranges from 0.5 to 0.59 (Fretheim 2008). The experimental average water activity scores ranged from 0.69 to 0.8, which is above the optimal range. Thus, decreasing water activity is a move in the direction of optimality and is expected to be associated with an increase in sensory score. It is also important to note that for neither the regressions with or without the logarithm of ratio of moisture content (lnrmc), time in storage did not become significant until month 7, indicating that green coffee bean quality was not affected significantly until month 7. The PICS2 dummy variable had a positive coefficient and was not significant, which indicated that lnrss was maintained and PICS did not affect the sensory score change. This also indicated that there was no significant difference in lnrss between PICS2 and PICS3 bag types.

Table 4.2. OLS results on logarithm of change in sensory score

Variable	Sensory Regression 1	Sensory Regression 2
	β	*β*
	(Std. Err.)	*(Std. Err.)*
lnraw	-1.130**	-1.128**
	(0.415)	(0.4023)
lnrmc	0.006619	-
	(0.4015)	(-)
X2	0.05245	0.05249
	(0.05525)	(0.05493)
X3	0.06891	0.06886
	(0.05502)	(0.05467)
X4	-0.03369	-0.03375
	(0.05630)	(0.05588)
X6	0.02575	0.02517
	(0.06507)	(0.05433)
X7	-0.1505**	-0.1507**
	(0.05587)	(0.05485)
PICS2	0.02142	0.02149
	(0.03220)	(0.03177)
Intercept	-0.1465**	-0.1461***
	(0.04874)	(0.04402)
R^2	0.2088	0.2088
Adjusted R^2	0.1449	0.1534
Root MSE	0.1638	0.1630

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

4.3.1.3 Absolute Sensory Score

Table 4.3 presents regression results for analyses of the logarithm of the absolute sensory score. Ordinary Least Squares (OLS) regression analysis was also completed on the logarithm of absolute sensory score (lnss), logarithm of absolute water activity (lnaw), logarithm of absolute moisture content (lnmc), months in storage dummy variables, and PICS dummy variables. Sensory Regression 4 in table 4.3 excluded moisture content in the regression. In Sensory Regression 3, no variable was significant. This is most likely due to the fact that changes in water activity and moisture migration created more detrimental quality effects than the high water activity alone (Kornman 2016). The logarithm of water activity still had a negative coefficient and PICS2 also maintained its statistically insignificant positive coefficient. This indicates that there was still no difference between PICS2 and PICS3 bags at maintaining quality. In Sensory Regression 4, month 7 had a significantly negative affect on the sensory score at the 0.05 probability level, while both water activity and PICS2 remained insignificant.

Table 4.3. OLS results on logarithm of absolute sensory score

Variable	Sensory Regression 3 β *(Std. Err.)*	Sensory Score Regression 4 β *(Std. Err.)*
lnaw	-0.2574	-0.1564
	(0.5740)	(0.2709)
lnmc	0.05661	-
	(0.2833)	(-)
x2	0.06482	0.06705
	(0.04021)	(0.03843)
x3	-0.01815	-0.01602
	(0.03400)	(0.03837)
x4	0.03636	0.03692
	(0.04007)	(0.03978)
x6	-0.06146	-0.06290
	(0.03981)	(0.03896)
x7	-0.08052*	-0.08189*
	(0.03962)	(0.03884)
PICS2	0.01090	0.01114
	(0.02223)	(0.02209)
Intercept	4.018***	4.197***
	(0.9026)	(0.09072)
R^2	0.1878	0.1875
Adjusted R^2	0.1222	0.1306
Root MSE	0.1145	0.1139

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

4.3.2 Water Activity

Table 4.4 presents the results for the water activity regression analysis. The variables PICS2, PICS3, x2, x4, and over were all significantly negative at the 0.001 probability level. The results indicate that water activity of green coffee stored in PICS2 or PICS3[15] bags is maintained. The variable “over” is a dummy variable for observations that belonged to bags that were over 14

[15] No significant mean difference between PICS2 and PICS3 coefficients.

percent moisture content at month 0. “Over” is significantly positive because bags that were over 14 percent moisture content at month 0 were also higher in water activity. Water activity values range from 0 to 1, with the optimal water activity range for green coffee beans being between 0.5 to 0.59 (Fretheim 2008). The average water activity value PICS2 bags was 0.7041, PICS3 bags was 0.7109, and Traditional bags was 0.7604. The negative relationship between the PICS bags and water activity can be viewed positively because it is moving toward the more optimal water activity as assessed by the limited previous literature.

Table 4.4. Water activity regression results

Water Activity Regression	
Variable	*β* *(Std. Err.)*
PICS2	-0.06595***
	(0.003801)
PICS3	-0.06371***
	(0.003943)
x2	-0.01556***
	(0.005080)
x3	-0.01160
	(0.005038)
x4	-0.02153***
	(0.005195)
x6	-0.01673**
	(0.005169)
x7	-0.007458
	(0.005195)
over	0.04343***
	(0.004191)
Intercept	0.7725***
	(0.004189)
R^2	0.7301
Adjusted R^2	0.7160
Root MSE	0.01915

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

Figure 4.9 presents the trends in water activity over time. The figure portrays an overall positive trend for PICS2 and Traditional bags and an overall negative trend for PICS3 bags. When compared to moisture content trends over time, all bag types had negative trends over time as seen in figure 4.10. Because water activity and moisture content are so dependent on the humidity surrounding the green coffee beans, figure 4.11 shows the humidity in Manizales over the experimental time. As seen in figure 4.11, the overall humidity follows a similar downward trend line to the traditional bags' moisture content. The increase in water activity for the traditional bags while the overall atmospheric humidity decreases is most likely due to moisture permeation into the depths of the bag.

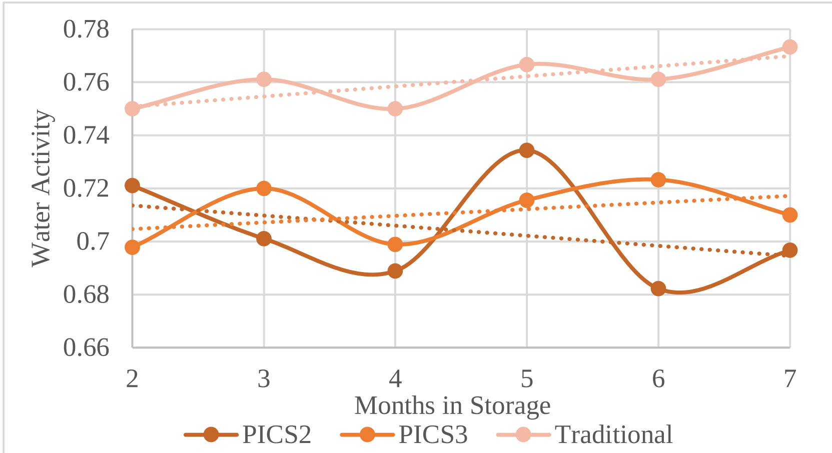

Figure 4.9. Water activity over months in storage

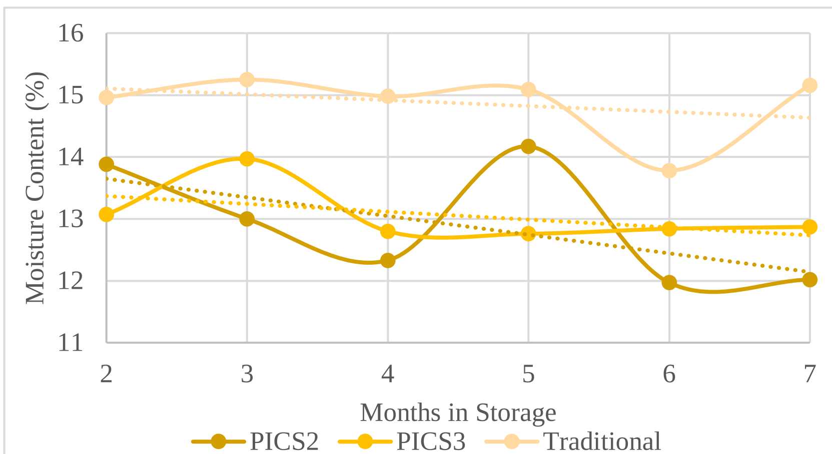

Figure 4.10. Moisture content over months in storage

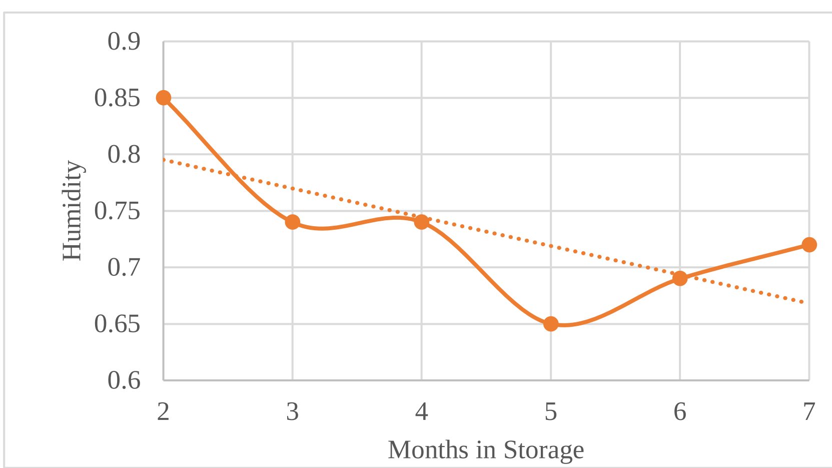

Figure 4.11. Humidity in Manizales, Colombia over months in storage

4.4 Discussion

The quality of green coffee beans stored in PICS2 and PICS3 bags was maintained over the 6 month storage time. PICS bags' layered hermetic system was able to inhibit moisture transfer between the environment and the green coffee beans. Moisture content and water activity were both maintained in the PICS bags, while only water activity was found to have a significant effect on the change in sensory score. However, it is extremely important to coffee farmers that moisture content be maintained because it remains an important component in current Colombian coffee pricing. Green coffee that exceeds 14 percent moisture will not be accepted (not even purchased at a discount) by buying agents at cooperatives. Quality of the green coffee beans was also maintained over time during storage. However, as seen in table 4.2 and table 4.3, month 7 had a significantly negative effect on sensory score. This indicated that storage in both PICS2 bags and PICS3 bags were only effective at maintaining the sensory score until month 6. However, this did not necessarily indicate that the PICS bags failed. Other factors leading to green coffee bean quality degradation that are not controlled in the PICS bags, such as lipid oxidation or enzymatic activity, could easily have caused the downfall of the green coffee bean quality. Out of the ten sensory attributes that make up the sensory score, sweetness and cleanness of cup are the drivers of the quality decrease, as seen in the appendix. Analysis for the seventh month in storage was also only based on nine samples taken from three bags. It is also important to note that because Colombia has two coffee harvest seasons, it is highly unlikely that coffee farmers or cooperatives would store green coffee beans longer than 6 months.

