Essays on Global Coffee Supply Chains: Improving Small-Scale Producers' Income

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ABSTRACT OF THE THESIS

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Many of the world's poor still directly or indirectly depend upon agricultural commodities for their income, most of them as small-scale producers. Price volatility and agro-climatic risks over the past several decades, however, have threatened the efforts of most producers to secure sustainable livelihoods. This is particularly true for small-scale coffee producers who constitute 70% of the world's coffee production. Recently, there has been renewed focus on producer organizations as important means of linking producers to markets and ultimately reducing poverty. Yet strategies for producer organizations to make better use of what is already produced, such as improving post-harvest marketing and inventory management have not received much attention. Does collective marketing by small-scale coffee producers improve the prices they receive in world trade? How should they hedge the price risk and judiciously decide how much to sell and carry in inventory? What is the impact of such a hedging strategy relative to the current "selling-all" practice? This dissertation attempts to answer these and other questions by combining empirical and analytical studies. Part I of the dissertation estimates the effect of collective marketing by Kenya Cooperative Coffee Exporters (KCCE) on coffee prices at the auction. We use a 'difference-in-differences' approach to compare coffee prices received by small-scale producers with a comparable group (estates) of producers, both before and after the formation of KCCE. We find evidence to suggest that collective marketing tends to increase coffee prices for small-scale producers. We also apply a life-cycle assessment of the coffee supply chain to identify the greatest source of greenhouse gas emissions and suggest strategies for improvement. In Parts II and III, we provide decision support for post-harvest marketing and inventory management for producer organizations in Kenya and Colombia. Based on empirical evidence, we model KCCE as a price taker and Colombia Coffee Growers Federation (CCGF) as a price maker and derive their optimal inventory hedging strategy for various cost structures. Applying the models to empirical data, we show that for KCCE the optimal hedging strategy outperforms the selling-all strategy quite significantly; while for CCGF, the optimal hedging strategy only outperforms the current practice marginally.

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Just like in the African proverb, “it takes a whole village to raise a child”, this dissertation would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

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Last but not the least, I thank my family for their love and prayers. They gave me the strength to plod on despite my constitution wanting to give up and throw in the towel. Asanteni Sana.

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Chapter 1

Introduction

1.1 World Coffee Supply Chain

Coffee is undoubtedly one of the most important agricultural commodities in world trade. In early 1990s, sales by the 52 coffee exporting countries in Latin America, Africa and Asia were approximately U.S. $10-12 billion with retail sales value, mainly in industrialized countries (e.g., the U.S. and Europe), of about U.S. $30 billion (Osorio, 2002). This made coffee the second most traded commodity worldwide after petroleum in terms of volume and value. The global coffee supply chain consists of exporting countries (i.e., coffee growing countries, mainly developing countries), exporters/importers (traders), roasters, retailers and consumers (mainly in developed countries, such as the U.S. and West Europe). The coffee supply chain is often complex, and varies in different countries but typically includes: See Figure 1.1.

- **Producers:** There are large-scale producers and small-scale producers (working on small plots of land of less than 5 hectares). The small-scale producers harvest the coffee cherries and many do some primary processing (drying or hulling) themselves but others deliver the cherries to cooperative factories for the primary processing.
- **Intermediaries:** Intermediaries may be involved in many aspects of the supply chain. They may handle coffee at any stage between coffee cherries and green beans, they may do some of the primary processing, or they may collect together sufficient quantities of coffee from many individual producers to transport or help selling them to a processor, another intermediary, or to a dealer. There may be as many as five intermediary links in the chain. eg. processors (secondary processing of coffee), exporters (buy coffee from co-operatives or auctions and then sell to dealers).
- **Importers:** Supply the green coffee beans to the roasters.
- **Roasters:** Roast the green coffee beans and also adds value to the product through marketing, branding and packaging activities.
- **Retailers:** Sellers of coffee products to consumers. Retailers can range from large supermarkets, to hotel and catering organisations, to small independent retailers.

While the coffee cherry has a short shelf-life (usually it needs to be processed within 24hrs of harvesting), parchment coffee and green coffee beans can be stored for an indefinite period (e.g., ten years) under proper conditions (Mabbett, 2007; Selmar et al., 2008). As green coffee is more stable than roasted coffee, the roasting process tends to

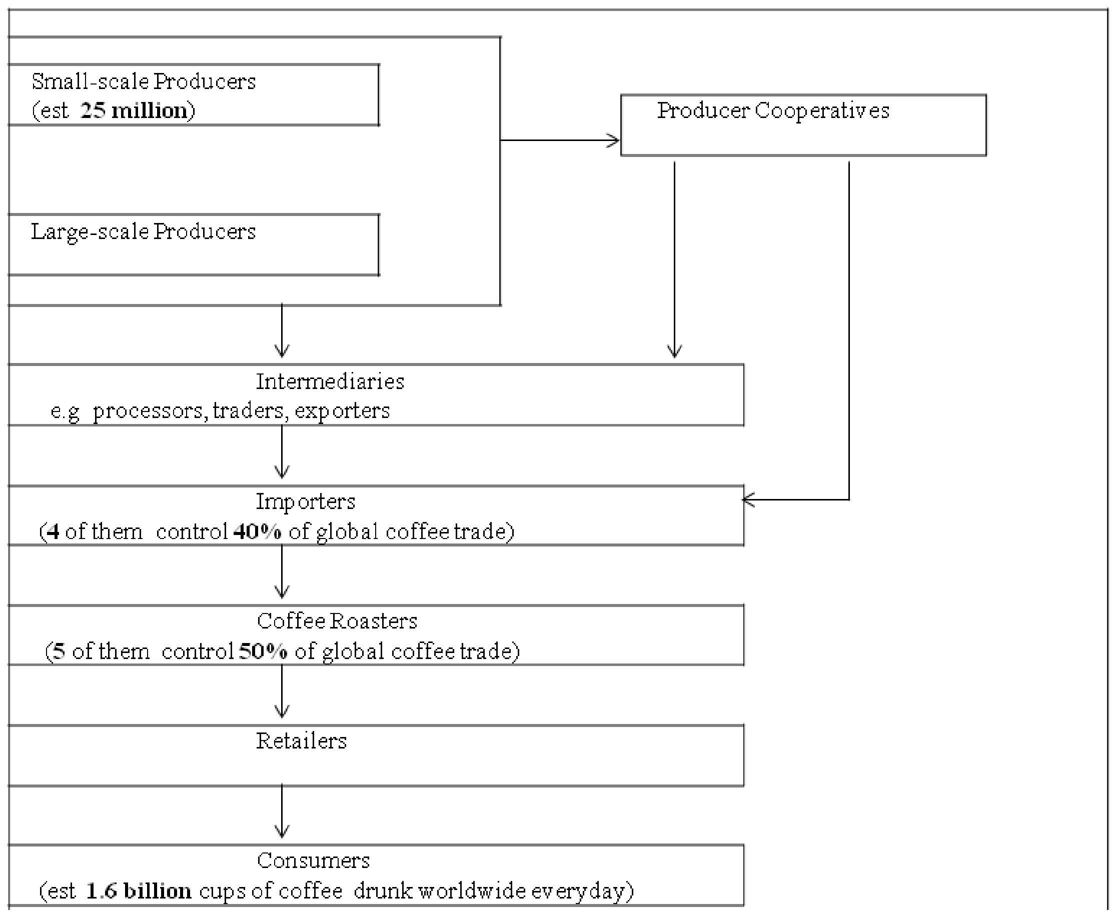


Figure 1.1: Global Coffee Supply Chain

Source: Author's Own Description

take place close to where it will be consumed. This reduces the time that roasted coffee spends in distribution, helping to maximize its shelf life. Roasted coffee beans can be considered fresh for up to one month. Once coffee is ground it is best used immediately. The vast majority of coffee is roasted commercially on a large scale, but some coffee drinkers roast coffee themselves in order to have more control over the freshness and flavor profile of the beans.

Coffee Supply - Exporting Countries

Coffee is almost entirely produced in developing countries (See Figure 1.2). Over 60% of the world's coffee is produced and exported by just four countries: Brazil, Vietnam, Colombia and Indonesia (See Figure 1.3). Coffee requires specific temperature, rainfall, and altitude conditions that limit the growing region to tropical areas. Coffee production (harvest) depends on three factors: acreage, weather and farm input. However, the impact of acreage is not immediate as coffee is a perennial crop that takes 5-6 years to mature. Global coffee production averaged around 6 million tonnes a year during the 1990s. Increased output from Brazil and Vietnam saw production grow to an average of 7.6 million tonnes a year between 2007 and 2011, peaking at a record 8.05 million tonnes in 2010.

An estimated 25 million small-scale producers grow about 70% of the world's coffee. The income from coffee is an important component of their total income and approximately 125 million people around the world depend directly on coffee for their livelihoods (Oxfam, 2001). Most importantly, coffee is a crucial source of foreign exchange for many producing countries in Latin America, Africa and Asia. Over the period 2003-2008 the annual export quantity was ranging from 4.8 million to 5.8 million tonnes while the export value was from $5.7 billion to $14 billion (ICO, 2009).

There are two primary types of coffee, Arabica and Robusta. Arabica accounts for 70% of the world production with a growth rate of 8.5% from 2005-07. Robusta comprises only 30% of the total market, but has been growing at a higher rate of 11.5% from 2005-07. Arabica is considered to be of higher quality and more aromatic, while Robusta

Figure 1.2: Coffee Producing Countries

Source: National Federation of Coffee Growers of Colombia

has a bitter taste and is typically used in low-quality instant blends. More specifically, the International Coffee Organization (ICO) has classified green coffee beans into four categories as shown in Table 1.1:

Colombian milds are produced in Colombia, Kenya and Tanzania with Colombia being the largest producer in this category (see Figure 1.4). Although Kenya's share of world coffee export is insignificant (1-3%), Kenya coffee has earned a longstanding reputation as Arabica – Columbian Mild by its unique taste, aroma and finest quality (Kiwanuka & Zhao, 2009).

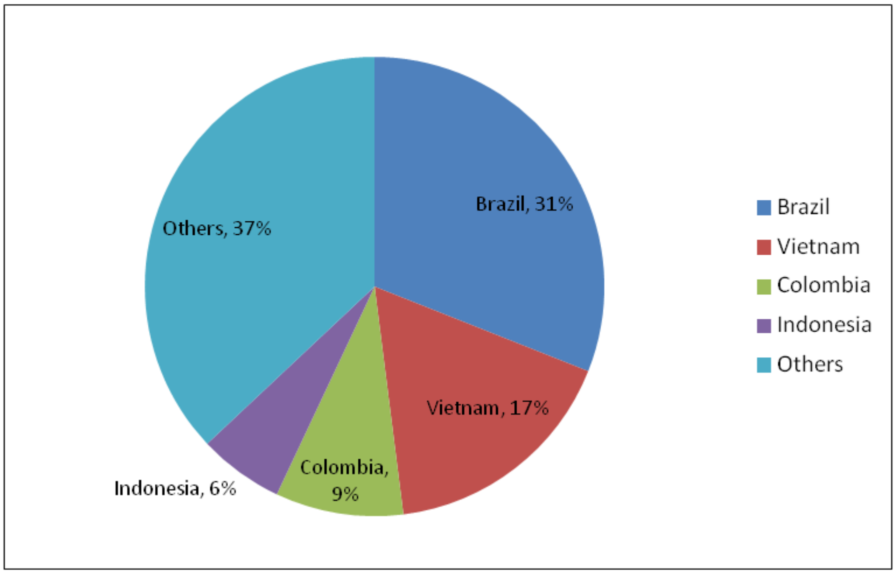


Figure 1.3: Largest Exporters of Coffee (2007-2011)

Source: ICO Statistics

Coffee Consumption - Importing Countries

Coffee consumption has grown steadily for the last decade from 6.3m tonnes in 2000 to 8.1m tonnes in 2010. The US is the biggest importer of coffee, averaging 1.27 million tonnes a year in the period 2006-10, followed by Germany (546,000 tonnes) and Japan (431,000 tonnes) as shown in Figure 1.5. While the growth of coffee consumption has been slow in the more mature markets like the U.S, Japan and Western Europe where consumption grew by 12%, some other countries are increasing their consumption at greater rates, particularly in emerging markets such as Eastern Europe and Asia with 46%.

The world's coffee production is increasing but inherently fluctuating due to unpredictable weather conditions (see Figure 1.6). On the other hand, the world's coffee

Table 1.1: Coffee Categories

Coffee Category	Country Exporting
Arabica- Colombian Milds	Colombia, Kenya, Tanzania
Arabica- Brazilian Naturals	Brazil, Ethiopia, Paraguay
Arabica- Other Milds	Bolivia, Burundi, Costa Rica,
	Jamaica, Cuba, Dominican Republic,
	Ecuador, El Salvador, Guatemala,
	Haiti, Honduras, India
Robusta	Angola, DRC, Ghana, Guinea,
	Liberia, Nigeria, Uganda, Vietnam

consumption has been growing steadily over time (Daviron and Ponte, 2005) and is insensitive to price in the short term (Akiyama and Varangis, 1990).

1.2 Challenges and Trends

The random production and the inelastic consumption of coffee leads to price fluctuations of the green coffee beans in the international market, see Figure 1.7. Thus, coffee exhibits low price elasticities of demand and supply, low income elasticity of demand, high levels of stock hangover and lagged output response (Mohan & Love, 2004) leading to high levels of price volatility.