There is also no statistical difference in the quality of green coffee beans stored in PICS2 bags and in PICS3 bags. The regression analysis for both logarithm of the ratio of sensory score and the logarithm of absolute sensory score showed that there was no significant difference between PICS2 and PICS3 bags in terms of either changes in sensory scores or the level of the sensory score, as seen in tables 4.2 and 4.3. This has large implications for the application of PICS bags into the Colombian coffee market. Theoretically, PICS2 bags would have lower manufacturing costs and would be less expensive than PICS3 bags. This in turn would decrease initial investment costs for farmers and cooperatives looking to store their green coffee beans hermetically. Furthermore, coffee growers and buyers are extremely sensitive to the environmental footprint of their industry. Designations such as *Rainforest Friendly*, for example, add value to coffee. The use of plastic bags has to be balanced with the reduction in product losses and increase in product quality in order to be marketable. One less plastic bag enhances the potential sustainability. Thus, demonstrating the effectiveness of PICS2 potentially increases the rate of adoption by lowering both financial and market access risks of switching from Traditional bags to hermetic storage.

Water activity was also found to be a significant quality indicator for green coffee beans. In Sensory Regressions 1 and 2 (see table 4.2), the logarithm of the ratio of water activity was found to have a significant effect on the logarithm of the ratio of sensory score. Also, in Water Activity Regression in table 4.4, analysis showed that PICS2 and PICS3 bags both had significantly negative effects on water activity, which indicates that the green coffee bean water activity was maintained at a lower level and closer to the optimal water activity range of 0.5 to 0.59 by the PICS technology. In table 4.3, which presented the results for the logarithm of absolute sensory score, there was no significant effect between the logarithm of absolute water activity and the logarithm of absolute sensory score, indicating that the changes in water activity are significant rather than the absolute value of water activity. Water activity is widely used in the modern food industry; however, it is not a common measurement in coffee production regions. Water activity has a much more linear relationship to sensory score than moisture content does, which makes it a better indicator for overall quality for green coffee beans (Fretheim 2008). Cupping coffee is a time consuming and expensive process for cooperatives and utilizing water activity as a quick and easy quality indicator that corresponds with the final sensory score can save time and money. Convincing international buyers to accept water activity as a substitute or at least corroborating measure of quality would be an important step.

The effectiveness of PICS bags at maintaining quality during storage has proven to mitigate crop loss. By studying the effects of PICS bags on green coffee storage, results have shown that green coffee bean quality can be maintained during storage in hermetically sealed bags. This study provides a framework for further investigations into green coffee storage in hermetically sealed systems and for the adoption of PICS bags for coffee farmers and cooperatives in Colombia. Further research on hermetic green coffee bean storage should focus on more accurately determining the relationship between sensory score and water activity. The ability to predict the sensory score with a corresponding water activity could allow cuppers and cooperatives to better utilize resources when analyzing green coffee beans. Using an optimal water activity range as an entrance into various markets, somewhat like how they currently utilize moisture content measurements, could greatly decrease the labor and cost associated with cupping all green coffee samples. Another area of focus for additional research on green coffee storage is understanding quality changes further down the supply chain. Exporting and shipping green coffee beans decreases quality further. Understanding hermetic storage’s ability to mitigate quality detriment will be important for maintaining coffee’s quality between the drying to roasting steps.

CHAPTER 5. ECONOMIC ANALYSIS OF GREEN COFFEE BEAN STORAGE

5.1 Introduction

Agricultural investments are on the rise in Colombia due to the newly formed peace accords between the Colombian government and the Revolutionary Armed Forces of Colombia (FARC) (Beeckmans and Emsden 2016). Governmental programs, including agricultural subsidies, rural credit schemes, agro tourism enhancement, and food and nutrition programs, focus on creating an attractive and vibrant industry that lightens the volatility of agricultural markets. These programs provide producers of illegal crops, such as coca and opium poppy, opportunities to switch towards other agricultural commodities, which the government hopes will decrease the drug trade and the corresponding violence (Beeckmans and Emsden 2016). Coffee, a leading Colombian export, is one of the replacements suggested for producers of illegal crops. With coffee production representing 16 percent of the country's GDP and with an estimated 600,000 Colombian coffee farmers, coffee is an important commodity to focus on when attempting to raise economic well-being and limit the drug trade (Gilbert and Gomez 2016). The increase in agricultural investments and focus on new beginnings makes it the ideal time for technological innovation and economic revitalization in Colombia.

While agricultural investments are on the rise in Colombia, coffee farmers still face significant challenges during production and processing. Processing begins as coffee cherries are picked from coffee trees by hand. The coffee cherries are then deskinned and depulped, taking the meat of the cherry away from the bean or seed inside. A sticky film covers the beans, which is then washed away with water or fermented off over time. The coffee is then dried to 10-12 percent moisture content (mc), resulting in green coffee. High humidity in Colombia's Central Mountain Range, where the majority of coffee production resides, plagues coffee farmers and cooperatives during drying and storage. The high humidity makes drying green coffee beans to the desired 10-12 percent moisture content difficult. Once dry, green coffee beans easily reabsorb moisture from the environment. High moisture content green coffee beans (>14 percent) may illustrate off-flavors and mold during storage that affect the final product's quality even after roasting. Cooperatives in Colombia will not purchase beans over 14 percent moisture content. Farmers typically redry these beans but redried beans are generally lower quality.

Green coffee in Colombia is traditionally stored in woven jute sacks that do little to protect the beans from moisture or insect damage. This forces coffee farmers to sell their yield immediately after drying and to accept traditionally lower prices at harvest. The volatility of the international coffee market, low prices, and the inability to store increases the risk of coffee farming and leaves farmers vulnerable until the next harvest period. While farmers are able to sell their green coffee beans immediately after harvest, cooperatives must collect enough volume to be eligible for export and are therefore left exposed to moisture damage. Because coffee has no nutritional content and is a luxury commodity, its price is almost entirely dependent on its quality, which makes maintaining green coffee beans' quality during production, processing, and storage essential.

To maintain the quality, and thus the price, of green coffee beans during storage, quality detriments need to be controlled, such as exposure to moisture and insects. Hermetic storage is a viable option for inhibiting moisture and gas transfer between the environment and the crop stored, and thus maintaining quality. Hermetic storage bags, such as the Purdue Improved Crop Storage (PICS) bags, have proven to be an effective solution at maintaining crop quality, minimizing postharvest loss, and increasing overall income. The three-layer polyethylene bag system drastically reduces the available oxygen inside the bags, suffocating any insects, and maintains the crop’s moisture content by inhibiting moisture transfer from the outside atmosphere (Williams, Murdock, and Baributsa 2017). By ensuring the quality of green coffee beans is maintained over time, farmers and cooperatives can become more flexible and autonomous in their market decisions.

The Colombian peace accords not only look to increase agricultural production, but agro tourism as well to enhance rural incomes in the post-conflict period. Coffee farmers who wish to capitalize on the influx of tourists and sell green or roasted coffee beans directly to consumers must maintain quality during year-round operations and will be forced to store. To maintain quality, farmers must adopt new storage techniques to adhere to Colombia’s high coffee quality standards and be competitive in the consumer tourist market. With the influx of agricultural investments and coffee farmers, diversifying income by storing green coffee to overcome price volatility can enhance the profitability of the Colombian coffee industry.

By studying the effects of PICS bags on green coffee bean prices over time, the volatility of the international coffee market, and how farmers and cooperatives can better navigate it, can be more fully explored. The ability to store green coffee beans without detrimental quality effects gives farmers and cooperatives more control over their production and harvest. This study focuses on evaluating the economic effects of storing green coffee beans in Traditional bags, PICS bags with two layers (PICS2), and PICS bags with three layers (PICS3) over time. PICS2 bags utilize one outside bag layer of woven polypropylene that protects the integrity of the inner bags from physical damage and one inner layer bag made of high-density polyethylene (HDPE) that provides the hermetic seal. PICS3 bags (standard PICS bags) utilize one outside bag layer and two inner HDPE bag layers. As seen in Chapter 4, PICS2 and PICS3 bags maintained overall coffee quality and there was no significant difference in quality between the two bag types. The outcomes of this study will reveal the effects of hermetic storage technology on green coffee bean prices over time and if storing green coffee beans creates positive expected net returns to Colombian coffee farmers and cooperatives.

5.2 Materials and Methods

5.2.1 Sample preparation and experimental procedures

The experiment was conducted at the Universidad de Caldas in Manizales, Colombia from March to October 2017. Seven hundred kilograms of green coffee beans were purchased from the Cooperativa de Caficultores de Manizales in Manizales, Colombia. The green coffee beans were parceled into 50 kilogram quantities into 9 Traditional bags, 9 PICS2 bags, and 9 PICS3 bags, totaling 27 bags. Samples were taken from 3 bags of each technology every month, totaling 9 bags sampled each month. Three representative samples were taken from each sample bag each month, totaling 27 samples per month. Samples were taken to the Cooperativa de Caficultores de Manizales in Chinchiná, Colombia for quality testing and price assignment.

5.2.2 Cooperative pricing schematic

Various quality indicators were analyzed on the green coffee bean samples each month in order to assign a price. Moisture content is measured first and must be within 10-14 percent to be eligible for purchase by the cooperative. Green coffee beans that are over the 14 percent moisture content threshold can either be redried at the farm or farmers can pay 200 COP per kilogram for the cooperative to dry the beans using ovens. Experimental samples over 14 percent moisture content were not redried or analyzed further by the cooperative. All Traditional bag samples were over 14 percent after month 0. There were five PICS bags (2 PICS2 and 3 PICS3 bags) that were over 14 percent moisture content at initial testing at month 0. Because the purpose of PICS bags is to maintain the moisture content over time, it may be misleading to include those bags into the results. Various methods were used to control for these initial high moisture effects, including adding a dummy variable into the regression equations that represented observations sampled from the bags that were over 14 percent moisture content at month 0.

Green coffee bean physical attributes were analyzed to calculate the rendimiento that partially determines the price coffee farmers receive. The rendimiento is determined by taking a 100g sample of green coffee beans, dehulling the beans, and subtracting the weight of the beans that are defective. Defective beans are determined by small size, insect damage, discoloration, or broken beans. The highest rendimiento score possible is 94 (subtracting the weight of the hulls). The score is then entered into an equation that determines the rendimiento, which is then entered to another equation (equation 5.1) along with other attributes to determine the price farmers receive. The price that farmers receive is per arroba[16]. Equation 5.2 utilizes a base price that is determined in the New York Stock Exchange (NYSE) price for coffee and is provided to the cooperatives by the National Federation of Colombian Coffee Growers. The equations are as follows:

$$\frac{7000}{(\text{100g green coffee bean} - \text{weight of broken and damaged beans and hull})} = \text{rendimiento} \qquad (5.1)$$

$$94 \times \text{NYSE Price} \div \text{rendimineto} = \text{price to farmers (per 12.5kg)} \qquad (5.2)$$

Green coffee bean samples deemed high quality during the physical analysis are analyzed further through sensory analysis. Cupping score is determined by roasting green coffee beans, grinding, brewing, and analyzing the samples for ten key sensory characteristics, such as aroma,

[16] Arroba is a Colombian coffee mass measurement corresponding to 12.5 kilograms.

flavor, acidity, balance, cleanness of cup, sweetness, body, uniformity, residual flavor, and cupper's score. Cooperatives use this method to differentiate various lots of green coffee beans and to determine key flavor profiles that importers desire. Samples that cup remarkably high can be sold for higher prices to more influential buyers. Pricing and access to specific markets or buyers on an international level is determined through cupping score and volume.

For this study, the cooperative assigned prices on analyzed samples and provided the base price (NYSE), which was used to determine the price farmers receive in equation 5.2. Samples that were not analyzed due to high moisture content (>14 percent) were assigned the NYSE base price minus the cost of redrying the beans (200 COP per kilogram or 10,000 COP per 50 kilogram bag). Redrying significantly decreases the quality of green coffee beans and thus the price, which indicates that redried samples would not receive prices higher than the base price. Thus, the estimated price represents the maximum price for high moisture content samples.

5.2.3 Price

Green coffee bean experimental prices were analyzed using Ordinary Least Squares (OLS) regression methods. Price data was assigned to each green coffee bean sample by certified cuppers at the Cooperativa de Caficultores de Manizales. The relationship between price and PICS2 bags, PICS3 bags, and time was analyzed using various forms of price. The absolute price premium (ap) was calculated by subtracting the observational price at month x from the base price at month x. The logarithm of the absolute price (lnp) was also analyzed. The absolute price change (p0) was also calculated by subtracting the observation price at month x from the price paid for the green coffee beans at month 0 (87851 COP). Prices were analyzed using two sets of data: the entire data set and a data set excluding bags that were over 14 percent moisture content at month 0.The price analysis equations are as follows.

$$ap_{it} = \beta_0 + \beta_1 PICS2_{it} + \beta_2 PICS3_{it} + \beta_3 x2_t + \beta_4 x3_t + \beta_5 x4_t + \beta_6 x6_t + \beta_7 x7_t + u_{it} \tag{5.3}$$

$$lnp_{it} = \gamma_0 + \gamma_1 PICS2_{it} + \gamma_2 PICS3_{it} + \gamma_3 x2_t + \gamma_4 x3_t + \gamma_5 x4_t + \gamma_6 x6_t + \gamma_7 x7_t + \epsilon_{it} \tag{5.4}$$

Where i and t denote for bag technology and time, ap is the absolute price premium, PICS2 and PICS3 are bag technology dummy variables, x2, x3, etc. are dummy variables for months in storage, u is the error term.

Analysis was also completed utilizing interaction variables between the PICS bag technology (combining both PICS2 and PICS3[17]) and monthly storage dummy variables. The equations are as follows.

$$ap_{it} = \beta_0 + \beta_1 PICS2_{it} + \beta_2 PICS3_{it} + \beta_3 x2_t + \beta_4 x3_t + \beta_5 x4_t + \beta_6 x6_t + \beta_7 x7_t + \beta_8 PICSx2_{it} + \beta_9 PICSx3_{it} + \beta_{10} PICSx4_{it} + \beta_{11} PICSx6_{it} + \beta_{12} PICSx7_{it} + \beta_{13} over_{it} + u_{it} \tag{5.5}$$

$$lnp_{it} = \gamma_0 + \gamma_1 PICS2_{it} + \gamma_2 PICS3_{it} + \gamma_3 x2_t + \gamma_4 x3_t + \gamma_5 x4_t + \gamma_6 x6_t + \gamma_7 x7_t + \gamma_8 PICSx2_{it} + \gamma_9 PICSx3_{it} + \gamma_{10} PICSx4_{it} + \gamma_{11} PICSx6_{it} + \gamma_{12} PICSx7_{it} + \gamma_{13} over_{it} + u_{it} \tag{5.6}$$

5.2.4 Counterfactual

To determine the effect fluctuations in the NYSE coffee prices had on the experimental green coffee bean sample prices, a counterfactual analysis was undertaken. The counterfactual was calculated by using OLS regression methods for analyzing price against PICS2, PICS3, dummy variable for high moisture content bag observations (>14 percent mc at month 0) and the NYSE prices to obtain the equation for price. The framework for that equation is as follows:

$$\text{Price}_{it} = \beta_0 + \beta_1 \text{PICS2}_{it} + \beta_2 \text{PICS3}_{it} + \beta_3 \text{NYSE}_t \tag{5.7}$$

Estimated coefficients calculated from the regression were inserted into the equation for β_0, β_1, β_2 and β_3. The month 0 NYSE base price was inserted into the equation for *NYSE*. To

[17] There was not enough data to analyze bag type and months in storage interactions for the PICS treatments separately.

determine the effects on specific bag types and prices, PICS2 or PICS3 dummy variables were set to 1 or 0 accordingly. The counterfactual estimated the sample prices if the NYSE price had remained constant over the experimental time frame and considered the effect changes in the NYSE base price had on the patterns of the assigned sample prices that were observed. That is, to what extent was the pattern of observed sample prices during the study period a result of the storage treatment versus the underlying market price.

5.2.5 Seasonality

One of the primary benefits of crop storage is the ability to delay marketing from harvest time to a later date when prices are typically higher. Supply of crops is at its highest during harvest time and thus prices are typically low. As supply is utilized, processors must bid the crop out of storage with higher prices. Coffee is a global crop which is produced throughout the tropics of the world. Coffee flowering is driven by rainfall and other weather phenomena. Therefore, the presence of seasonality is not a given because at least some coffee harvest takes place virtually year around in the world. However, Colombia's position in the world market is unique. It is the world's third largest producer of coffee, the world's second largest producer of Arabica coffee, and the world's largest producer of premium grade coffee (Halstead 2017). Thus, seasonality in Colombian coffee production has a strong potential to impact world coffee prices and thus those received by Colombian farmers and cooperatives.

Seasonality analysis was completed to better understand the intra-year fluctuations in Colombian coffee prices and to provide a benchmark storage premium for analysis of the expected return to storage by analyzed storage method. Seasonal patterns of prices were analyzed using historical monthly NYSE coffee prices in COP (per 12.5 kilograms) calculated by weighting the prices of the last 6 days of the month. Data ranged from 1989 to 2017 and was provided by the

National Federation of Coffee Growers of Colombia ("Historical Statistics | Federación Nacional de Cafeteros" 2018). Data was obtained in USD cents/pound and converted into COP pesos per 50 kilograms utilizing monthly exchange rate averages. Monthly effects were aggregated into quarterly dummy variables to reflect harvest and non-harvest periods that span multiple months. Regression analysis was completed utilizing OLS regression methods to estimate the following equation.

$$P_t = \beta_0 + \beta_1 P_{t-1} + \beta_2 P_{t-12} + \beta_3 Q1_t + \beta_4 Q2_t + \beta_5 Q3_t + \beta_6 T + u_t \tag{5.8}$$

Historical prices (P_t), lagged historical prices of 1 month (P_{t-1}), lagged historical prices of 12 months (P_{t-12}), quarter dummy variables (Q1, Q2, Q3, and Q4), and a deterministic time trend (T) were used to specify the model for NYSE prices. Quarter 4 is the largest harvest period and was excluded from the seasonal regression because Q4 is most likely when storage would begin. This also indicates that Q1 and Q2 are important for understanding the changes in prices in prime storage months by portraying the average change in prices in Q1 and Q2 when compared to Q4. The coefficient on Q1 represents the CARRY variable in Net Present Value calculations below.

5.2.6 Net present value

Net present value (NPV) is a measurement of return on investment calculated by comparing the present value of cash outflows to the present value of cash inflows over a period of time (Gallo 2014). In other words, it answers the question of whether or not investing in PICS bags now becomes profitable over time, and if so, when – measured in present time monetary units. Net present value is an appropriate method to analyze the PICS bags' potential return to storage because it translates future cash flows to present values and takes into account the higher buying power of present money than that same money in the future.

Net present value was determined to better understand the PICS bags effect on return to storage and the effects of storage over three years[18]. In other crops, PICS bags have shown to be reusable over years (Coulibaly et al. 2012). Net present value for the first year of storage was determined by the equation below:

$$E(\mathrm{NR1}) = \mathrm{CARRY} * (\%\mathrm{success}) + 10{,}000 * (1 - \%\mathrm{success}) - \mathrm{bag\ cost} \tag{5.9}$$

With *E(NR1)* being the expected first-year net return to storage per bag, *CARRY* being the average price gain in COP per 50 kilogram bag expected from storing coffee from Quarter 4 to Quarter 1 estimated using the above mentioned seasonal regression, *%success* being the percentage of samples of PICS2 and PICS3 bags that were under 14 percent moisture content at month 0, and *10,000* being the cost of redrying a 50 kilogram bag of green coffee beans in COP. The cost of the PICS bags is ~$2.00 USD, which is approximately 5480 COP (Jones, Alexander, and Lowenberg-DeBoer 2011). The equation[19] for second-year expected net return to storage is as follows:

$$E(\mathrm{NR2}) = \frac{\mathrm{CARRY}*(\%\mathrm{success}^2)+10{,}000*(1-\%\mathrm{success} \times \%\mathrm{success})}{(1+\mathrm{Interest\ Rate})^2} \tag{5.10}$$

With the *interest rate* representing discounting back to year one in COP. The equation for year three expected net return to storage is as follows:

$$E(\mathrm{NR3}) = \frac{\mathrm{CARRY}*(\%\mathrm{success}^3)+10{,}000*((1-\%\mathrm{success}) \times (\%\mathrm{success})^2)}{(1+\mathrm{Interest\ Rate})^3} \tag{5.11}$$

Theoretically, PICS2 bags would have lower manufacturing costs due to the decrease in plastic required. Analysis was also completed by determining a theoretical PICS2 bag cost of 1.33 USD (2.00- 2.00/3 USD) and calculating a net return based on the reduced cost bag system. This

[18] Three years is the average lifespan of the PICS bags (Foy and Wafula 2016).
[19] Equation 5.8 and equation 5.9 assume the same percentage of bags will fail each year.

method of reducing bag cost assumes each bag layer costs the same amount and the entire discount would be reflected in the consumer price. Analyzing PICS2 with the full price, PICS3, and PICS2 with the reduced cost leads to a better understanding of overall potential for return to storage.