Price volatility on the international coffee market is a result of the relationship between

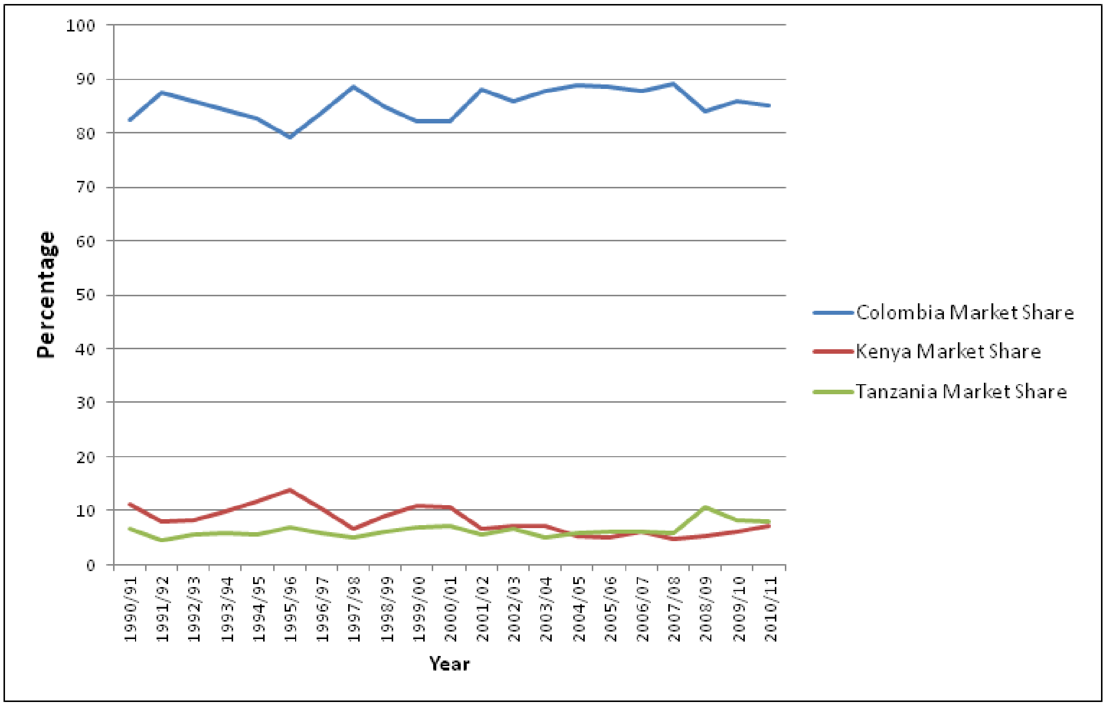


Figure 1.4: Colombian Milds Market Share

Source: ICO Statistics

supply and demand with the principal cause being climatic variability. There is evidence to show that agro-climatic risks are giving rise to a greater frequency of extreme weather events, increasing volatility in the international coffee market. For example, the sharp price spikes in 1975-77 and 1994-97 were due to adverse weather conditions in Brazil. According to Ponte (2002), frosts and droughts in Brazil where some 31% of the world's coffee is grown have normally led to sudden upward movements in coffee prices.

In the past two decades, a number of changes have taken place in the agricultural supply chains of developing countries (Reardon & Barrett, 2000; Swinnen & Maertens, 2007) that are creating new challenges and opportunities for small-scale coffee producers. Glob-

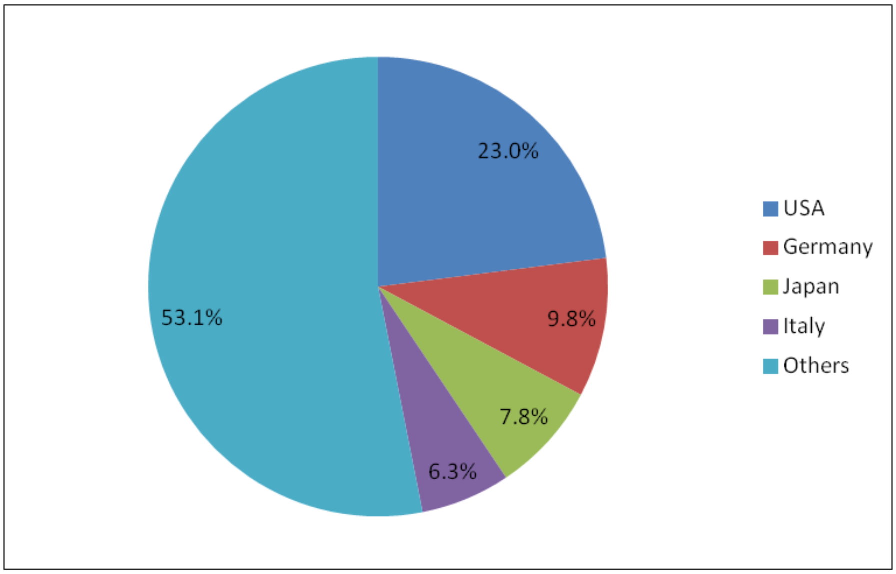


Figure 1.5: Largest Importers of Coffee (2006-2010)

Source: ICO Statistics

alization, the collapse of International Coffee Agreement (ICA), market liberalization, reduced government intervention in market regulation and dismantling of agricultural marketing boards which previously helped producers market their products and access inputs such as credit and fertilizers are among the driving factors of these changes. The combined effect of these changes has been market imperfections manifesting themselves as price volatility; declining terms of trade; and agro-climatic risks, however, threatening the efforts of most small-scale coffee producers to secure sustainable livelihoods.

The Collapse of ICA

Coffee prices were stable and relatively high during the period from 1963 to 1989 when the ICO maintained a regulated quota system for exporters on the basis of an

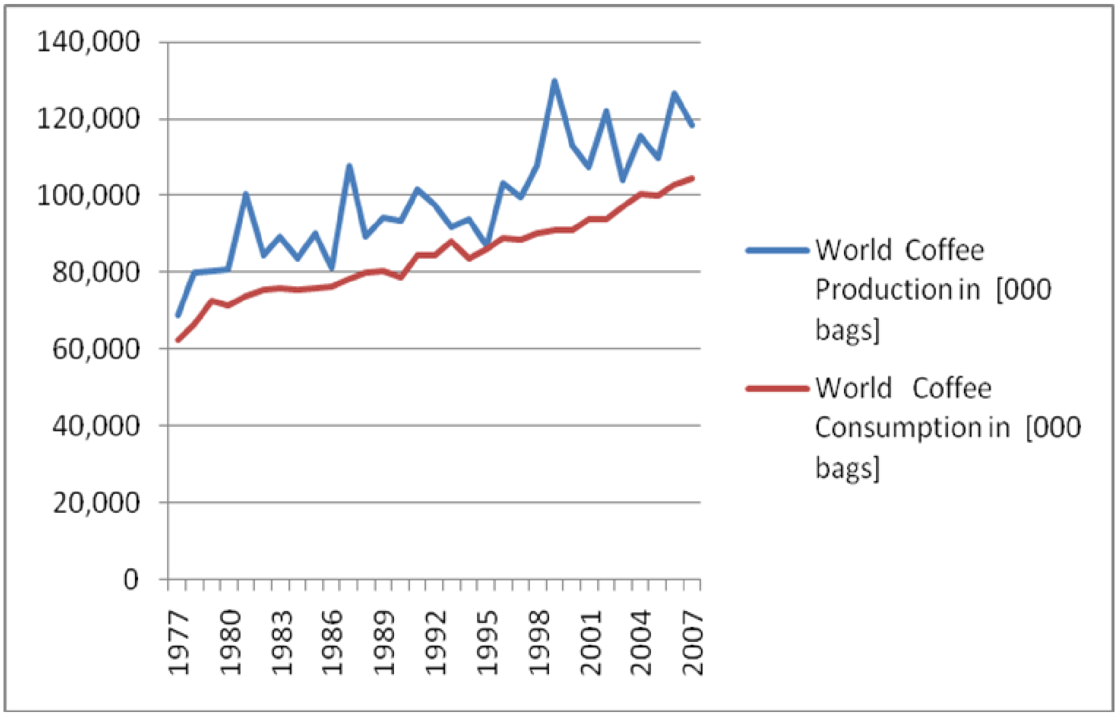


Figure 1.6: World Coffee Production & Consumption

Source: ICO Statistics

International Coffee Agreement (ICA) signed by the major coffee producing nations in 1962. During the ICA years, signatory importing nations could only import coffee from member producing nations, and only up to those nations' quota allocations. The international quota allocations were adjusted in response to world price levels according to a well-publicized schedule. The goal was to restrict a coffee indicator price to a negotiated range, with quotas being tightened in response to price decreases, and suspended when prices increased.

The year 1989 saw the end of a regulated quota system that ensured stable prices in the coffee market (Bates, 1997; Ponte, 2002). Subsequently, volatility became inherent

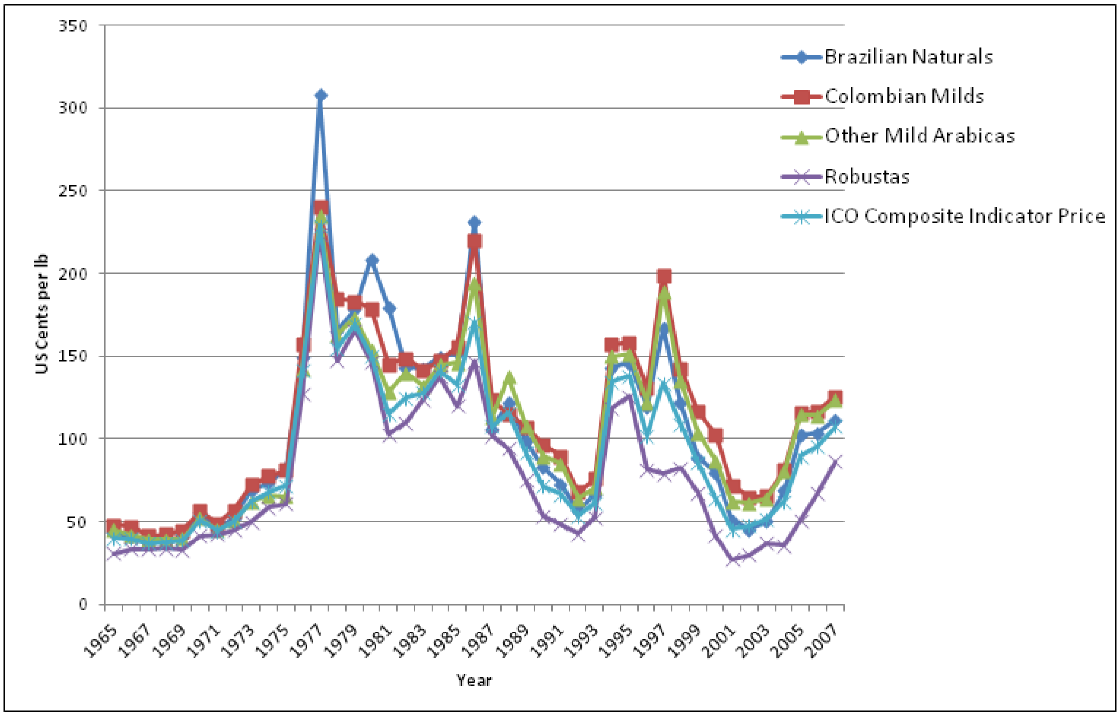


Figure 1.7: Real Indicator Green Coffee Prices in US Cents per lb

Source: ICO Statistics

to the coffee market leading to income volatility and market vulnerability for the small-scale coffee producers. With the end of the ICA regime in 1989, green coffee bean prices started to decline rapidly (Gilbert, 1996; Ponte, 2002). From Figure 1.7, we can observe that the average ICO indicator price for the last five years after the breakdown of the ICA (1990-4) was only \$0.77 per pound, as opposed to \$1.34 per pound in the last five years before the breakdown (1984-8). From 1989 to 1994, excess supply drove the real price of coffee to historically low levels, with export increases among all the major coffee producers. There was a brief recovery after an intense Brazilian frost episode in 1994, which reduced Brazil's coffee exports. Although prices rose between 1994 and 1997, they dropped again drastically starting 1997 when production increases in Vietnam and Brazil triggered what has come to be called the "International coffee crisis" of the 1990s. These low prices had adverse effects on coffee producing countries and coffee producers (Lewin et al., 2004).

Growing Power of Traders

Following the collapse of ICA, the coffee price has been driven primarily by market forces, and declined to a 30-year low in 1999-2001. In addition, increased activity by large funds in commodity futures markets over the past two decades has led to a weakened connection between price determination and market fundamentals resulting in a greater price uncertainty (UNCTAD, 1996). The growing power of traders, roasters and retailers may also have contributed to the long-term price declines for green coffee beans. For example, in 1998 coffee traders Neumann Kaffee and Volcafe controlled 29% of the world market, and the largest four (Neumann Kaffee, Volcafe, Ecom, Drefyus) control 40% of global coffee trade. In the 2000s, mergers and acquisitions have made the market even more concentrated amongst traders. At the roaster level, Nestle and Philip Morris control 49% of the world market share for roasted and instant coffees, while the top five companies control 69% of the market (Bates,1997). While coffee roasters and traders depend fundamentally upon futures markets and hedging operations to manage their price risk profile, small-scale coffee producers do not have access to such tools.

Market liberalization and Dismantling of National Marketing Boards

The impact of price volatility on small-scale coffee producers has been exacerbated by deregulation in national markets and dismantling of marketing boards in producer countries (Ponte, 2001). During the 1980s and 1990s most countries in Sub-Saharan Africa and Latin America implemented structural adjustment reforms, which included liberalization of export crop markets. With the view to improve the efficiency of marketing channels, marketing boards were dismantled and replaced by private traders and exporters. Market liberalization in coffee producing countries was expected to bring benefits to producers through efficient markets.

However, the market liberalization experience varied across countries, both in the scope of reforms and the outcomes with the result being new challenges of exposing small-scale coffee producers to the vagaries of the market as pointed out by Dr. Juan Manuel Santos, the former Finance Minister of Colombia, in the following remark made on 19th May 2003,

> *"I will never tire of saying that the market should be given a free hand. In the case of coffee, however, total liberalization of the market (i.e., the collapse of ICA) has brought only disaster and penury for growers. The free market imposed on us after the breakdown of ICA has favored only the interests of big businesses in the developed world. Neither coffee growers nor final consumers have benefited from this new order".*

Other Challenges in the Coffee Supply Chain

In most developing countries, lack of information on prices and technologies; lack of connections to established market actors; distortions or absence of input and output markets and credit constraints continue to make it difficult for small-scale producers to realize potential gains from the existing market opportunities (De Janvry et al., 1991). This is particularly true with regard to small-scale coffee producers in developing countries.