Break-even calculations were performed to understand how much change in bag cost, %success, interest rate, and net return value would result in a zero net return to storage after three years for PICS2, PICS3 and reduced cost PICS2 bags. The calculations between PICS2 and PICS3 bags vary because of the difference in success rate. PICS2 bags have a 76.2 percent success rate at maintaining the moisture content of green coffee beans under 14 percent after month 0, while PICS3 bags have an 83.3 percent success rate[20]. Break even analysis demonstrates how much the variable must change to just meet the profitability threshold for storage over a three year horizon.

Calculations were also performed to determine the elasticity of the Net Present Value with respect to bag cost, success rate, interest rate, and net return value to understand the effect on prices at the 1 percent change level for PICS2, PICS3, and reduced cost PICS2 bags. Elasticity calculations give a better understanding of the relative impacts of changes in underlying determinants than the break-even calculations. This is because the determinants are all measured in differing units. Elasticities are unitless measurements of the impacts of changing the underlying determinants and are thus directly comparable. Such information is a useful guide to practitioners and researchers in their efforts to improve economic outcomes and sustainability. Elasticity was calculated by shocking the underlying variable by 5 percent of its base value. The net present value was recomputed for the shocked variable, put into an elasticity equation, and divided by 5 to obtain the results for 1 percent elasticity. The equation for elasticity calculations is as follows:

$$\varepsilon = \left(\frac{\Delta \text{NPV}}{\Delta \text{V}}\right) * \left(\frac{\text{V}}{\text{NPV}}\right) \tag{5.12}$$

[20] Bags that were over 14 percent moisture content at month 0 were excluded from the success rate calculation.

5.3 Results

5.3.1 Price

Table 5.1 presents the regression analysis for the variables used in the price analysis. Price Models 1 and 2 utilized the entire data set and Price Models 3 and 4 analyzed the same data set but excluded the observations from bags that were over 14 percent moisture content at month 0. Table 5.1 shows that PICS2 and PICS3 have a significantly positive effect on price[21] when both absolute price premium (ap) (Price Models 1 and 3) and the logarithm of absolute price (lnp) (Price Models 2 and 4) are used as dependent variables and also regardless of whether or not bags with more than 14 percent moisture at month 0 were included. Price Model 3 has larger absolute price premiums than Price Model 1 due to excluding the high moisture content bags, which skewed the Price Model 1 regression. For all models presented in table 5.1, the price increase is higher for PICS2 than for PICS3 when compared to Traditional bags. However that difference in price between PICS2 and PICS3 is not statistically significant[22]. This is important for further return to storage analysis and has important implications for PICS2's effectiveness and profitability. All significant month coefficients were positive. This indicates positive relationship between PICS bags and storage and that time in storage did not have a negative effect on prices.

[21] The exchange rate between COP and USD is ~2740 COP to 1 USD.
[22] Price Model 1 t-statistic for PICS2 and PICS3 bags: 1.423
Price Model 2 t statistic for PICS2 and PICS3 bags: 1.348
Price Model 3 t-statistic for PICS2 and PICS3 bags: 0.7528
Price Model 4 t-statistic for PICS2 and PICS3 bags: 0.6408

Table 5.1. Results for price regression analysis

Variable	Price Model 1 (ap)	Price Model 2 (lnp)	Price Model 3 (ap)	Price Model 4 (lnp)
	β *(Std. Err.)*	*β* *(Std. Err.)*	*β* *(Std. Err.)*	*β* *(Std. Err.)*
PICS2	3404***	0.0422***	4242***	0.0525***
	(419.1)	(0.00521)	(374.8)	(0.00464)
PICS3	2560***	0.0322***	3835***	0.0482***
	(419.2)	(0.00521)	(390.9)	(0.00484)
x2	647.3	0.0281***	747.6	0.0296***
	(577.7)	(0.00719)	(542.62)	(0.00671)
x3	1192*	-0.00316	1381*	-0.0004214
	(572.8)	(0.00713)	(536.9)	(0.00664)
x4	1965***	0.0676***	1743**	0.0648***
	(587.8)	(0.00731)	(537.2)	(0.00665)
x6	138.6	0.0521***	102.5	0.0517***
	(587.77)	(0.00731)	(554.5)	(0.00686)
x7	2358***	-0.00811	2184***	-0.00991
	(587.77)	(0.00731)	(537.2)	(0.00665)
Intercept	-3550***	11.24***	-3526***	11.24***
	(475.8)	(0.005920)	(426.7)	(0.005279)
R^2	0.3901	0.6251	0.6110	0.7541
Adjusted R^2	0.3623	0.6080	0.5890	0.7402
Root MSE	2177.6	0.02709	1815.5	0.02246

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

Table 5.2 presents the results for the price regressions including interaction variables for PICS technology and months in storage dummy variables. Price Model 5 analyzes the absolute price premium (ap) and Price Model 6 analyzes the natural logarithm of price (lnp). Table 5.2 shows the PICS bags received higher prices in months 4 and when compared to months 5 and Traditional bags. The increases in price for months 3 and 7 are most likely due to increases in the NYSE price. The high moisture content bags at month 0 were controlled for by including the “over” dummy variable.

Table 5.2 Results for price regression analysis with interaction variables

Variable	Price Model 5 (ap)	Price Model 6 (lnp)
	β *(Std. Err.)*	*β* *(Std. Err.)*
PICS2	2954*** (675.7)	0.03581*** (0.008335)
PICS3	2516*** (686.5)	0.03093*** (0.008468)
x2	3.27e-11 (757.8)	0.01917* (0.009349)
x3	3.55e-11 (757.8)	-0.01954* (0.009349)
x4	1.98e-11 (757.8)	0.04417*** (0.009349)
x6	2.96e-11 (757.8)	0.05033*** (0.009349)
x7	2.86e-11 (757.8)	-0.03949*** (0.009349)
PICSx2	857.3 (917.1)	0.01190 (0.1131)
PICSx3	1607 (913.6)	0.02222 (0.01127)
PICSx4	2239* (926.9)	0.02619* (0.01143)
PICSx6	117.2 (924.5)	0.001509 (0.01141)
PICSx7	2827** (926.9)	0.03814** (0.01143)
over	-3714*** (353.8)	-0.04644*** (0.004364)
Intercept	-2500*** (535.9)	11.26*** (.006610)
R^2	0.6805	0.8070
Adjusted R^2	0.6525	0.7900
Root MSE	1608	0.01983

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

Figures 5.1 and 5.2 present the distributions of change in price from month 0 (p0). Figure 5.1 presents results analyzed using all data observations and figure 5.2 presents results of the data that excluded the high moisture content bags that were over 14 percent mc at month 0. While almost all samples for all bag types had negative changes in price, PICS bags had a less detrimental effect on price loss than Traditional bags. On average, Traditional bags had a -9601 loss in price, while PICS2 and PICS3 bags only lost -6197 and -7019, respectively. This indicates that PICS bags mitigated price loss due to quality loss during storage.

Figures 5.1 and 5.2 also compare the results using data with all observations and data without high moisture content bag observations (>14 percent mc at month 0). As seen in figure 5.2, excluding the high moisture content bag observations from the distributions decreased the negative effect of storage on price for PICS bags. There were no traditional bags excluded because they all began with less than 14 percent moisture. PICS2's average price change went from -6197 to -5296 and PICS3 bags went from -7019 to -5729. Excluding the high moisture content bags not only presents a clearer result of the ability of PICS bags to maintain price during storage, but it also diminished the discrepancy between PICS2 and PICS3 bags that was present in the distributions of all data observations. Overall, PICS2 and PICS3 had similar distributions and mitigated the decrease in prices during storage when compared to Traditional bags.

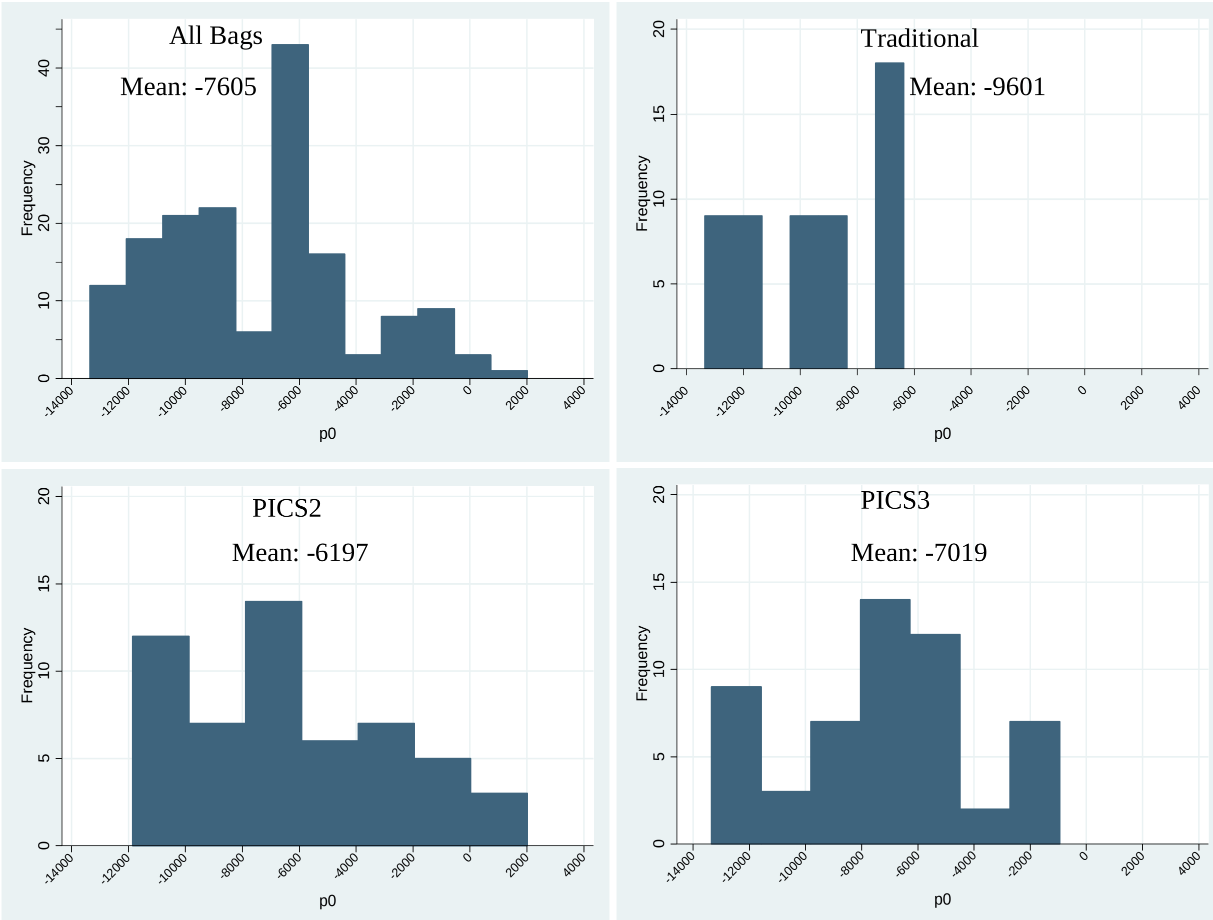

Figure 5.1 Price change distributions based on bag technology for all data observations