First, high transaction costs exacerbate the challenges faced by small-scale coffee producers due to their small size especially in quality-conscious and niche markets such as organic or fair trade (Poulton et al., 2005). Access to these markets often requires expensive third party certification, which in turn may be a major barrier to small-scale producer participation (Barrett et al., 2001). Yet, the opportunity for small-scale coffee producers to raise their incomes increasingly depends on their ability to participate successfully in the market.

Second, small-scale coffee producers often have limited technical skills but no access to training or information on market requirements since coffee has transformed into a more buyer driven market (Gereffi, 2001) with middlemen retaining the dominant market power. The middlemen are often considered a barrier to the growth of productivity due to the asymmetry of bargaining power and the lack of transparency (Dorward et al., 2005; Poulton et al., 2005).

Consequently, there is an unequal distribution of wealth among the actors in the coffee supply chain (see Figure 1.8). Whereas coffee is clearly profitable for downstream players, it's very different for the coffee producers themselves. There is evidence to show that the share of the retail value retained by coffee producers has fallen over the decades: in the 1970s, producers retained on average 20% of the retail price of coffee sold while during the coffee crisis, producers received just 1-3% of the retail value (Milford, 2004). Export earnings fell from around \$10 bn to \$6 bn, reducing rural incomes and trapping coffee prodcers and their families in chronic poverty (Oxfam, 2002). Following the recovery of coffee prices, coffee producers might now expect to receive between 7% and 10% of the retail price of coffee.

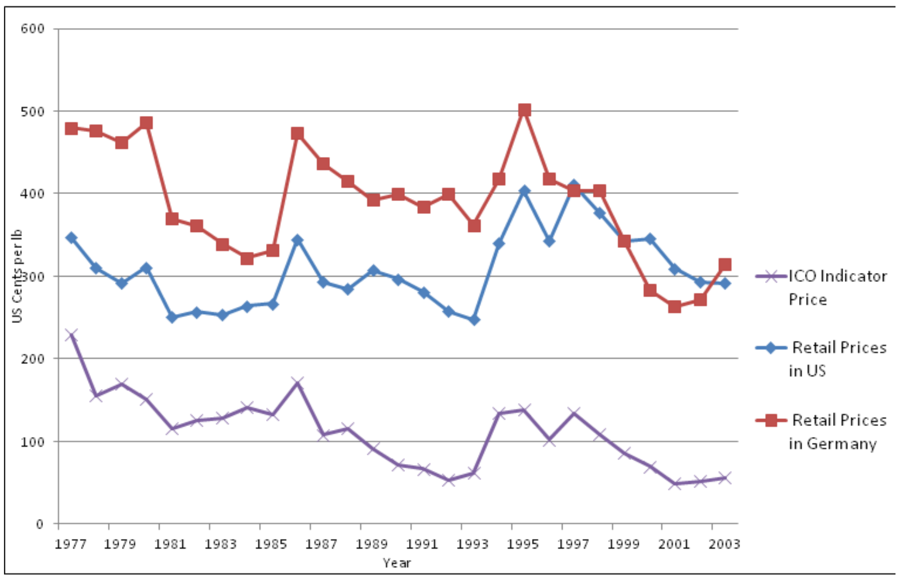


Figure 1.8: Distribution of Wealth

Source: ICO Statistics

Lastly, the negative effects of climate change (increasing temperatures and consequent damage by pests and diseases) are already evident for many of the 25 million coffee producers across the tropics and the \$90 billion US coffee industry (Jaramillo et al., 2011). This has serious implications for coffee production and sustainable livelihoods for the small-scale coffee producers due to the increased cost of pest and disease management further reducing their income.

1.3 Objectives and Main Results

In policy, research and development agendas, there has been renewed interest in collective action for development and for strengthening small-scale producers' access to markets (Collion & Rondot, 1998; Bosc et al., 2001; IFAD, 2003; World Bank, 2007; Shepherd, 2007). In this dissertation, we use the term collective action in the sense of "voluntary action taken by a group to achieve common interests" (Meinzen-Dick & Di Gregorio, 2004). Indeed, the United Nations (UN) declared 2012 as the International Year of Cooperatives, highlighting the contribution of producer organizations to socioeconomic development, and in particular recognizing their impact on poverty reduction.

Cooperation between small-scale producers is presented as a useful tool to increase their access to global markets and obtain the necessary market information (Stockbridge, 2003). Thus, small-scale coffee producers can leverage the power of collective action to (1) pool resources and realize scale economies (Di Gregorio et al., 2004; Markelova et al., 2009; Valentinov, 2007); (2) overcome the high transaction costs resulting from their small size and gain power in bargaining for better terms of trade at the market place (Bosc et.al., 2002); (3) facilitate better environmental management leading to certification and labelling; (4) manage the coffee price risk through post harvest marketing and inventory management of the output.

In this thesis, we focus on coffee producer organizations in Kenya and Colombia. In Kenya, the coffee act of 2001 was amended to allow direct sales of coffee to buyers in 2006 after the coffee producers complained of price manipulation at the auction. However, the small-scale coffee producers failed to benefit from the direct sales option (also known as the “second window”) due to lack of market access, high transaction costs and lack of information on market requirements among others. The small-scale coffee producers then formed the Kenya Cooperative Coffee Exporters (KCCE) in 2009 to market their coffee collectively to buyers both at the auction and via the “second window” option.

In Colombia, the e‘lites allied themselves with small-scale coffee producers to form the Colombian Coffee Growers Federation (CCGF) in 1927. This was after the realization that their competitors were the foreign companies that dominated the coffee export trade and often paid Colombian coffee producers only half of the international price for coffee. CCGF now collectively markets the coffee and provides other services such as coffee research to all the coffee producers.

We consider the following research questions: First, does collective marketing by small-scale coffee producers have an impact on prices and buyer behaviour at the coffee auction? Second, what is the impact of post-harvest marketing and inventory management on the producer organizations’ expected total profits and small-scale coffee producers’ income? Third, what sectors contribute the most green house gas emissions in the coffee supply chain?

Part I of the dissertation answers the first question by estimating the effect of collective marketing on coffee prices at the auction. We use a ‘difference-in-differences’ approach to compare coffee prices received by small-scale producers with a comparable group (estates) of producers, both before and after the formation of KCCE. We present evidence to suggest that collective marketing has a positive impact on coffee prices received by small-scale producers and buyer behaviour at the auction. We also apply life cycle assessment to analyze the environmental impact of the coffee supply chain and find that coffee farming, electric services (utilities), trucking & courier services and the roasted coffee sectors contribute most of the green house gas emissions. We conclude that efforts to reduce green house gas emissions that only focus on direct impacts by the various sectors in the coffee supply chain may not be targeting areas where the most effects are created.

In parts II and III, we show that the answer to the second question depends on whether the producer organization is a price taker or a price maker and the various cost structures. The decision variables are how much coffee to sell and how much inventory to carry over to the next selling period. To this end, we provide decision support for post-harvest marketing and inventory management for producer organizations in Kenya and Colombia. We model KCCE as a price taker and CCGF as a price maker and derive their optimal inventory hedging strategies respectively. We then use real-life data to quantify the impact of the inventory hedging strategy on producers' income by comparing the performance of the optimal selling strategy to the prevailing practice - the selling-all strategy. The results show that for a price taker, the inventory hedging strategy always outperforms the selling-all strategy quite significantly while in the case of a price maker, the optimal selling strategy (the Sell-Down-to policy) only outperforms the selling-all strategy marginally.

Our work is related to agricultural marketing literature which demonstrate successful cooperative marketing for small-scale producers for the dairy and grain sectors in achieving higher prices (Holloway et al., 2000; Bernard et al., 2008). In the agricultural economics and operations management literature, post-harvest inventory management is applied to grain storage decisions and manufactured products respectively. However, for producer organizations in the coffee market there is much less evidence, partly because from case studies and anecdotal evidence we know that cooperatives have not always been successful and partly because analytical research for agricultural products is still rare compared to manufactured products.

Therefore, there is need to enhance the understanding of ways that producer organizations and other forms of collective action improve small-scale coffee producers' income as well as the implications that these findings have for policy. In this dissertation, we posit that the key elements in strategies to promote development and achieve the Millenium Development Goal 1 of eradicating extreme poverty and hunger in coffee producing countries may be the improvement of small-scale producers' access to markets, post-harvest marketing and inventory management to hedge the price risk and environmental management to assure supply of green coffee beans in the long term.

The rest of the dissertation is organized as follows: in Chapter 2 we present the study on collective marketing and environmental management, Chapter 3 provides the post-harvest marketing and inventory management model for KCCE as a price taker while Chapter 4 presents the post-harvest marketing and inventory management model for CCGF as a price maker respectively. We also compare the performance of optimal selling policies to that of the current practice via numerical studies. Finally, Chapter 5.1 concludes the dissertation and provides directions for further research.

Chapter 2

Part I: Collective Marketing and Environmental Management

Coffee is a key export crop in Kenya with 95% of the crop destined for the export market. This makes the coffee industry a very crucial sector to the Kenyan economy providing employment to millions people through its forward and backward linkages. The coffee industry provides livelihoods to an estimated 700,000 small-scale producers with less than 5 hectares of land each and 3,400 estates (large-scale) producers. Small-scale coffee producers represent 3.5 million families organized into producer cooperatives and account for 60% of Kenya's coffee production with the balance from the estates. The crop has been grown in Kenya for over a century since 1893 when it was first introduced in the country. Figure 2.1 shows the main growing area stretches south from the slopes of 17,000-foot Mt. Kenya almost to the capital, Nairobi. There is a smaller coffee-growing region on the slopes of Mt. Elgon, on the border between Uganda and Kenya.

Figure 2.1: Coffee Growing areas in Kenya

Despite the pivotal role played by coffee in Kenya's economy, the sector faces many challenges (see Figure 2.2) that continue to impact on the profitability of the coffee supply chain. Consequently, over the last 20 years coffee production and exports have been on a downward trend from an all time high of 129,300 metric tons in 1987/88 to a low of 42,000 metric tons in 2007/08. This is a decline of 68% (see Figure 2.3). The upswings of production in the 1990s were mainly attributed to increases in coffee prices following drought/frost in Brazil in 1994 and 1998. Paradoxically, the global coffee production has been increasing at an average rate of 3.6% annually in the last decade. Indeed, in the 2006/07 crop year the small-scale coffee producers' production decreased by 66% as compared to the 1987/88 while the estates (large-scale producers) decline was around 44%.

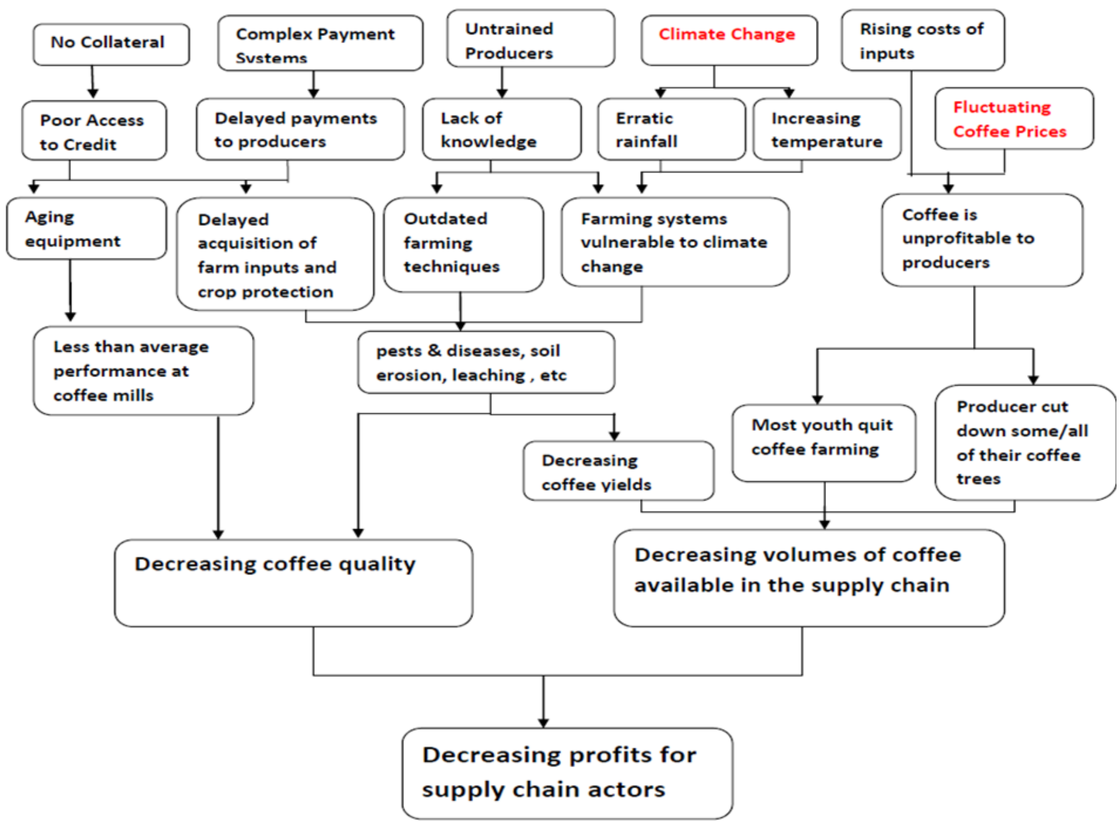


Figure 2.2: Challenges facing Small-Scale Coffee Producers in Kenya

Source: Author's Own Description

In 2009, small-scale producer cooperatives formed a national coffee marketing producer organization (KCCE) to collectively market their coffee in order to benefit from reduced transaction costs, economies of scale and increased bargaining power at the coffee market.

An interview with KCCE CEO Lucy Murumba highlighted some other key challenges for the small-scale producers:

i) The small-scale producers had no information about milling losses and the grade of their coffee from the millers (service providers). This has an impact on the prices the coffee received at the auction since coffee prices depend on the grade (quality). The small-scale producers were dissatisfied with the marketing process of their coffee due to the low prices received, high milling losses and gray areas in grading of their coffee.

ii) The lack of understanding about the international coffee market among the small-scale coffee producers in Kenya is due to poor information flow among players in the supply chain. Also, the small-scale coffee producers get their product to the market with little information about how payments are made, price setting for their coffee at the auction, market demand, international prices and buyer preferences or when their coffee will actually reach the auction. They have little choice in selecting a miller/marketing agent because they do not have reliable access to good information to compare the performance of different millers/marketing agents. A preliminary analysis of the coffee auction data show that 87% of the prices at the auction are below the reserve price. This means that the small-scale producers did not have any bargaining power to negotiate for better prices at the coffee auction.

In the recent past, the coffee market has become more concerned with environmental issues (Tallontore, 2002; Damodaran, 2002) and the demand for high quality, sustainably sourced coffee continues to grow globally. It is important to note that, even if the selling prices are less than the costs of production, the small-scale producers cannot stop coffee

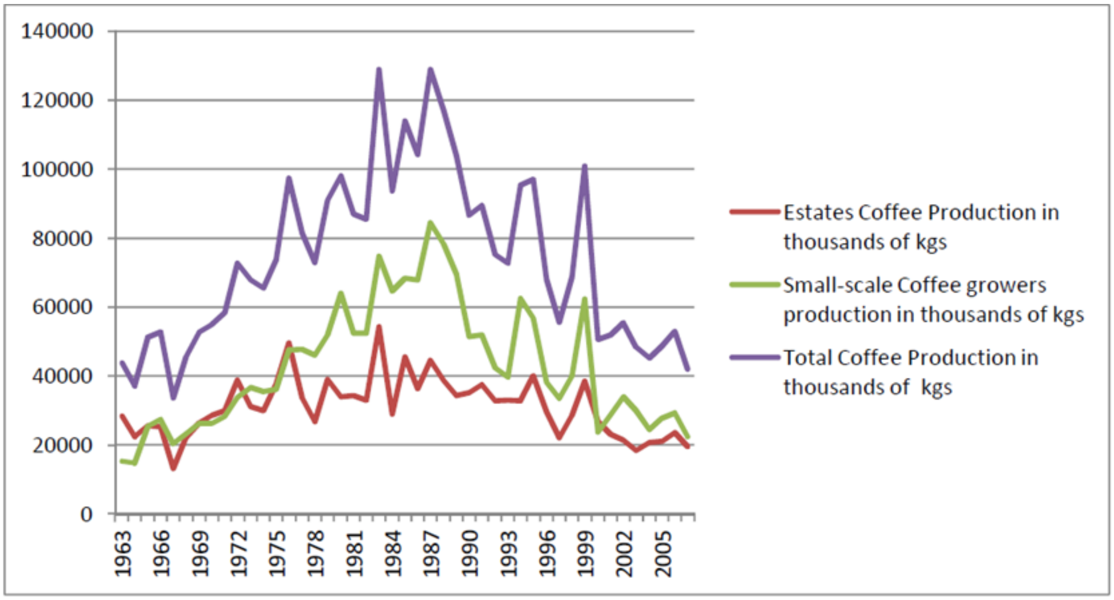


Figure 2.3: Coffee Production in Kenya (1963-2007)

Source: Coffee Board of Kenya Statistics

production immediately with a perennial crop such as coffee. The most likely outcome will be to reduce cost by, for example, paying low wages or engaging child labour. The small-scale producers are also likely to carry out deforestation to increase acreage if expanding land under coffee cultivation achieves economies of scale. In a nutshell, low prices may lead producers to engage in poor environmental management and this in turn damages the profitability of coffee production in the long run due to negative impact on yields and quality.

At the same time, consumers and buyers are willing to pay a price premium for coffee that is cultivated in an environmentally friendly manner. Several Life Cycle Assessment (LCA) studies have been performed on coffee yet few of these address the environmental burdens of coffee production at a life cycle stage under the control of the coffee producer. Humbert et al., (2009) notes that on average one half of the environmental burdens occur at this stage. In addition, little research has been done on the environmental impacts of crop production (Boko et al., 2007) in developing countries. There is need to examine ways in which crops such as coffee production impact on the environment in order to identify the sectors in the coffee production life cycle where environmental improvements can easily be achieved in line with "life cycle thinking".

Cooperatives are institutional arrangements, the importance of which has increased recently to organize small-scale producers in developing countries in the wake of agricultural market liberalization. For cooperatives in the coffee market, however, there is much less evidence of successful producer organizations, partly because empirical research is still rare and partly because from case studies and anecdotal evidence it is known that cooperatives have not always been successful, often due to extensive government interventions (Hussi et al., 1993). Available literature also suggests that producer organizations can fail to mobilize collective action due to either shirking (Hoff & Stiglitz, 1993) or conflicts within the organization (Karantininis & Zago, 2001). Therefore, the overall performance of collective action remains highly contested (World Bank, 2007; Rondot & Collion, 2001) and there is need to enhance the empirical understanding of ways that collective action improves market access to raise small-scale producers' income as well as the implications that these findings have for policy.

In light of the above, we consider three research questions in this part of the dissertation. First, does collective marketing by small-scale producers have a positive impact on coffee prices at the auction? If there is a positive impact on coffee prices, we would also expect it to affect buyer behavior. This motivates our second research question: Are coffee buyers likely to pay higher coffee prices during the KCCE post-registration period? And lastly, what sectors contribute the most green house gas emissions in the coffee supply chain?

Drawing from transaction cost economics, we estimate the impact of collective marketing on coffee prices and buyer behaviour at the coffee auction in Kenya. According to Kherallah & Kirsten (2002), the frequent occurrence of market failure and incomplete markets due to high transaction costs and information asymmetries in developing countries cannot be explained by conventional neo-classical economics and requires an institutional analysis. Transaction cost economics is therefore relevant for agricultural market analysis in developing countries and the changes in the agricultural supply chains in general. As agricultural supply chains become more globalized, with the aftermath of market liberalization and increased deregulation in the industry, the transaction becomes the unit of analysis. Institutional arrangements, such as producer cooperatives in the coffee supply chain are transaction cost minimizing mechanisms. Thus, by marketing collectively producers may offer the members better market access through reduced transaction costs (Russell & Franzel, 2004; Bienabe et al., 2004).

Using a difference-in-difference approach, we compare the prices received by small-scale coffee producers before and after KCCE was registered to market coffee for small-scale producers with the prices received by estates during the same time period. KCCE's registration impact is identified as the estimated difference in differences of coffee prices pre- KCCE registration and post-KCCE registration between the two groups of coffee producers. The difference-in-differences approach allows us to estimate the impact of KCCE's registration on the prices received by small-scale producers at a commodity coffee market.

We show that there is a positive impact of collective marketing by small-scale producers on coffee prices and buyer behaviour at the auction. We then conclude that there is increased information sharing among the market players and reduced transaction costs in searching for information, negotiation and monitoring of transactions. Coffee buyers may also have benefited from less transaction costs when buying from more organized small-scale producers which lead to a positive impact on the coffee prices.

Next, we use the Economic Input-Output life cycle assessment (EIO-LCA) which is quick, cost effective, and yet comprehensive (Lave et al., 1995) to develop a framework for a LCA model. In the case of the global coffee supply chain, EIO-LCA is appropriate because it captures the upstream environmental burdens associated with raw materials acquisition for the manufacturing of coffee and provides a useful initial screening device to prioritize further data collection efforts. The EIO-LCA model provides the ability to assess where the biggest environmental impacts are in the life cycle of coffee production and thus target research programs to address those impacts or improve agric-environmental program delivery by producer organizations, governments and other policy makers. This will be a fundamental step in understanding the potential environmental impacts of the global coffee chain.

We provide estimates of the environmental burdens/impacts in the coffee supply chain and identify the sectors in the coffee production life cycle where the most green house gases are emitted. Further, we observe that efforts to reduce green house gas emissions in the coffee supply chain that only focus on direct impacts by the various sectors may not be targeting areas where the most effects are created. Coffee fruit farming, electric services (utilities), trucking & courier services and the roasted coffee sectors contribute most of the green house gas emissions in the coffee supply chain. The study shows that collective action can play a critical role for small-scale coffee producers not only to get a better price for their products, but also to adapt to the changes in global supply chains as well as a changing climate.

The rest of part I of the dissertation is organized as follows: we review related literature in section 2.1. The section also presents a brief analysis of transaction costs as a conceptual basis for producer organizations in a small-scale producer context and a further background on the Kenyan coffee sector. In section 2.2, we draw attention to a series of key reforms that have taken place in the Kenya coffee supply chain. In addition, we provide a brief overview of LCA in this section. Section 2.3 describes the data and methodological approach. The estimation results for collective marketing and environmental management are presented and discussed in section 2.4 and section 2.5 respectively. Finally, section 2.6 concludes part 1.

2.1 Literature Review

Existing empirical evidence show mixed levels of success for producer organizations, cooperatives and similar forms of collective action in developing countries for small-scale producers participation in agricultural supply chains (Narood et al., 2009; Fischer & Qaim, 2011) and their ability to access markets (Shepherd, 2007).

On the one hand, there are cases where cooperatives have played an important role and small-scale producers have successfully participated in the agricultural supply chain in Latin America and Asia (Roy & Thorat, 2008; Damiani, 2001; Berdegue, 2001). In India, it was shown that marketing cooperatives for grapes reduced transaction costs and contributed to a better bargaining position of small-scales vis-a-vis foreign traders. Similarly, Okello et al., (2007) find that producers organized into producer groups in the green bean sector in Kenya, Ethiopia, and Zambia, were able to gain access to markets in Europe, thus demonstrating the positive role of collective marketing by small-scale producers. Holloway et al., (2000) demonstrated a positive impact of collective marketing for small-scale producers for the dairy sector in Ethiopia while Bernard et al., (2008) find that small-scale grain marketing cooperatives achieve higher prices.

On the other, there are also some recent studies of producer organizations that find mixed performance of producer organizations in improving small-scale producers' access to markets (Obare et al., 2006; Shiferaw et al., 2007). For example, (Markelova et al., 2009; Poulton et al., 2010) find cases where collective action did not improve the producers' gain and where groups dissolved after a disappointing experience. In particular, while cooperative organization has proven successful for the diary sector, food grains and other staples, there is little empirical evidence that the same is true for coffee marketing cooperatives. One exception is Wollni & Zeller (2007) who found that coffee cooperatives in Costa Rica facilitated small-scale producers' participation in specialty coffee markets with higher prices.

2.1.1 Market Access and Small-Scale Producers

The major obstacle facing small-scale producers is the lack of market access (Dorward et al., 2003; Stiglitz, 2002; Poulton et al., 1998). The International Fund for Agricultural Development (IFAD, 2003) considers market access in three dimensions: physical access to markets (distances, costs etc.); structure of the markets (asymmetry of relations between producers, market intermediaries and consumers); and producers' lack of skills, information and organization (market knowledge, prices, bargaining etc.). Thus, small-scale producers' inability to access markets is often attributed to lack of information on prices and technologies, lack of connections to contact market actors, distortions or absence of input and output markets, credit constraints and high transaction costs related to marketing activities (Bienabe et al., 2004; Russell & Franzel, 2004).

Small-scale coffee producers in Kenya face a range of marketing and exchange problems, among which informational constraints are high on the list. Small-scale coffee producers experience a weak bargaining position vis-a -vis traders because often they do not have timely access to salient and accurate information on prices, locations of effective demand, nor on preferred quality characteristics of the coffee produce. In addition, most of the literature related to small-scale producer agricultural marketing e.g. Dorward et.al., (1998), IFAD, (2003) and Jayne et.al., (2002) reiterates that the problem of market access is linked to the following constraints: price risk and uncertainty, difficulties of contract enforcement, cost of bulking small dispersed quantities of produce and inability to meet standards.

2.1.2 Transaction Costs and Producer Cooperatives

Transaction costs include the costs of searching for a buyer with whom to exchange, screening potential buyers to ascertain their trustworthiness, bargaining with potential buyers to reach an agreement, transferring the product, monitoring the agreement to see that its conditions are fulfilled, and enforcing the exchange agreement. All transaction costs derive from a combination of bounded rationality (which reflects both imperfect information and a limited capacity to analyze it) and opportunism, which Williamson (1996) defines as "self-interest seeking with guile".

There is growing evidence that producer cooperatives offer one way for small-scale producers to participate in the market more effectively. Acting collectively, small-scale producers may be able to reduce the transaction costs of accessing inputs and outputs, obtain the relevant market information, secure access to new technologies, and tap into high value markets, allowing them to compete with larger producers (Stockbridge et al., 2003). Moreover, there is evidence that collective action can enable small-scale producers reduce barriers to entry into markets by improving their bargaining power with buyers or sellers (Thorp et al., 2005; Kherallah et al., 2002; Cook, 1995; Cook & Iliopoulos, 2000)

A review of agricultural marketing literature (Bienabe et al., 2004; Russell & Franzel, 2004) reveals that collective marketing in agricultural supply chains may enable the members of a cooperative to have better market access through reduced transaction costs by: (a) increased negotiation/bargaining power for higher prices; (b) increased information sharing; and (c) reduced transaction costs involved in searching for information, negotiation and monitoring of transactions.

2.1.3 Life Cycle Analysis (LCA)

Climate change represents an immediate and unprecedented threat to agriculture (IPCC, 2007). In the recent past, the coffee berry borer (Hypothenemus hampei) has remained a major concern in Arabica coffee production. According to Jaramillo et al., (2011), the pest attacks the coffee beans which are the marketable product resulting in considerable losses exceeding $500 million annually to the global coffee industry. Arabica accounts for 70% of the world's production of high quality coffee (Davis et al., 2006) and it is susceptible to several pests and disease causing pathogens.

Life Cycle Analysis provides a tool to assess and manage the environmental impacts of coffee production and processing for the small-scale producer cooperatives. Although, several LCA studies have been performed on coffee (DeMonte et al., 2005; Humbert et al., 2009; Salomone, 2003) few of these address environmental burdens of coffee production at a life cycle stage under the control of the coffee producer. It is also important to note that most of these studies use conventional LCA methodologies that suffer from problems of subjective boundary definition, inflexibility, high cost and data confidentiality (Joshi, 2000).