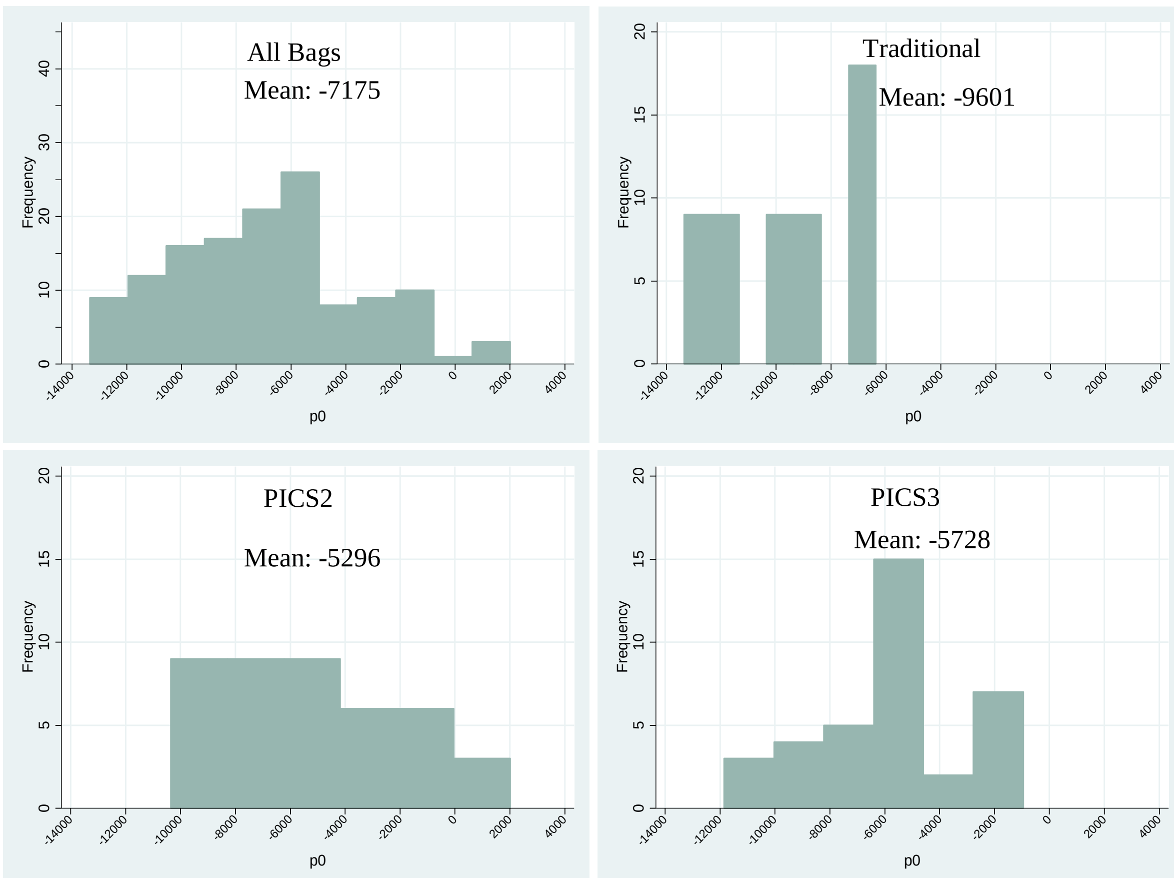

Figure 5.2 Price change distributions based on bag technology for data observations excluding high moisture content bags

Figures 5.3 and 5.4[23] present the distributions of the change in price over the time in storage. Figures 5.3 and 5.4 both present a fairly volatile market, with price changes unstable from month to month. This is mostly likely due to changes in the market price of coffee over the experimental time frame, rather than changes in green coffee bean quality, at least in the case of the PICS treatments. The differences between the two datasets are not as pronounced in the time in storage distributions. However, overall the dataset that excludes high moisture content bags has lower negative price changes than the dataset with all observations. By excluding the bags that were already over 14 percent moisture content at month 0, the rate of failure of the bags is much lower and the maintenance of price during storage is more pronounced. The general skewness toward lower prices versus the initial month led to further regression analysis that adds the NYSE price as an additional concomitant variable in the regressions presented in table 5.1.

[23] As a reminder, bags were only opened every three months. Months 2 and 5, months 3 and 6, and months 4 and 7 are the same bag sets and should be compared accordingly.

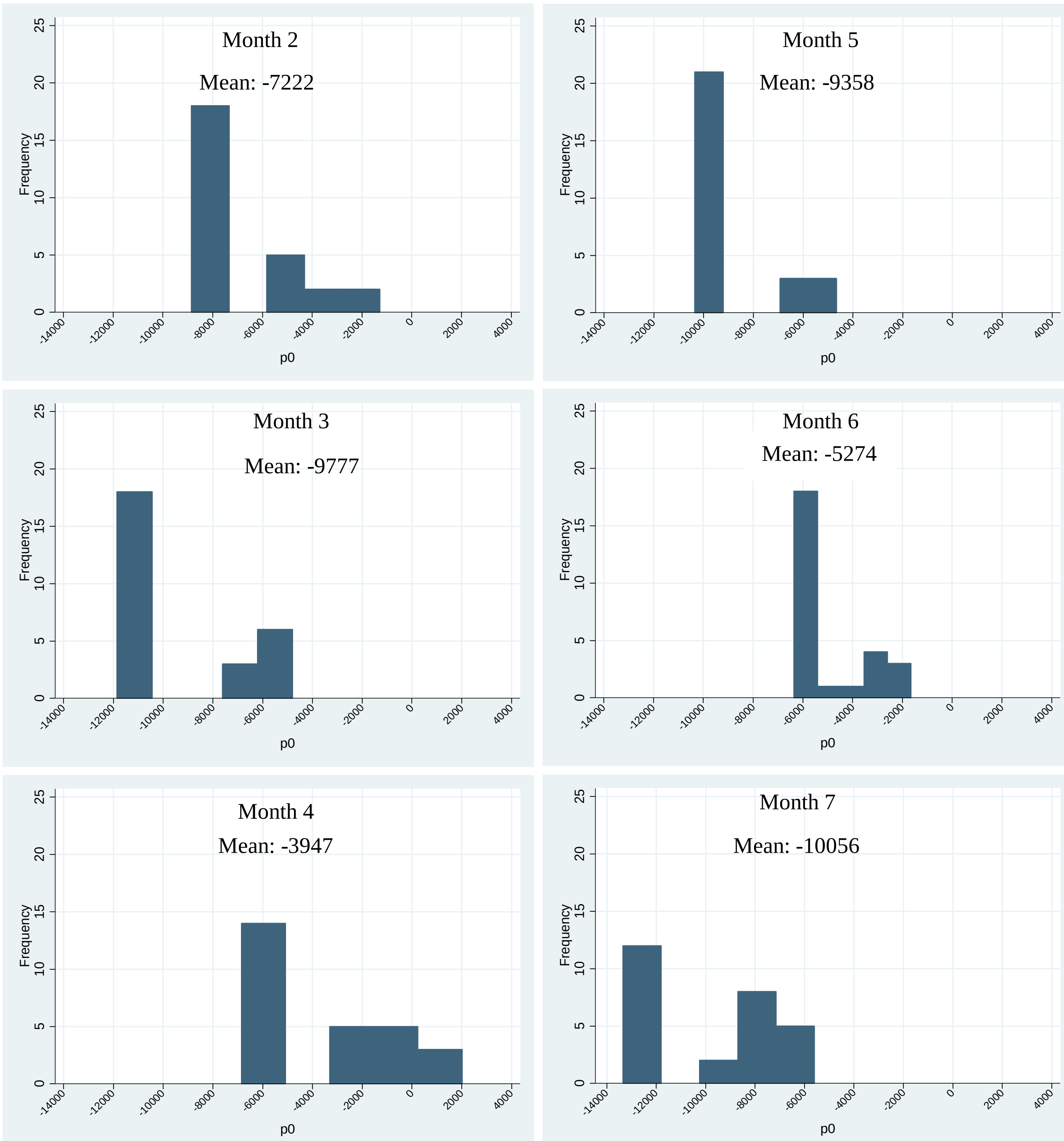

Figure 5.3 Price change distributions based on time in storage for all data observations