In this study, we use the EIO-LCA that is based on a well established tool in economic analysis (the input-output technique) to estimate the greenhouse gas emissions from the coffee supply chain. This may enable KCCE examine ways in which coffee production and processing impacts on the environment. In addition, it presents an opportunity for the small-scale producers through the cooperative to collectively identify ways to reduce those impacts and improve the sustainability of coffee production in line with"life cycle thinking". We present a summary of the literature review on LCA of coffee production and consumption in Table 2.1 below for more details:

Reference	**Evaluation**
Coltro et al., (2006)	Environmental profile of Brazilian green coffee-conventional LCA
Chanakya and De Alwis (2004)	Describes environmental issues and management in primary coffee processing in India- not a LCA
De Monte et al., (2005)	Compares the impacts at a roasting plant of alternative packaging systems at a roasting plant-conventional LCA
Humbert et al., (2009)	A comparison of environmental burdens associated with spray dried, drip filter and capsule espresso coffee-conventional LCA
Salomone (2003)	Environmental impacts connected to a coffee business in Sicily that included all life cycle steps- conventional LCA

Table 2.1: Literature Review Summary

2.2 Coffee Market Reforms

Before marketing their crop, small-scale producers' coffee is processed at the primary processing pulping stations and dried into "parchment" coffee. The parchment must then milled during the secondary processing in a curing factory to reveal the "clean" coffee beans, which are graded based on international standards and auctioned for export. Small-scale coffee producers face multiple transactions in this system. First, they may require finance to purchase inputs for coffee production and will make some transactions to purchase inputs. Second, the small-scale producers sell parchment coffee, receiving the export price less marketing fees and other costs charged by the marketing agents.

After coffee is sold, the marketing agents receive payments from the buyers within seven days from the date of sale for onward payment to coffee producers within 14 days as per the law. However, this is never the case in many instances and there have been complaints of delayed payments for even over six months especially for small-scale coffee producers. The coffee supply chain is shown in Figure 2.4.

Prior to 2002, the market for coffee was completely controlled by government organizations. Small-scale producers received inputs at their primary cooperative societies, delivered coffee to primary cooperative societies and received an initial payment based on a government-mandated price. Parchment coffee was transported from cooperative societies to Kenya Planters Cooperative Union (KPCU) for secondary processing. This was a government-supported cooperative union. After milling and grading, the "clean" coffee was then delivered to the Kenya Coffee Auction where private exporters were

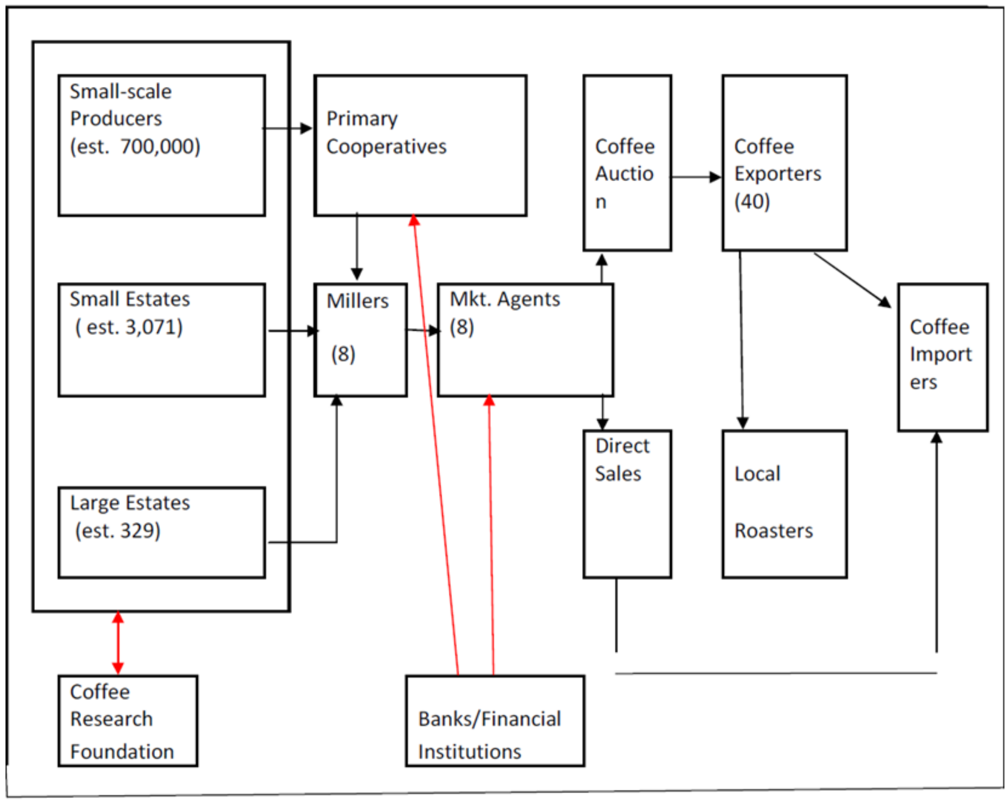


Figure 2.4: The Kenya Coffee Supply Chain

Source: Author's Own Description

allowed to purchase the coffee. Auction realizations were remitted to the cooperative societies, which deducted processing costs and charges for input credit and transferred remaining funds to small-scale producers. In this system, the credit, input, and output transactions were linked.

In April 2002, a new coffee act was passed in Kenya that allowed private sector participation in domestic trading and processing (milling) of coffee (referred to as market liberalization hereafter). Since then private traders, most of whom had been coffee exporters prior to market liberalization quickly entered the domestic market, and gained power to the detriment of the small-scale producers. But overall, Kenya's coffee supply chain is characterized by extreme fragmentation at the producer level and a heavy concentration of powerful players further downstream (e.g., millers, marketing agents). Estates are vertically integrated, with most of them owning their own primary processing plants and their size allows them to have some bargaining power with the marketing agents.

Prior to market liberalization, the Coffee Board of Kenya (CBK) was the sole marketing agent. After market liberalization, CBK was no longer a marketing agent but relegated to an industry regulator and a number of private marketing agents were licensed to perform the coffee marketing function. Multinational corporations (MNCs) now dominate domestic procurement, secondary processing (milling) and export markets. Currently, there are eight marketing agents with a majority of them being subsidiaries of the MNCs. The principal role of the marketing agents is to: collect, prepare and catalogue coffee for auction; warehouse and catalogue coffee in preparation for auction; prepare and make available samples for licensed buyers to auction; represent growers during auction and; collect and distribute proceeds to growers following final sales.

In November 2006, the Kenyan government authorized a new legislation known as "Second Window" that allowed coffee producers to have an alternative marketing channel alongside the coffee auction. However, the small-scale coffee producers lacked the capacity and negotiation skills to exploit the opportunities presented by the direct sales marketing channel. They still had to use existing marketing agents to sell their coffee to buyers and roasters as shown in Figure 2.4.

Following the coffee reforms, estates have been able to bypass marketing agents and the coffee auction entirely, selling up to 30% of their production volume directly to exporters via the "Second Window" option. However, the small-scale coffee producers failed to benefit from the "Second Window" option due to the high transaction costs and lack of bargaining power among other challenges. As such in 2009, small-scale coffee producers put their synergies together through their co-operative societies and established KCCE to create linkages between the small-scale coffee producers and the world market through a consistent and transparent supply chain.

2.2.1 The Kenya Coffee Auction

Nairobi Coffee Exchange (NCE) is the national coffee market where licensed coffee buyers buy bags of green coffee beans from licensed marketing agents through competitive bidding. Kenya coffee is sold in US dollars per 50 kilogram bags at the auction. At least eight working days prior to auction date, the marketing agents are required to forward samples representing what they want to offer to all potential coffee buyers. This allows the customers to evaluate the quality of each lot offered and decide which lots they would bid for in the auctions.

There is an electronic bidding system with a large display screen indicating the price movements. When there is only one bidder remaining, an electronic hammer seals the deal. The marketing agents in consultation with the coffee producers set the reserve price for each lot. If the highest bid reaches or exceeds the reserve price, the deal will be "confirmed" immediately and the winner will pay the bidding price. If the highest bid is lower than the reserve price, the bid will be "noted" and at the end of the day after all transactions, the supplier has the right to accept or reject the "noted" bids as shown in figure 2.5. If he rejects, the coffee is returned and will then be re-offered in subsequent auctions in two or three weeks. It is worth noting that once coffee has been milled, fading starts taking place immediately and this is reflected in the cup that becomes woody and the price comes down (such coffee sells at a discounted price).

A summary of the price discovery at the auction is shown in Figure 2.5.

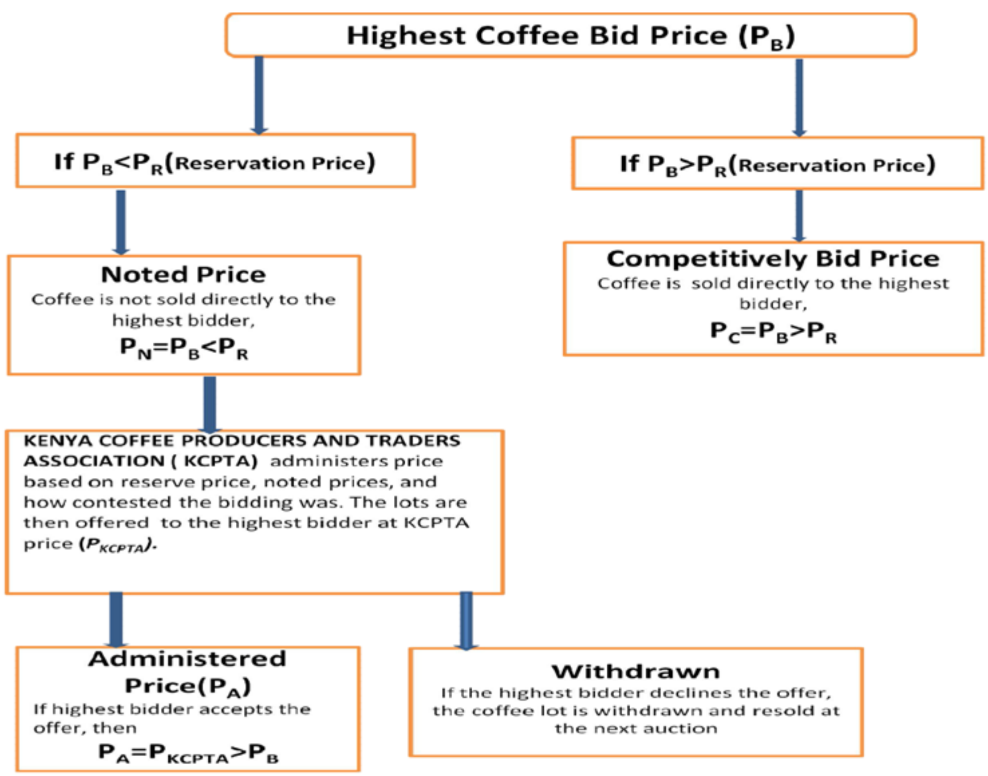


Figure 2.5: Price Discovery at the Nairobi Coffee Auction

Source: Author's Own Description

2.2.2 Impact of KCCE on Producers Income: A Mini Case Study

Table 2.2 shows the total volume of sales in both the "Second Window" marketing channel and Nairobi Coffee Auction for KCCE.

Table 2.2: Total Volume of Coffee Sales by KCCE in Both Market Channels

Sales Period	Number of Bags Sold	Total Weight (kg)	Total Value (USD)
2009/2010	65,716	3,943,998	17,630,632
2010/2011	33,839	2,030,260	12,501,927
Total	99,555	5,974,258	30,132,559

Tendelyani Farmers' Cooperative Society is a member of KCCE. It was established in 1954 with a membership of 10,000 small-scale producers. In the 2010/2011 coffee season, Tendelyani marketed its coffee through KCCE and has realized the highest payment to its members only witnessed during the coffee boom of the 1970s. The small-scale producers were able to realize a minimum of $ 0.85 per kg of red coffee cherries which translate to a 32% increase from the previous season when they used other marketing agents.

Mrs. Wambua, the Tendelyani Farmers' Cooperative Society chairperson remarks that "KCCE has given us confidence that there is income in coffee farming and we are once again proud coffee producers. We look forward to even better prices". This clearly indicates that access to a consistent and reliable market for Tendelyani and other small-scale coffee producers in Kenya will have a significant impact on their socioeconomic status.

Collective marketing has the potential to increase incomes that can be used to secure economic access to food, investment in food production, finance education and meet daily financial obligations. Such incomes can have a multiplier effect on Kenya's economy as other enterprises can develop to tap into the incomes and create employment. Coffee farming will also become attractive to the youth who have since left their rural homes in search of employment in urban areas further decreasing the rural–urban migration, unemployment and curb negative social behaviour.

2.3 Data and Methodology

2.3.1 The Difference-in-Differences Methodology

Our investigation of coffee prices takes advantage of a natural experiment. The basic intuition of the difference-in-differences approach is that to study the impact of some "treatment" one compares the performance of the treatment group pre-and post-treatment relative to the performance of some control group pre-and post-treatment. In principle, the control group shows what would have happened to the treatment group in the absence of any treatment.

Applied to the effect of collective marketing by KCCE on coffee prices at the auction, this approach suggests that we compare the coffee prices among small-scale producers during the KCCE pre-and post-registration period with the coffee prices among control producers (estates) during the same period. The impact of collective marketing is identified as the estimated difference-in-differences of coffee prices pre-and post-registration between the two groups of producers. If collective marketing by KCCE causes a decrease (increase), then collectively marketing coffee should decrease coffee prices (increase) relative to what the coffee prices would have been absent of KCCE.

Therefore, evaluating the success of KCCE involves answering causal questions, such as "did the collective marketing of coffee by KCCE produce a positive effect on the socioeconomic conditions of the small-scale cooperatives involved?". The difference-in-differences method can provide an answer as long as the outcome of interest can be measured both before and after the formation of KCCE in a representative sample of both small-scale coffee producer cooperatives and estates.

Let us take the impact on the auction coffee prices: it is estimated by subtracting the difference observed between the two groups of producers before the registration of KCCE from the difference observed after the registration. We provide a graphical illustration in Figure 2.6 of this interpretation of the difference-in-difference method as applied in this dissertation. On the horizontal axis we have time, with two points, one before and one after the KCCE initiative was implemented. In this case, it was 2009 and 2010. On the vertical axis we put the auction coffee price. Each of the four circles in the graph represents an average: two are taken in 2009 and two in 2010, respectively among the two groups of producers:transactions from small-scale producer cooperatives and among a sample of transactions of estate producers operating in the same coffee exchange,but not using KCCE as their marketing agent to sell their coffee at the auction.

Obviously, the difference observed between the two groups of producers in 2010 is not the impact of KCCE's registration: this difference could be caused entirely by the coffee quality–that is, producers with higher quality had better chances of receiving a higher price for their coffee. If taken as an indication of KCCE's registration impact, the difference shown in the graph would represent a disappointing result. It is the increase in the coffee prices gap that can be interpreted as the impact of KCCE's registration.

However, the validity of this conclusion depends on a crucial assumption: that in the absence of KCCE, the trend among small-scale producer prices would have been similar to that of the estate producers. Graphically, this is tantamount to drawing a dotted line parallel to the trend observed among estate producers, but starting where the small-scale producer cooperatives are in 2009. This dotted line points a square in 2010: this is the counter factual, our estimate of what would have happened to the coffee prices for small-scale producer cooperatives had the KCCE initiative not been implemented.

To develop this empirical strategy, we first present the typical difference-in-differences approach, following the detailed discussion in Meyer (1994). We then discuss how we modify this typical approach to cases of collective marketing by KCCE, with particular focus on the issues of defining treatment and determining control groups. Suppose a group of economic agents has some treatment applied at a single point in time, and suppose further that some outcome for these agents can be observed both before and after treatment application. Then one could try to estimate the treatment effect with the following regression:

$$y_{it} = \alpha + \beta_{dt} + \epsilon_{it} \tag{2.1}$$

where y is the outcome for agent i ($i = 1, \cdots, N$) at time t ($t = 0$ or 1), is a dichotomous

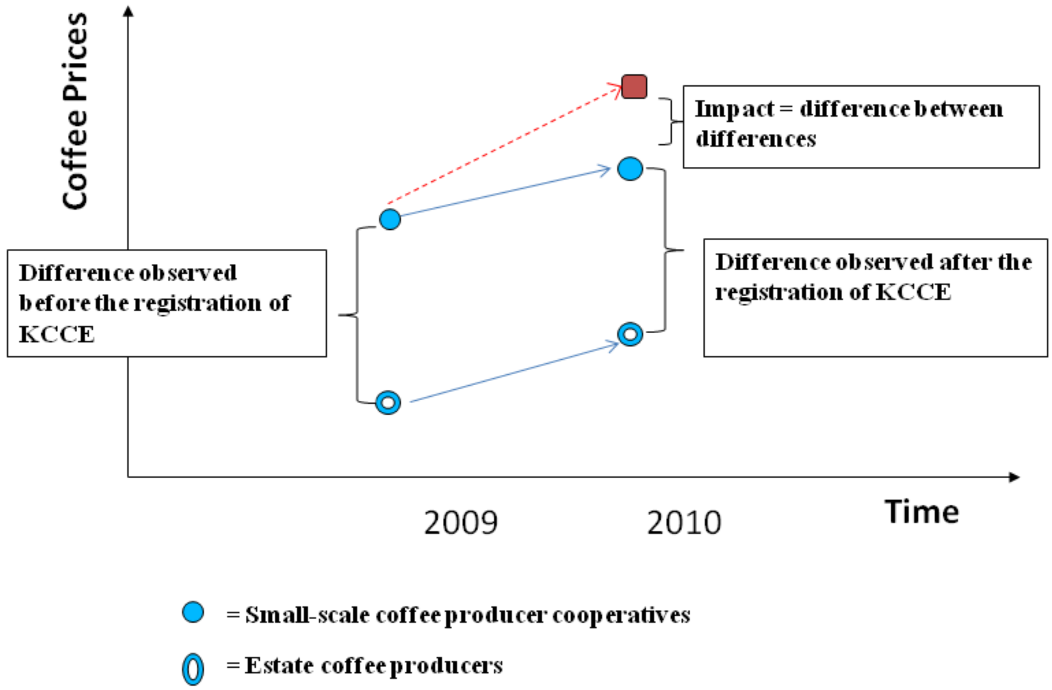


Figure 2.6: Difference-in-Difference

variable equal to one if $t = 1$ and zero if $t = 0$, and ϵ_{it} is an error term (whose variance varies by t). β identifies the causal effect of treatment under the identifying assumption that $E[\epsilon_{it}|dt] = 0$, i.e., that without treatment all agents would be comparable over time (such that without treatment $\beta = 0$). β can be determined by estimating Eq. (2.1) or simply by calculating the single difference of the change in mean outcomes before and after treatment (i.e., the average outcome at $t = 0$ minus the average outcome at $t = 1$. A problem with this single-difference approach is potential violation of the identifying assumption. Between $t = 0$ and $t = 1$ many forces other than treatment might affect the outcome of interest. The essence of the difference-in-differences approach is to try to account for these other forces by also examining the outcomes for a control group that does not receive the treatment but that presumably is affected by these other forces. This suggests

$$y_{it}^{j} = \alpha + \alpha_1 d_t + \alpha_1 d^j + \beta d_t^j + \epsilon_{it}^{j}, \tag{2.2}$$

where now j indexes the two groups with $j = 1$ for the treatment group and $j = 0$ for the control group; d^j is a dichotomous variable equal to one if $j = 1$ and zero if $j = 0$; and d_t^j is a dichotomous variable equal to one if both $j = 1$ and $t = 1$, and zero otherwise. β is again the key coefficient which identifies the causal effect of treatment. It is obtained by estimating Eq. (2.2) or simply by calculating the "difference in differences" equal to the change in mean outcomes for the treatment group minus the change in mean outcomes for the control group. The parameter α_1 captures how both groups are affected over time by any non-treatment forces, while the parameter α^1 captures any time-invariant difference in outcomes between the treatment and control groups. Similar to Eq. (2.1), the key identifying assumption in Eq. (2.2) is that $E[\epsilon_{i_t}^{j} | d_t^j] = 0$, i.e., that $\beta = 0$ in the absence of treatment. This assumption "is most plausible when the untreated comparison group is very similar to the treatment group" (Meyer, 1994 pg. 18).

2.3.2 Application to the Coffee Market

We have chosen to study the impact of collective marketing by small-scale producers in the Kenyan coffee supply chain because it offers a good context for this study. First, the Kenyan government as an institutional response to the tremendous changes taking place in the coffee supply chain registered KCCE (a small-scale producer marketing cooperative) in 2009. This is in contrast to what was happening before where small-scale producers were using private traders (marketing agents) to sell their coffee for a service fee at the coffee auction.

Second, in contrast to typical auction markets where buyers bidding price determines the transaction, marketing agents (or auctioneers) also make decisions. 87% of the time in this coffee market, the highest bidding price is below the reserve price. In such cases, marketing agents can decide whether or not to accept the offered price. The sample consists of 38,112 weekly coffee transactions at the auction for a period of two years.

The task now is how to apply the difference-in-differences approach to the issue of collective marketing by KCCE at the Nairobi coffee auction. A first issue to consider is the treatment. In typical difference-in-differences studies in economics the treatment is a one-time change in government policy applied equally to all members of the treatment group. The equal application allows identification of the treatment and control groups. And the one-time nature of the change makes it easy to select specific pre- and post-treatment points in time, whereby in the latter it is assumed that the full treatment effect has been realized.

KCCE was registered as a collective marketing cooperative in June 2009. This fundamental change in the coffee market means that we can consider the panels both before and after June 2009 to compare the coffee prices at the Nairobi Coffee auction. The outcome of interest is the coffee prices at the Nairobi coffee auction paid for the treatment group and for the control group of producers' coffee. For this average measure, the analog of Eq. (2.1) which we estimate is given by Eq. (2.3).

$$y_{r_t} = \alpha_1 + \alpha_2(d_r) + \beta_{1(t)} + \beta_{2(t)}(d_r) + \epsilon_{rt}, \tag{2.3}$$

where t indexes time in years running from $t = 1$ until $t = T$; r indexes the two equal-length registration periods of interest: $r = 0$ for the KCCE registration running from $t = 1$ until $t = (T/2)$ and $r = 1$ for the KCCE post-registration running from $t = (1 + T/2)$ until $t = T$; dr is a dichotomous variable equal to one if $r = 1$ and zero if $r = 0$, and ϵ is an error term (whose variance varies by r). The regressor and y_{rt} is the mean of the coffee prices among the small-scale producers for KCCE registration r at time t. Eq. (2.3) is basically a spline regression where both registration periods are allowed to have different intercepts and parameters on time.

The rate of change in coffee prices during the KCCE pre-registration is given by β_1 and KCCE post-registration is given by $(\beta_1 + \beta_2)$. In both registration periods the coffee price increase (decrease) is indicated by positive (negative) slope coefficients. The single difference β_2 indicates whether KCCE post-registration change differs from that of KCCE pre-registration period. This single-difference coefficient is analogous to the coefficient β in Eq. (1). For the difference-in-differences specification, let the superscript j indicate producer group, with $j = 1$ the small-scale producer group and $j = 0$ some control group (estate producer). Then the analog to Eq. (2.2) which we estimate is given by Eq. (2.4)

$$\begin{aligned} y^j_{it} = \alpha_1 + \alpha_2(d_r) &+ \alpha_3(d^j_r) + \alpha_4(d^j_r) \\ &+ \beta_{1(t)} + \beta_{2(t)}(d_r) + \beta_{3(t)}(d^j_r) + \beta_{4(t)}(d^j_r) + \epsilon^j_{rt}, \end{aligned} \tag{2.4}$$

where the dichotomous variable d^j indicates producer group; the dichotomous variable d^{jr} equals one if both $j = 1$ and $r = 1$ and zero otherwise; and $\epsilon^j_{r_t}$ is an error term (whose variance varies by both j and r). For each of the four producer-group /KCCE registration periods, Eq. (2.4) estimates a separate intercept term and change for coffee prices as shown Table 2.3.

Producer-group/KCCE Registration	**Intercept**	**Change in Coffee Prices**
Small-scale Producers KCCE Pre-Registration	α_1	β_1
Small-scale Producers KCCE Post-Registration	$\alpha_1 + \alpha_2$	$\beta_1 + \beta_2$
Control group (Estates) KCCE Pre-Registration	$\alpha_1 + \alpha_2 + \alpha_3$	$\beta_1 + \beta_2 + \beta_3$
Control group (Estates) KCCE Post-Registration	$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$	$\beta_1 + \beta_2 + \beta_3 + \beta_4$

Table 2.3: Change in Coffee Prices

The effect of collective marketing by KCCE on coffee prices at the coffee auction can be obtained by calculating the "difference-in-differences" of the estimated rates. The difference in change in coffee prices within the small-scale producer group KCCE pre- and post-registration is given β_2. The similar difference in coffee prices within the control group is given by $(\beta_2+\beta_4)$. Thus the difference in differences is given by $(\beta_2+\beta_4)-(\beta_2) =$

β_4. Assuming that the only treatment pre-and post-registration between the two groups is collective marketing by KCCE, β_4 identify its effect. If registration of KCCE tends to increase (decrease) coffee prices among the small-scale producers then β_4 is positive (negative). Any cross-registration time effect on coffee prices common to both groups of producers is captured by β_2, and any time-invariant differences in coffee prices between groups is captured by β_3.

2.4 Impact of Collective Marketing on Coffee Prices and Buyer Behaviour

We examine changes in coffee prices after the registration KCCE by the government of Kenya to market small-scale producers coffee. Importantly, this is the first collective marketing cooperative in the country for small-scale coffee producers. We use a differences-in-differences approach to measure the effect on coffee prices at the auction. In particular, we compare the difference in coffee prices before and after the registration of KCCE between two types of coffee producers. One sample of producers is the small-scale producers who were eligible to use the collective marketing cooperative. These producers did not use a collective marketing cooperative to sell their coffee before the registration of KCCE but were able to use KCCE to sell their coffee after the cooperative was registered.

The second sample of producers is the estates. These producers were not eligible to use KCCE to market their coffee either before or after the registration of KCCE. By comparing the difference in coffee prices over time between the two groups of producers (the differences-in-differences), we benefit from two inherent controls. Measuring the change in coffee prices by the same producers over time enables us to control for individual producer characteristics, while comparing producers of either type controls for time trends or other events that are common to both producer samples.

Our analysis recognizes some potential confounds in the natural experiment. First, the coffee price may be affected by the type of buyer depending on whether it is a multinational firm or a local firm buying the coffee. To isolate the registration effect from other effects, we control for the type of buyer. We therefore expect the only impact on the coffee prices to be the registration of a collective marketing cooperative for the small-scale producers. Secondly, we control for the coffee grade in our transaction analysis. This is because different grades fetch different prices depending on their quality. In addition, we also control for the marketing agent. Finally, our interpretation of the natural experiment requires that any factors that could affect the change in coffee prices in the small-scale producer transactions also affect coffee prices in the estate transactions as shown in Figure 2.6.

We focus on the change in the coffee prices of small-scale coffee producers and estates at the Nairobi coffee auction before and after the registration of KCCE. We begin by reporting univariate results and then turn to a multivariate approach. The univariate results appear in Table 2.4, in which we summarize the average coffee prices received by producers in the KCCE pre- and post-registration periods.

2.4.1 Descriptive Statistics

We analyze 17,608 small-scale producer transactions and 20,504 estate producer transactions. Table 2.4 summarizes descriptive statistics for key variables. In the descriptive statistics reported we further classify the coffee prices as those that were competitively bid and the administered prices (those that were below the reserve price and had to be negotiated).