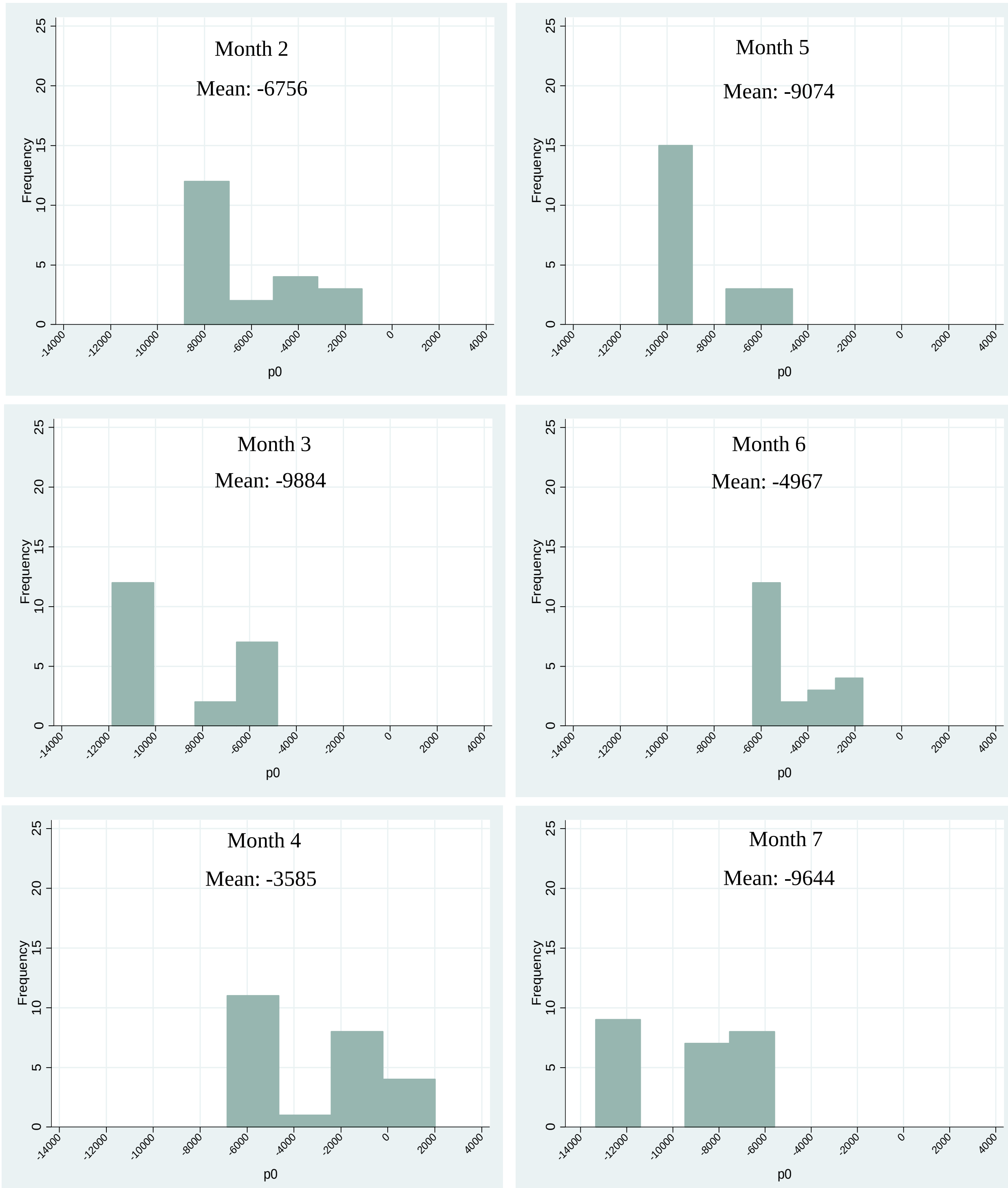

Figure 5.4 Price change distributions based on time in storage for observations excluding high moisture content bags

Figures 5.5 and 5.6 present the price premium (p0) for PICS2 and PICS3 bags on all observations. Figure 5.5 shows that PICS2 bags possess a fairly volatile price premium when compared to PICS3 bags. Month 5 for PICS2 is particularly volatile and possess the same price premium as that of Traditional bags. PICS2 samples for month 5 were all above 14 percent moisture content. Figures 5.7 and 5.8 control for the high moisture content bags for PICS2, however month 5 is still low. PICS3 bags possessed very consistent price premiums over traditional bags, and while overall PICS3's price premium was lower than PICS2, consistency is important as well. Figures 5.7 and 5.8 present the price premiums for PICS2 and PICS3 bags when compared to Traditional bags and excluding high moisture content bag at month 0 observations. The patterns of price changes month to month did not change much between the two datasets. However, the overall price premiums were higher for the excluded high moisture content bag dataset.

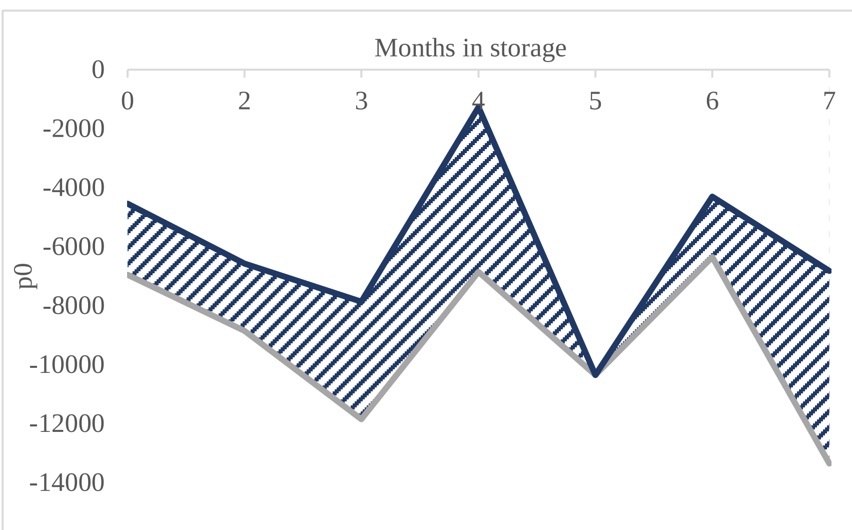

Figure 5.5. Price premium for PICS2 bags compared to Traditional bags

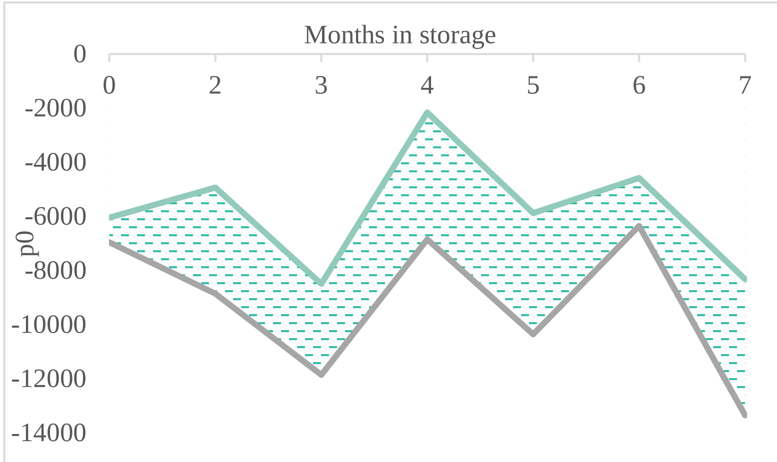

Figure 5.6 Price premium for PICS3 bags compared to Traditional

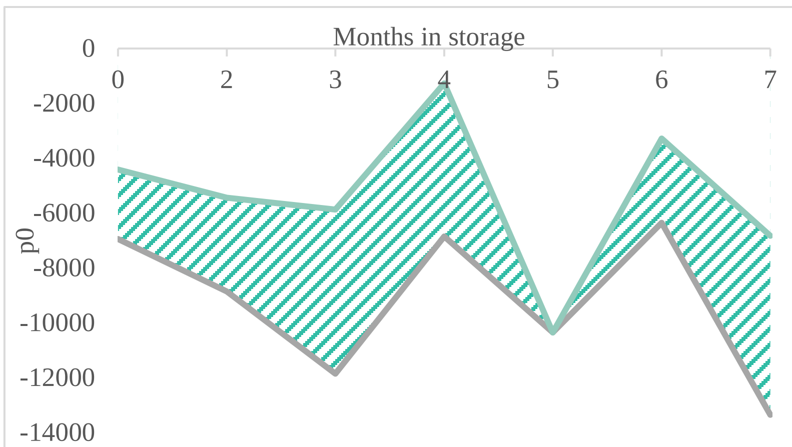

Figure 5.7 Price premium for PICS2 bags compared to Traditional bags and excluding high moisture content bags

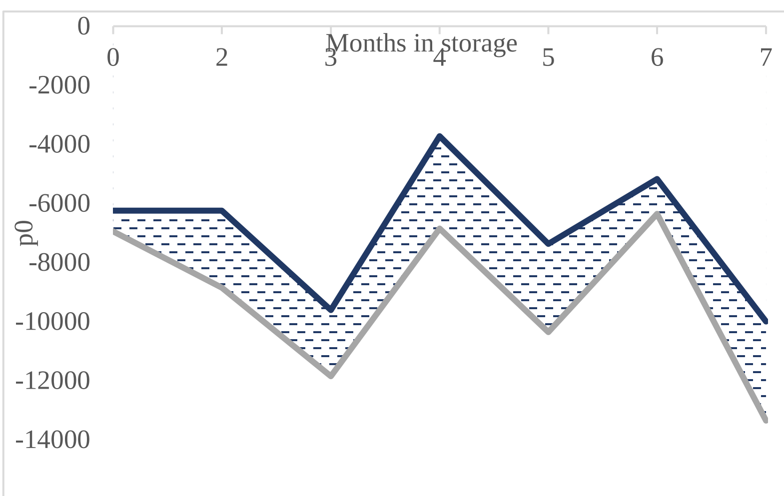

Figure 5.8 Price premium for PICS3 bags compared to Traditional bags and excluding high moisture content bags

5.3.2 Counterfactual

Table 5.3 presents the results for the regression analysis used to calculate the counterfactual for prices to determine how much affect the change in NYSE[24] price had on the prices for the samples. All variables are significant, with PICS2, PICS3, and NY having positive coefficients, while the “over” dummy variable (representing observations from bags that were over 14 percent moisture content at month 0) was negative. This is understandable because the samples were always over 14 percent mc and therefore always received the drying discount and were below the base price.

Table 5.3. Results for counterfactual analysis

Variable	Counterfactual Regression 1 β *(Std. Err.)*
PICS2	4279***
	(551.4)
PICS3	3895***
	(571.3)
NYSE	0.1669**
	(0.05432)
Over	-3939***
	(601.8)
Intercept	57911***
	(6631)
R^2	0.3811
Adjusted R^2	0.3653
Root MSE	2780

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

The results of the counterfactual, along with monthly averages by bag type can be seen in table 5.4. The counterfactual calculations for Traditional, PICS2, and PICS3 bags are much higher than each technologies average price received. This indicates that if the NYSE price had stayed constant over the experimental time frame, the average prices for all bag types would be higher than what was observed.

[24] The NYSE prices used in analysis were constant for all samples in each month. This is why it was not possible to include both monthly dummy variables and the NYSE variables in the same regression equation.

Table 5.4. Results for counterfactual calculations

Variable	Counterfactual Calculations 1							
	Counterfactual	*Average*	*Month 2*	*Month 3*	*Month 4*	*Month 5*	*Month 6*	*Month 7*
Traditional	79398	78250	79000	76000	81000	77500	81500	74500
PICS2	83677	81653	81275	79984	86580	77500	83549	81031
PICS3	83293	80831	81611	78238	84128	80478	82679	77854

5.3.3 Seasonality

Table 5.5 presents the results for the seasonality analysis and shows that Q2 coefficients are not statistically significant and are negative. This indicates that there would not be a positive return to storage for green coffee beans harvested in Q4 and were stored into Q2. However, Q1 is significant and has a positive coefficient. This indicates that on average there is a significantly positive difference between the prices in Q4 and Q1, which indicates, on average, storing green coffee beans to Q1 could lead to higher prices received. The average difference between Q1 and Q4 prices is ~1900COP/ 12.5 kilograms (rounded from 1920), which is ~7600 COP per 50 kilogram bag. This value was represented by the variable *CARRY* in earlier general representations of expected net return to storage (see equation 4). Average annual production for Colombian coffee farmers is 222.5 fifty kilogram bags, which could result in an additional ~1,691,000 COP per year for farmers (Gilbert and Gomez 2016).

Table 5.5. Results for seasonality analysis

Variable	Seasonality Regression β *(Std. Err.)*
P_{t-1}	0.97*** (0.01850)
P_{t-12}	-0.05321** (0.01849)
T	28.96*** (7.479)
Q1	1920* (786.6)
Q2	-575.2 (787.0)
Q3	129.1 (783.3)
Intercept	-2694* (1174)
R^2	0.98
Adjusted R^2	0.98

* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
*** Significant at the 0.001 probability level

As seen in the table 5.5, there is a strong stochastic trend (one month lag in price with a coefficient close to one) imparting a lot of inertia in coffee prices over time. That is, high prices breed high prices and low prices breed low prices, all else constant. The coefficient on P_{t-1} indicates that 97 percent of last month's value carries over to the next month. The inclusion of the 12 month lag incorporates year over year stochastic effects and also enables potential cyclical price effects that may spill over from global economic business cycles and the importance of global trade in Colombian coffee. In fact, all 12 of the roots of the characteristic polynomial of the estimated equation are complex and lie outside the unit circle.[25] The deterministic time trend variable is also highly statistically significant and positive. This term likely captures general global price inflation over the sample period. The regression analysis for seasonality determined that there is significant seasonal price increases on average between Q4 and Q1, which indicates that there is a potential of a positive net return to storage by investing in PICS bags.

5.3.4 Net present value

Table 5.6 presents the results for the net present value analysis and the return to storage over the 3 years[26] of reuse of the PICS bags. The table compares the profitability between bags, farms, and export minimums, which represent profitability for cooperatives. PICS2 bags that were priced the same as PICS3 bags (~$2.00/ bag) were not as profitable over the 3 year horizon but still had a positive net return to storage at 1480 COP per bag. PICS3 bags generated a negative net return in the first year (-1147 COP per bag), but had a positive net return to storage beginning in the second year and become profitable after the second (2250 COP per bag) and third year (4895

[25] Complex root give rise to limit cycles and roots outside the unit circle ensure that the dynamics of the estimated equation are stable.

[26] Due to Colombia having two harvests per year, calculations were also completed for three harvests, rather than for three years. It was found that storing over three years from Q4 into Q1 led to higher net present value return to storage than over three harvests.

COP per bag). PICS2 with the reduced cost (~$1.33/ bag) also had a negative return to storage in the first year (-457.4 COP per bag), but was much lower than the initial loss for the other two bag types. Because the initial cost of the bag was lower, PICS2 reduced cost bags reached a positive return to storage in the second (4062 COP per bag) and third years (3427 COP per bag). This indicates that PICS2 bags, with their lower success rate, are not as profitable as PICS3 bags unless the cost is reduced. PICS3 bags were the most profitable over the three years and farmers could begin to see positive net returns in the second year. Reduced cost PICS2 were the most profitable over two years of storage. However, farmers would lose money in the first year of storage for all bag technologies at the current prices.

Table 5.6. Net present value analysis results

	PICS2	PICS3	Reduced cost PICS2
Year 1			
Per bag	-2404	-1147	-457.4
Per farm	-534996	-255282	-101768
Per export minimum	-818003	-390323	-155603
Year 2			
Per bag	2269	3397	2269
Per farm	504844	755767	504844
Per export minimum	771900	1155559	771900
Year 3			
Per bag	1616	2645	1616
Per farm	359479	588604	359479
Per export minimum	549640	899968	549640
Total			
Per bag	1480	4895	3427
Per farm	329327	1089089	762554
Per export minimum	503537	1665205	1165937

Table 5.7 presents the break-even costs when adjusting the bag cost, success rate, interest rate, and net return to storage to understand how much those variables could change to create a zero net present value over three years. All PICS bags bag cost break-even point are higher than the current bag price of 5814 COP, indicating that all bag types have the potential profitable. It is

also important to note how the success rates can drop and still break even, especially reduced cost PICS2 (67.97 percent). PICS bags effectiveness at mitigating moisture transfer over subsequent uses for green coffee is an area for further research and understanding how low the PICS bags success rate can be to still make a profit is important.

Table 5.7. Net present value break-even analysis results

Variable	PICS2	PICS3	Reduced Cost PICS2
Bag Cost	7294	10709	7294
Success rate	72.79%	72.79%	67.97%
Interest Rate	30.76%	116.6%	170.0%
CARRY	6692	5040	5497

Table 5.8 presents the elasticities for bag cost, success rate, interest rate, and net return to storage for PICS2 bags, PICS3 bags, and PICS2 reduced cost bags. These elasticities are interpreted as the percentage change in three-year NPV from a one percent change in the underlying determinant and are measured around the base values of the determinant. The strongest elasticities belonged to success rate and bag cost. The elasticities were more pronounced in reduced cost and full cost PICS2 bags than in PICS3 bags. This is due to a decrease in marginal net return for success rate. Because the success rate varies from 0-1, the closer the success rate is to 1, the smaller the change effects the overall equation, and therefore the change has a smaller effect on the already

Table 5.8. Net present value elasticity analysis results

Variable	PICS2	PICS3	Reduced Cost PICS2
Bag Cost	-0.7856	-0.2376	-3.915
Success Rate	4.779	1.792	8.717
Interest Rate	-0.08249	-0.03915	-4.314
CARRY	1.674	0.5938	0.02730

5.4 Discussion

This study uses experimental data and data recorded by the National Federation of Coffee Growers in Colombia to estimate the economic effects of storing green coffee beans in PICS2 and PICS3 bags for a period of six months. This study also examines seasonality for the Colombian coffee prices in the NYSE and whether or not that seasonality is strong enough to make an impact on storage patterns and could lead to higher received prices. Net return to storage calculations were completed to estimate the effects of storing green coffee beans in PICS2 and PICS3 bags and whether it could lead to higher prices received per bag, per farm, and per export minimum. This is the first study of its kind to estimate changes in price during green coffee storage and will add to the literature on hermetic storage and the economics of Colombian coffee.

The results of this study suggest that storing green coffee beans in PICS bags is effective in maintaining quality and can lead to higher received prices. The ability to maintain quality is key to obtaining higher price, on average, through storage due to seasonal price patterns. The size of the price premium depends on bag type and the initial cost of the bags. An analysis of Net Present Value revealed that all bag technologies resulted in a negative net return in the first year of storage, which indicates that only a long-term investment will lead to profitable outcomes. PICS3 bags had the best overall outcome in the long-term net return to storage for three years. This is due to PICS3's higher success rate at 83.3 percent. Reduced cost PICS2 (~ 1.33USD/ 50 kilogram bag) bags were the next most profitable. Reduced cost PICS2 bags had the smallest first-year price loss due to the decreased bag cost, which lead to a positive profit over the three years in storage. Both PICS3 and reduced cost PICS2 became profitable in year two of storage. Full-price PICS2 bags only become profitable in the third year. This indicates that without a reduced cost or improvements in performance, PICS2 bags are unlikely to be adopted to store green coffee beans and PICS3 bags would be chosen due to the higher return rates. While this study estimated the cost of PICS2 bags to be 1.33 USD, the highest the PICS2 bags can cost before a negative net return to storage is ~2.66 USD. So unless the price of PICS bags rise from the standard ~2.00 USD per bag, PICS2 bags will remain profitable in the long-term. However, PICS3 bags had overall higher positive return to storage and become profitable faster than full priced PICS2. Therefore, without a reduced cost, PICS3 bags are more profitable in the long term.

Price regressions on absolute price premium and the logarithm of absolute price from the storage experiment showed a positive effect of storing in PICS2 and PICS3 bags when compared to storing in Traditional bags. Because the Traditional bags did little to protect the green coffee beans from moisture damage, there were significant drops in quality and price for Traditional samples. There was also no significant difference between the PICS2 and PICS3 bags when it came to quality, as seen in Chapter 4. Price regressions were analyzed on all data observations and with high moisture content bags excluded from the regressions. The price premiums between the two datasets had limited discrepancies, indicating that the analyses were not highly affected by including the high moisture content bag observations. As seen in figures 5.5, 5.6, 5.7, and 5.8, the price premiums changed only slightly when excluding the high moisture content bag observations. However, price premiums were slightly larger when high moisture content bag observations were excluded. The volatility of the price premiums can also be due to the NYSE price changes. As seen in table 5.4, counterfactual calculations for the absolute prices were higher than the observed average prices per bag technology.

All absolute price premiums were negative, indicating that all prices went down during storage. However, because the experimental time-frame was from March to October, this study only represents half of the harvest year. In the seasonality analysis above in table 5.5, Q1 was the only quarter that was significant, which would be from January to March. The experimental time-frame missed the storage period where prices significantly rise from the main harvest period from October to December. If the study had extended or begun in Q1, the results may have been different and positive absolute price premiums may have been possible. One must also take into account that while farmers have the option to sell immediately upon harvest and therefore bypass any quality or price loss due to moisture exposure, cooperatives must store green coffee beans in order to collect enough volume for export. Green coffee beans at cooperatives are stored in Traditional bags for up to two months. This means that cooperatives are losing on average -9601 COP (~3.50 USD[27]) per arroba or -768 COP per kilogram every month in Traditional storage. With an international export minimum of 17,010 kilograms, this means that cooperatives can lose up to 13,065,040 COP (~4,768 USD) per month in storage for every export (Gilbert and Gomez 2016). For a country that exports nearly 738,000,000 million kilograms of coffee each year, the loss for the Colombian coffee industry can be nearly 566,784,000,000 COP (206,855,474 USD) per month in storage (Gilbert and Gomez 2016). Losses like these can hold back industries and economies. Mitigating price loss during storage at the cooperatives by utilizing PICS bags or other forms of hermetic storage can help to close the gap between production realities and possibilities.

By incorporating hermetic storage into the Colombian coffee industry, farmers and cooperatives can become more independent in their production decisions. Farmers who were forced to sell their harvests immediately upon drying can afford to store part or all of the harvest until prices rise. Cooperatives that have to store green coffee beans until enough volume is collected for export can mitigate quality/price loss due to moisture or insect exposure. Cooperatives are either calculating this price loss into what farmer’s receive for their lots or

[27] The exchange rate between COP and USD is 2740 COP to 1 USD.

cooperatives are purchasing green coffee beans at a higher price than what they can sell it for later. Either way, by minimizing quality/price loss farmers and cooperatives can reap the benefits of increased profits through hermetic storage. It is also important to note that the price premium for storing green coffee beans in hermetic technology will not be constant over time. Once farmers and cooperatives begin storing large volumes of coffee between Q4 and Q1, they may arbitrage the storage premium away. It is important for further study to better understand the Colombian coffee market and at what point the shift in short run supply would trigger a substantial evening out of prices. However, this does not mean that storage would become unprofitable, but that as people's expectations about the value of storage evolve from year to year, the price premium pay outs may be less and storage becomes more risky.