Variable	Minimum	Mean	Maximum
Price (US Dollars/50kg Bag)	7	213	721
Marketing Agent	0	0.002	1
Post-Registration	0	0.37	1
Producer	0	0.46	1
Grade AA	0	0.25	1
Grade AB	0	0.35	1
Grade PB	0	0.14	1
Number of Bags	1	39.67	218
Buyer Type	0	0.57	1

Table 2.4: Coffee Prices Descriptive Statistics

The average competitively bid prices were higher at \$254.9 per 50 kg bag than the mean of combined coffee prices of \$213 per 50 kg bag for the period under consideration as shown in the Table 2.5. This reflects the fact that the presence of competition among buyers for the various coffee lots drove up the coffee prices.

Variable	Minimum	Mean	Maximum
Price	54	254.9	721
Marketing Agent	0	0.002	1
Post-Registration	0	0.63	1
Producer	0	0.41	1
Grade AA	0	0.22	1
Grade AB	0	0.33	1
Grade PB	0	0.14	1
Number of Bags	1	38.14	163
Buyer Type	0	0.56	1

Table 2.5: Competitively Bid Coffee Prices Descriptive Statistics

Lucy Murumba, KCCE's CEO corroborated this during an interview in June 2010 at the KCCE offices in Nairobi. She said that small-scale producers were earning on average $ 0.2 per kg of cherry (these are the raw coffee berries before primary processing) before KCCE came into the market in 2009. By then the highest paid small-scale producer would take home $0.45 per kg of cherry. It is noteworthy that international prices of green coffee beans had been on the rise since the year 2005 but Kenyan small-scale producers were not getting a commensurate increase in the price of their coffee.

KCCE has been able to pay some small-scale producers $1.4 per kg. This is a great improvement from the previous payments that the small-scale producers were receiving.

In contrast, the mean of the administered coffee prices was lower at $206.5 per 50 kg bag shown in Table 2.6.

Variable	Minimum	Mean	Maximum
Price	7	206.5	555
Marketing Agent	0	0.003	1
Post-Registration	0	0.33	1
Producer	0	0.47	1
Grade AA	0	0.26	1
Grade AB	0	0.36	1
Grade PB	0	0.14	1
Number of Bags	1	39.85	218
Buyer Type	0	0.57	1

Table 2.6: Administered Coffee Prices Descriptive Statistics

Table 2.7 presents the mean values of the coffee prices at the auction during the pre-and post-registration periods (18 months before and after KCCE was registered), calculated using 17,608 transactions for the small-scale producers and 20,504 transactions for the estates. The "difference" measure uses a Welch Sample t-test. We derive the "differences-in-differences" measure by calculating the difference between the KCCE pre- and post-registration periods in the coffee prices for each transaction at the auction and then comparing the mean of these differences between coffee prices for the small-scale producers and estates at the auction.

	Pre-Registration Period	Post-Registration Period	Difference	Differences-in-Differences
Coffee Prices				
Small-scale Producers	184.46	276.52	**92.06****	**6.51****
	(0.37)	(2.15)		
Estates	176.06	261.62	**85.55****	
	(0.32)	(0.92)		

***Difference is significantly different from zero, $p < .01$. ;*
Standard errors are in parentheses.

Table 2.7: Average Coffee Prices in the KCCE Pre-and Post-Registration Periods

Table 2.7 reports two findings of interest. First, the average coffee prices have increased for both producers during the measurement period. Second, average coffee prices for small-scale producers increased slightly more than the estate producers between the KCCE pre-and post-registration periods, which is consistent with the fact that small-scale producers in Kenya have better quality coffee on average due to the selective harvesting of coffee berries and only hand-pick the ripe cherries. The box plots in figure 2.7 visually show this fact that on average for most of the coffee grades, cooperatives representing small-scale producers received higher coffee prices than the estate producers. The results demonstrate that coffee buyers at the auction are willing to pay a premium for higher quality coffee beans.

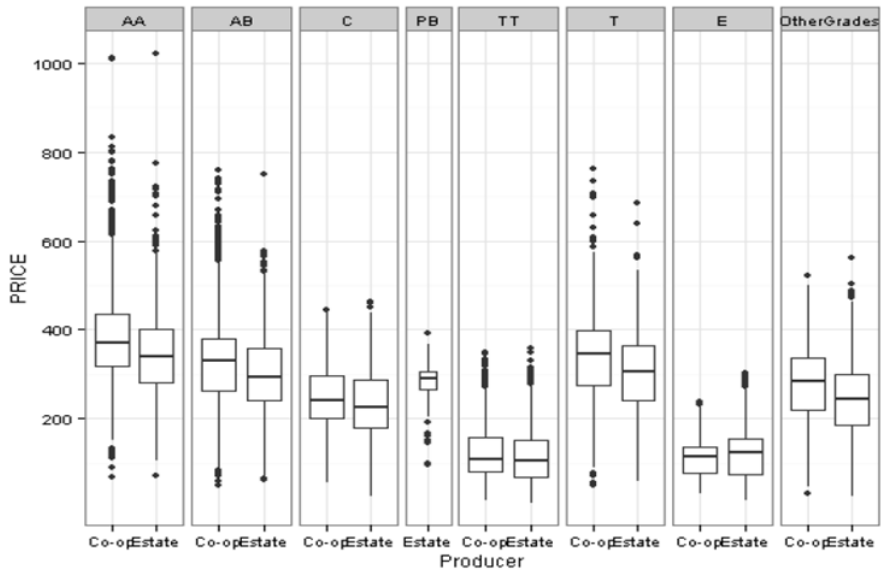


Figure 2.7: Comparing Coffee Prices per Grade for Small-scale and Estate Producers

2.4.2 Regression Analysis

Note that the comparison of interest is not merely the KCCE pre-versus post-registration difference, but whether this difference varies for small-scale producers and estates. We now directly estimate this interaction in the multivariate analysis that follows.

Multicollinearity problems are common in such studies. Neter et al.,(1989: 409) suggests that a maximum variance inflation factor (VIF) value in excess of 10 is often taken as an indication that multicollinearity may be unduly influencing the least square estimates. In addition, others (Hair et al., 1995; Marquardt, 1970; Mason et al., 1989) assert that a VIF of less than 10 are indicative of inconsequential collinearity. We have calculated the VIF of our regression and the VIF values range from 1.014 to 2.437. This further strengthens the conclusion that multicollinearity is not a problem in this case.

$$\begin{aligned} Price_{it} &= \beta_0 + \beta_1 MarketingAgent_{it} \\ &+ \beta_2 PostRegistration_{it} + \beta_3 PostRegistration_{it} * Producer_{it} \\ &+ \beta_4 Produce_{it} + \beta_5 GradeAA_{it} + \beta_6 GradeAB_{it} \\ &+ \beta_7 GradePB_{it} + \beta_8 NumberofBags_{it} \\ &+ \beta_9 BuyerType_{it} + \epsilon^j_{rt} \end{aligned} \tag{2.5}$$

The post-registration and producer variables are binary indicators identifying the post-registration period and producers respectively. Under this specification, producer controls for underlying differences between small-scale producers and estate producers. While post-registration controls for common price changes over time.

The coefficient of interest is the interaction coefficient (β_3), which measures the change in post-registration prices among small-scale producers compared with Estate producers. We interpret β_3 as the change in coffee prices due to the registration of a collective marketing cooperative that sells the small-scale producers coffee. Table 2.8 reports the linear regression coefficients from estimating Eq. (2.4) using pre-and post-registration observations for the 17,608 small-scale producer transactions and 20,504 estate producer transactions.

We also estimate the model separately using the competitively bid coffee prices or administered coffee prices as the dependent variable as shown in Table 2.9. We report our findings, distinguishing between competitively bid prices and administered prices. The results reveal the same pattern as the univariate results and appear to confirm

Dependent Variable	Coffee Price		
	Coefficient	Significance	Std.Error
(Intercept)	129.063	***	0.776
Marketing Agent	34.190	***	5.204
Post-Registration	88.419	***	0.748
Post-Registration * Producer	6.602	***	1.106
Producer	6.825	***	0.678
Grade AA	59.328	***	0.748
Grade AB	30.738	***	0.761
Grade PB	41.579	***	0.900
Number of Bags	0.188	***	0.010
Buyer Type	13.050	***	0.545
Number of Observations		38112	
R Squared		0.471	

****Significantly different from zero, $p < .001$.*

Table 2.8: Coffee Prices Regression

that a collective marketing effort by the small-scale producers has an impact on the coffee prices at the auction. The registration of the collective marketing cooperative is associated with a rate of $14.55 increase in competitively bid prices (after we control for the change in coffee prices for the estate producers). This effect is statistically significant ($p < .001$).

Similarly, there is a rate of $4.088 increase in administered prices sales and the effect is also statistically significant ($p < .001$). When we aggregate the competitively bid prices and administered prices (Table 2.7), the overall impact is positive and significantly different from zero ($p < .001$). Thus, the registration of KCCE is associated with a rate of $6.602 increase in coffee prices at the auction (after we control for the change in coffee prices for the estate producers).

Dependent Variable	Competitively Bid Price			Administered Price		
	Coefficient	Signif	Std.Error	Coefficient	Signif	Std.Error
(Intercept)	116.714	***	2.371	132.045	***	0.795
Marketing Agent	46.596	*	20.150	39.934	***	5.176
Post-Registration	101.495	***	2.133	81.904	***	0.792
Post-Registration * Producer	14.550	***	3.371	4.088	***	1.161
Producer	11.848	***	2.705	6.550	***	0.673
Grade AA	96.389	***	2.224	54.486	***	0.769
Grade AB	43.144	***	2.140	28.911	***	0.789
Grade PB	56.345	***	2.627	39.670	***	0.926
Number of Bags	0.146	***	0.031	0.193	***	0.010
Buyer Type	29.908	***	1.653	9.898	***	0.558
Number of Observations		5112			33000	
R Squared		0.579			0.442	

**Significantly different from zero, p < .05.*
****Significantly different from zero, p < .001.*

Table 2.9: Competitively Bid and Administered Price Regression

The post-registration and producer variables separately control for systematic differences over time and between producers respectively. As we expected, the positive coefficient for the post-registration variable captures the expected reduced transaction costs involved in searching for information, negotiation and monitoring of transactions and increased competition. The coefficient for producer is also positive and significant in the three models. This is consistent with the results in Table 2.7, which indicate that small-scale producers receive slightly higher coffee prices at the auction in both the pre-registration period and the post-registration period than the estate producers.

The price premium paid by the buyers for quality coffee at the auction may partially explain this difference. Coffee is a product that lends itself to differentiation. There is a wide diversity of flavors and aromas that emerge from different coffee growing soils and climates, tree varieties. These flavors and aromas constitute the coffee sensory attributes because they refer to quality aspects that are perceived by the senses.

According to Lingle (2001) coffee sensory attributes are evaluated through cupping which is the sensing of aromas, flavors and body through olfaction, gustation and mouth-feel, respectively. Consequently, coffee prices are determined both by the coffee sensory attributes measured through cupping and coffee reputation attributes.

Because the aroma and flavor of a particular coffee cannot be known until it is consumed, the situation is characterized by imperfect information. Thus, it is the primary reason why the pricing of differentiated products depends on reputation attributes, which in turn allows supply chain participants to make rational assumptions about the intentions and future behaviors of each other (Shapiro, 1983).

We conclude that collective marketing by KCCE improved the information flow from the small-scale producers and therefore led to the slight significant differences between the coffee prices received at the auction by the small-scale and estate producers.

The Impact of Collective Marketing on Buyer Behaviour

Our preceding analysis of coffee prices shows that collective marketing by small-scale producers has a positive impact on the coffee prices at the auction. This introduces an empirical question. The evidence that collective marketing raises coffee prices for the small-scale producers suggests that coffee buyers especially the multinational companies may respond positively to the collective marketing effort by small-scale producers since one advantage of buying from a cooperative would be the reduction in search costs thereby reducing their transaction costs. This presents coffee buyers with a trade-off: Should they respond positively to collective marketing by the small-scale coffee producers to reap the benefits of minimizing transaction costs that, though currently small, promises to be an important source of future benefits?

Dependent Variable	Coffee Prices		
	Coefficient	Signif	Std. Error
(Intercept)	134.485	***	0.868
Marketing Agent	34.203	***	5.168
Post-Registration	76.079	***	1.071
Post-Registration * Producer	1.380		1.697
Producer	6.625	***	1.048
Grade AA	59.679	***	0.743
Grade AB	31.254	***	0.756
Grade PB	41.467	***	0.894
Number of Bags	0.186	***	0.010
Buyer Type	2.756	**	0.919
Post-Registration * Buyer Type	23.697	***	1.486
Buyer Type * Producer	1.605		1.363
Post-Registration * Producer* Buyer Type	4.418	*	2.231
Number of Observations		38112	
R Squared		0.479	

**Significantly different from zero, p < .05.*
****Significantly different from zero, p < .001.*

Table 2.10: Buyer Behaviour at the Coffee Auction

In this section, we investigate how coffee buyers responded by evaluating whether collective marketing by small-scale producers affected the prices. To investigate how the collective marketing cooperative affect the prices paid by coffee buyers, we repeat our previous analysis with the Post-Registration variable interacting with the Buyer Type variable. The findings follow precisely the predicted pattern as shown in Table 2.10. The buyers at the coffee auction respond positively to the collective marketing effort by small-scale producers. The registration of KCCE does increase the prices paid by Multinational coffee buyers (after we control for the change in coffee prices for the Local Buyers). Collective marketing is associated with an increase of \$23.697 per 50 kg bag and is significantly different from zero, $p < .001$.

This is consistent with the competitively bid price and administered price models with an increase of \$21.618 and \$20.416 per 50kg bag respectively in Table 2.11and Table 2.12. The findings again follow the pattern that we would predict. The Post-Registration period Buyer Type coefficients are significantly different from zero (significantly different from zero, $p < .001$) in either model. These findings support the interpretation that multinational buyers recognize that they are likely to reduce their search costs and information asymmetry about the coffee quality by responding favourably to the collective marketing efforts by small-scale producers at the coffee market. Thus, buying their coffee from KCCE may eventually minimize their transaction costs.