Further research is needed to better understand ways to lower the cost of the PICS bags and make the PICS bags' success rate higher. In the elasticity analysis in table 5.8, success rate had the highest elasticity for PICS2, PICS3, and reduced cost PICS2, 4.779, 1.792, and 8.717, respectively. This indicates that focusing on success rate would create the biggest improvement in the net present value return to storage. PICS bag success rate can be affected by many factors, including the following: ensuring only properly dried green coffee beans are placed into the bags, properly creating the hermetic seal, protecting the bags from being punctured and rodents, and keeping the bags away from direct sunlight (Baributsa et al. 2015). Cooperatives that may be forced to store green coffee beans despite the high humidity should invest in long-term reusable hermetic storage options that allow for the largest net return to storage. While the initial cost of the PICS3 (standard PICS bags) bags creates a negative net return to storage in the first year, PICS3 bags do become profitable after the second year, indicating that farmers and cooperatives can reap the benefits a year after the initial investment. It is also important to better understand the PICS bags effectiveness at mitigating green coffee quality over subsequent uses and whether or not the success rate changes from year to year, which would greatly affect economic success. Another important area for future research is evaluating more closely the quarter 4 to quarter 1 storage seasonality and collecting observational data over those time periods in storage. This would give a better idea of the available premiums in the market.

Effective storage methods can decrease the effects of market volatility in the Colombian coffee industry and make it easier for illicit crop farmers to make the switch. Through the peace accords and influx of agricultural invests, opportunities and technological innovations like the PICS bags can revolutionize the industry. Now is the time for farmers and cooperatives to capitalize on the newfound interest in agriculture.

CHAPTER 6. CONCLUSIONS

Hermetic technology is a viable option for maintaining the quality of green coffee during storage, especially in areas with high humidity. Moisture content remained steady throughout the experimental time frame and, in both PICS2 and PICS3 bags, quality was maintained throughout a storage time of six months. There was also no significant difference between the quality[28] of green coffee stored in PICS2 bags and PICS3 bags, indicating that both can be utilized as viable storage options depending on the market needs. Water activity was also found to be an important quality indicator for green coffee quality and was a better quality indicator than moisture content alone. Changes in water activity were found to be significant, while absolute water activity was not, indicating that fluctuations in water activity has a greater detrimental effect on quality than high water activity alone.

Purdue Improved Crop Storage (PICS) bags were found to have a positive net present value return to storage during the three years of use. PICS3 bags were found to have the highest return to storage over three years. Reduced cost PICS2 bags were found to have the highest return to storage over two years. The success rate difference of the PICS2 and PICS3 bags was the determining factor for why PICS3 bags were more economically successful, even though there was no significant difference between PICS2 and PICS3 green coffee quality. This gives farmers and cooperatives choices based on available initial investment. Since storage is seen as a risk, farmers can opt for the less risky option of reduced cost PICS2 bags with the lower initial cost than PICS3, but would in turn lose out on the higher return to storage in the third year. However, all PICS options are better for quality and price than the standard Traditional bags. There was

[28] No significant mean difference between PICS2 and PICS3 for sensory score, water activity, and price analysis.

significant seasonality in the transition between the major harvest season from October to December to a storage period in January through March. This indicates that higher prices can be received through storage and quality will be maintained by utilizing PICS bags. Sensitivity and elasticity analyses on the net present value calculations found that changes success rate had the largest impact on changes in net present value. Bag cost had the second largest impact. These findings supply a potential framework for further research and are important for farmers, extension educators, and future researchers who are interested in storing green coffee hermetically.

Without the threat of diminishing quality, farmers and cooperatives in Colombia can make decisions based on the market, rather than fear of lower quality coffee and prices. This independence has large implications for the Colombian coffee industry, especially with the rejuvenation of agricultural investment currently happening within the country. By creating an environment where quality is maintained and storage is an option, buyers will have to give higher prices to lure stocks out of storage; giving famers and cooperatives higher profits and more autonomy in their market decisions. Future research that is important for further hermetic storage options into the Colombian coffee industry is needed on the following: defining water activity's relationship with green coffee quality, measuring quality detriment throughout the coffee supply chain, better understanding the Colombian coffee market, and determining the PICS bags quality and economic effectiveness over their three-year lifespan. Next steps for further research should include analyzing water activity in green coffee beans in a laboratory setting, analyzing green coffee prices from the major harvest into a storage period, and better defining a distribution method for the PICS bags in Colombia. Through further research in green coffee storage and the economics of the coffee industry, Colombia's market potential can reach its peak

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APPENDIX

The sensory Two-Staged Least Squares (2SLS) regression equations are presented below. Equations A.1 and A.2 are the first stage regressions in the 2SLS scheme and their fitted values are used to replace their raw values in second stage equation A.3.

$$lnraw_{it} = \beta_0 + \beta_1 PICS3x_{it} + \beta_2 P141_{it} + \beta_3 P142_{it} + \beta_4 P143_{it} + \beta_5 P144_{it} + \beta_6 P148_{it} + \beta_7 P149_{it} + \beta_8 P251_{it} + \beta_9 P253_{it} + \beta_{10} P255_{it} + \beta_{11} P256_{it} + \beta_{12} P257_{it} + u_{it} \quad \text{(A.1)}$$

$$lnrmc_{it} = \beta_0 + \beta_1 PICS3x_{it} + \beta_2 P141_{it} + \beta_3 P142_{it} + \beta_4 P143_{it} + \beta_5 P144_{it} + \beta_6 P148_{it} + \beta_7 P149_{it} + \beta_8 P251_{it} + \beta_9 P253_{it} + \beta_{10} P255_{it} + \beta_{11} P256_{it} + \beta_{12} P257_{it} + u_{it} \quad \text{(A.2)}$$

$$lnrss_{it} = \gamma_0 + \gamma_1 \widehat{lnraw}_{it} + \gamma_2 \widehat{lnrmc}_{it} + \gamma_3 x2_t + \gamma_4 x3_t + \gamma_5 x4_t + \gamma_6 x6_t + \gamma_7 x7_t + \gamma_8 PICS2_{it} + \varepsilon_{it} \quad \text{(A.3)}$$

Table A.1. 2SLS sensory ratio regression analysis with replacing missing sensory score observations with fixed scores

	Sensory Regression 5 50	Sensory Regression 6 50, no mc	Sensory Regression 7 70	Sensory Regression 8 80	Sensory Regression 9 90
Variable	β (Std. Err.)	β (Std. Err.)	β (Std. Err.)	β (Std. Err.)	β (Std. Err.)
lnraw	-2.72***	-2.58***	-0.417	0.575	1.17**
	(0.568)	(0.526)	(0.311)	(0.328)	(0.420)
lnrmc	0.618	-	0.634	0.614	0.956
	(0.920)		(0.515)	(0.543)	(0.695)
X2	0.0423	0.0459	0.0368	0.0347	-0.0152
	(0.0629)	(0.0624)	(0.0353)	(0.0373)	(0.0477)
X3	0.248***	0.244***	0.156***	0.118**	0.0907
	(0.0625)	(0.0619)	(0.0352)	(0.0371)	(0.0475)
X4	-.000411	-0.00663	-0.0744*	-0.102**	-0.129**
	(0.0647)	(0.0637)	(0.0364)	(0.0384)	(0.0491)
X6	0.233*	0.178**	0.169**	0.142*	0.150
	(0.102)	(0.0613)	(0.0571)	(0.0603)	(0.0771)
X7	-0.0456	-0.0597	-0.170***	-0.218***	-0.257***
	(0.0659)	(0.0621)	(0.0371)	(0.0392)	(0.0500)
PICS2	-0.00854	-0.00199	0.0122	0.0199	0.0345
	(0.0376)	(0.0362)	(0.0120)	(0.370)	(0.0284)
Intercept	-0.4120***	-0.3804***	-0.09965**	0.02902	0.1099*
	(0.06884)	(0.05050)	(0.03850)	(0.04065)	(0.05200)
R^2	0.2610	0.2683	0.5372	0.5932	0.5450
Root MSE	0.18492\	0.1840	0.1042	0.1100	0.1406

Table A.2. 2SLS sensory regression analysis on absolute sensory score and replacing missing observations with a fixed score

	Sensory Regression 10 50	Sensory Regression 11 50, no mc
Variable	β (Std. Err.)	β (Std. Err.)
lnaw	-0.450 (1.13)	-3.856*** (0.297)
lnmc	-1.72** (0.556)	- -
X2	0.0936* (0.0418)	0.0182 (0.0400)
X3	0.0385 (0.0411)	-0.0330 (0.0399)
X4	0.0179 (0.0368)	-0.0143 (0.0415)
X6	-0.0146*** (0.0361)	-0.114** (0.0406)
X7	-0.0808* (0.0358)	-0.0499 (0.0404)
PICS2	-0.0261 (0.0199)	-0.0370 (0.0230)
Intercept	8.370*** (1.801)	2.819*** (0.09896)
R^2	0.7222	0.6164
Room MSE	0.10067	0.1183

Table A.3. 2SLS results on ratio variables with imputed missing sensory scores

Variable	Sensory Regression 12 *β* *(Std. Err.)*	Sensory Regression 13 *β* *(Std. Err.)*
lnraw	-1.321**	-1.399**
	(0.471)	(0.439)
lnrmc	-0.369	-
	(0.780)	(-)
X2	0.489	0.0470
	(0.0535)	(0.0531)
X3	0.0707	0.0731
	(0.0533)	(0.0528)
X4	-0.0465	-0.0426
	(0.0552)	(0.0543)
X6	-0.00630	0.0262
	(0.0865)	(0.0524)
X7	-0.164**	-0.156**
	(0.0562)	(0.0530)
PICS2	0.0218	0.0181
	(0.0319)	(0.0308)
Intercept	-0.1375*	-0.1560***
	(0.05835)	0.04312
R^2	0.1980	0.2052
Root MSE	0.15787	0.15716

Table A.4. 2SLS regression results on absolute variables imputed missing sensory scores

	Sensory Regression 14	Sensory Regression 15
Variable	*β* *(Std. Err.)*	*β* *(Std. Err.)*
lnaw	-1.621	-0.136
	(1.27)	(0.275)
lnmc	0.747	-
	(0.624)	(-)
X2	0.0347	0.0675
	(0.0470)	(0.0370)
X3	-0.0468	-0.0156
	(0.0461)	(0.0370)
X4	0.0238	0.0378
	(0.0413)	(0.0385)
X6	-0.0481	-0.0623
	(0.0405)	(0.0376)
X7	-0.0678	-0.0813*
	(0.0402)	(0.0375)
PICS2	0.00660	0.0113
	(0.0222)	(0.0213)
Intercept	1.787	4.203***
	(2.021)	(0.09171)
R^2	0.1372	0.1875