In addition, we interacted the producer type variable (Post-Registration period Buyer Type Producer) the interaction was both small (\$4.418 per 50 kg bag) and only significant at $p < .05$. However, this interaction was not significant for the competitively bid price and the administered price models.

Dependent Variable	Competitively Bid Price		
	Coefficient	Signif	Std. Error
(Intercept)	122.285	***	2.729
Marketing Agent	45.134	*	20.063
Post-Registration	91.040	***	2.947
Post-Registration * Producer	8.160		5.232
Producer	16.326	***	3.967
Grade AA	97.064	***	2.219
Grade AB	43.725	***	2.132
Grade PB	56.447	***	2.617
Number of Bags	0.141	***	0.031
Buyer Type	17.330	***	3.322
Post-Registration * Buyer Type	21.618	***	4.240
Buyer Type * Producer	-4.764		5.395
Post-Registration * Producer* Buyer Type	5.043		6.903
Number of Observations		5112	
R Squared		0.583	

**Significantly different from zero, p < .05.*
****Significantly different from zero, p < .001.*

Table 2.11: Buyer Behaviour For Competitively Bid Coffee Prices

Next, we consider some explanations for why we observe an increase in coffee prices at the auction:

- **Reduced Transaction Costs** Transaction costs arise in the course of market exchange and involve the costs of information, search, negotiation, screening, monitoring, coordination, and enforcement (Gulati & Singh, 1998). The relevant transaction costs in this analysis are monitoring, negotiation, search and information costs, which in the context of the Kenyan coffee market involve: The costs of ensuring product quality handling, quality and grade uncertainty, and observation of the grading process. These are the monitoring costs; The costs in the negoti-

Dependent Variable	Administered Price		
	Coefficient	Signif	Std. Error
(Intercept)	136.431	***	0.886
Marketing Agent	39.930	***	5.149
Post-Registration	71.298	***	1.133
Post-Registration * Producer	0.533		1.763
Producer	1.048	***	3.967
Grade AA	54.712	***	0.765
Grade AB	29.307	***	0.785
Grade PB	39.538	***	0.921
Number of Bags	0.193	***	0.010
Buyer Type	1.691	.	0.923
Post-Registration * Buyer Type	20.416	***	1.577
Buyer Type * Producer	1.950		1.357
Post-Registration * Producer* Buyer Type	5.043		2.336
Number of Observations		33000	
R Squared		0.448	

**Significantly different from zero, p < .05.*
****Significantly different from zero, p < .001.*

Table 2.12: Buyer Behaviour For Administered Coffee Prices

ation process arising from the presentation of the coffee for inspection, viewing, and quality assessment and payment arrangements including the negotiation costs; The costs associated with price discovery, information and price uncertainty (for example, auction prices depend on product-information costs, among other things). These are the search and information costs.

- **Information Sharing** The coffee market may have high transaction costs in terms of screening for trust-worthy partners, obtaining information about prices or quality, and enforcing contracts. Sharing information reduces the cost of searching for market information, which entails transaction costs. Increased information sharing between buyer and seller during the KCCE post-registration period may have lowered the screening costs of small-scale coffee producers by buyers resorting in increased prices. Fafchamps (1998) posits that, by sharing information on bad players in a decentralized manner, producer cooperatives help the members to lower screening costs.

Hellin et al., (2007) and Darr (2005) suggest that collective action facilitates easier access to commodity markets and market information. Collective marketing cooperatives can therefore facilitate market access organization and low cost access to information, thereby enhancing contract enforcement (Narayan & Pritchett, 1999; Grootaert, 1999). Through collective marketing small-scale producer organizations lower the transaction costs of marketing produce by eliminating some of the intermediaries and also enabling producers to capture the economies of scale of joint marketing.

- **Increased Bargaining Power** Collective marketing enables producers to negotiate prices with buyers thereby increasing their bargaining power and empowering them to have greater control over the setting of prices and also reduces the time and the cost of marketing. In the case of the coffee auction in Kenya where 87% of the prices are below the reserve price, the small-scale producers may have increased their bargaining power in the KCCE post-registration period in setting of administrative coffee prices. Therefore, collective marketing cooperatives can have an impact on poverty through increasing small-scale producer incomes and money flows in the economy, opening networks and opportunities outside the community.

2.5 The Economic Input-Output Life Cycle Analysis Model (EIO-LCA)

Input-Output analysis is based on a well-established tool in economic analysis in the work of Leontief (1966) where the interdependencies across different sectors of the economy are represented by a set of linear equations. The model works as follows; the inter-sectoral direct requirements (technical coefficients) matrix defined as A where aij represents the dollar value of input required from sector i to produce a dollar worth output of sector$j$ ($i = 1, .., n$, and $j = 1, .., n$). Then, x represents the total outputs of the sectors with the exogenous change in final demand for the output from these sectors represented by y. For more details on input-output analysis, underlying assumptions about the structure of the economy and limitations, refer to the work of Leontief (1966) and Hendrickson et al., (1998). Because the total output of a sector is the sum of final demand y and intermediate demand Ax, the input-output system can be written as:

$$x = y + A\,x. \tag{2.6}$$

To obtain the vector of sectoral outputs to meet a given exogenous demand y we pre-multiply (1) above by $[I - A]^{-1}$.

$$x = [I - A]^{-1} y \tag{2.7}$$

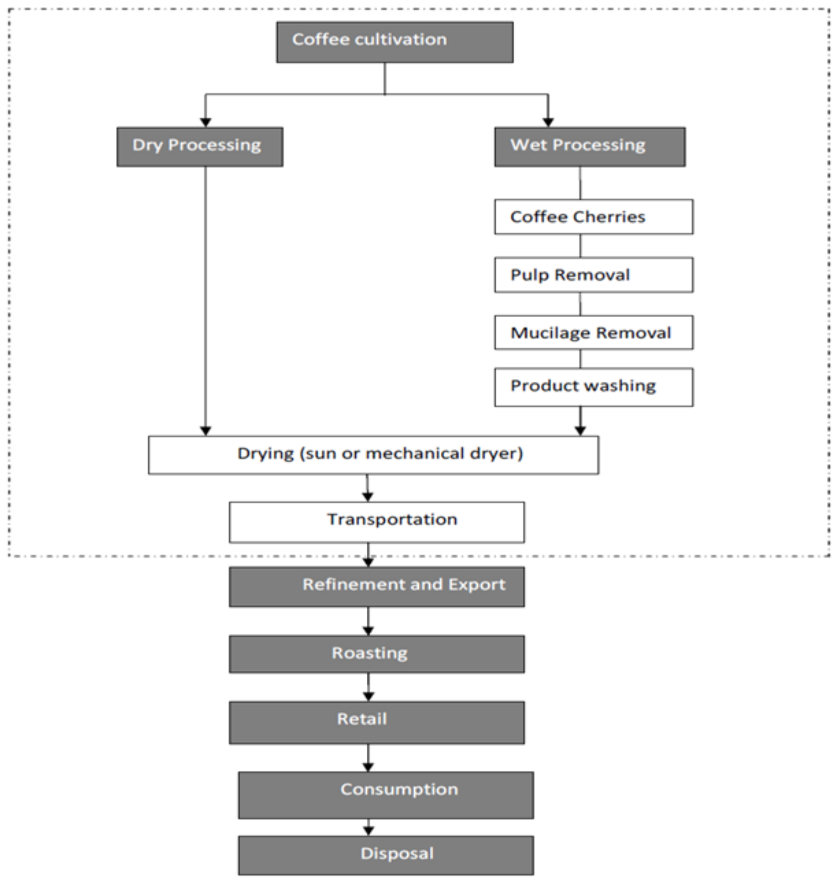
According to (Joshi, 2000), the input-output technique can be extended to include a matrix of environmental burden coefficients to facilitate environmental analysis. Let r be a $k \times n$ matrix of environmental burden coefficients, where r_{kj} is environmental burden k (e.g. carbon emissions) per dollar output of sector j (this matrix can include coefficient vectors for any environmental impact of interest such as greenhouse gas emissions, energy use, etc.); and e is a vector of total environmental burdens. Thus, the economy-wide total (direct and indirect) environmental burden associated with an exogenous demand vector y becomes

$$e = rx = r[I - A]^{-1}y. \tag{2.8}$$

2.5.1 Application of EIO-LCA to the Coffee Supply Chain

In this section, the EIO-LCA model is implemented to provide estimates of green house gas emissions in the coffee supply chain. In the case of small-scale producers in Kenya, collectively identifying the sectors in the coffee production life cycle (see figure 2.8) where environmental improvements can easily be achieved is a first step towards supporting a sustainable coffee supply chain. This can lead to improved processes and profitability for the small-scale coffee co-operatives. On the one hand, if the impact is primarily direct (directly from the sector), sustainable improvements may come from direct changes to production processes.

On the other, if the impact is primarily indirect (coming from suppliers and second or third tier suppliers), then reduction of impacts may come primarily from reduction of the use of commodities from other sectors that have the most environmental impact in terms of green house gas emissions. This implies that collective action by supply chain partners to reduce environmental burdens may lead to more improvements as compared to different sectors acting individually. Thus, there may be need for players in the coffee industry to collaborate in environmental management of the coffee supply chain.



Note: The dotted line indicates the stages in life cycle under the control of the coffee producer

Figure 2.8: Coffee Production Lifecycle Stages

Source: Author's Own Description

The coffee supply chain starts with agricultural processes in producer countries and ends with the consumption and disposal stages, predominantly in industrialized countries in cooler latitudes. The main stages of the coffee life cycle and environmental impacts are highlighted in Figure 2.8 and comprise (ICO, 2001):

- **Coffee Cultivation:**

  There are different ways of growing coffee depending on cultivation practices (conventional or organic), typology of plantation (shaded or sunlight crops; mono culture or poly-culture crops), harvesting method (manual or mechanized), etc. For example, in Kenya, small-scale producers use conventional cultivation practices with sunlight mono culture coffee plantations and harvest their coffee manually. Coffee production activities such as planting coffee trees, applying fertilizer, pesticides and herbicides are associated with soil erosion and loss of biodiversity due to the extension of agricultural land use; eutrophication, eco-toxicity and greenhouse effect due to fertilization; mammal and aquatic life toxicity due to pesticide use; and resource depletion due to the fuel and water consumption required for coffee farming.

- **Dry/Wet processing:**

  The coffee berries have to be processed to release the green coffee beans. The green coffee beans obtained through the dry method is sometimes referred to as unwashed coffee or natural coffee. The dry method is used for most of the Arabica coffee produced in Brazil, Ethiopia, Haiti and Paraguay, as well as for some Arabicas produced in India and Ecuador. Almost all Robusta is processed through the dry method (ICO, 2001).

The essential difference between the wet and the dry method is that in the wet method the berries are pulped (removal of fruit skin) and washed before the drying stage leaving two beans surrounded by their parchment. The pulping generally leaves some residual flesh to the beans as well as the sticky mucilage adhering to the parchment surrounding the beans.

The beans are put in fermentation tanks for at least 48 hours to accelerate the process of destruction of the residual pulp and mucilage. After fermentation, the beans are washed and dried. After drying, the parchment coffee is hulled and ground to release the green coffee bean. Although, wet processing is therefore more harmful from an environmental point of view, it gains higher selling prices for the coffee beans due to better quality.

Modern mechanical mucilage removal machines producing semi-washed coffee use only about $1m^3$ per tonne of fresh cherries (without finish fermentation and washing) compared to the traditional fully washed technique without recycling that uses up to $20m^3$ per tonne of cherries. Most of the small-scale producer coffee co-operatives in Kenya use the traditional fully washed technique without recycling (Mburu et al., 1994). According to Chanakya and De Alwis (2004), the organic pollutant load of the generated waste water from wet processing waste water are extremely high, while the pH is low. Therefore, untreated waste-water from the wet processing stage is a major driver of environmental problems caused by coffee production.

- **Coffee Refinement and Export:**

  Coffee beans vary in size, shape, color and/or moisture content and are not homogeneous. In the refining step, coffee beans are separated and to improve quality grades they are polished, sorted, washed and dried. The refinement process requires energy, either in the form of electricity or fuel input.

- **Coffee Roasting and Retail:**

  Thermal energy is required to roast the green coffee beans. This thermal energy can cause air emissions including greenhouse gases. Decaffeinated and soluble coffee in particular requires water in the roasting process as well. After roasting, coffee needs to be packaged. Polyethylene foil (PET) is used for packaging to ensure that no oxygen reacts with the coffee to avoid aging. Other packaging types are glasses with screw caps for soluble coffees. Roasting does not necessarily happen after export, it is also common to export roasted coffee.

- **Consumption:**

  According to Salomone (2003), coffee consumption is another crucial step of coffee production. The most important environmental issue of this step of the coffee life cycle is energy consumption. The making of coffee requires energy, mainly electricity, for the percolator. The habit of leaving coffee on the hot plate of the percolator to keep it warm increases the energy demand further. Of course, coffee-making involves a certain amount of water input as well.

- **Disposal:**

The coffee grounds, filters as well as the packaging are disposed by the consumers. Coffee grounds and filters are often composted, but have a comparably long and irregular rotting process. Packaging as well as jute and plastic bags from previous supply chain steps is recycled, incinerated or dumped. Energy consumption, acidification, and greenhouse gas emissions are the common environmental problems related to waste treatment.

- **Transportation:**

  This occurs between almost all steps of the coffee life cycle. The biggest transportation distance concerns the shipping of green beans or roasted coffee from the producing to the consuming countries. Transportation is associated with the depletion of natural resources, in particular fossil fuels, and the environmental impacts of combusting the fuels, most prominently global warming.

2.5.2 Estimating the Value of Inputs and Greenhouse Gas Emissions

Next we estimated the value of inputs and green house gas emissions at each stage. All the inputs at each stage are approximated by their corresponding US-IO commodity sectors. We augment the 485 x 485 commodity by commodity direct requirements (or technical coefficients) matrix of the U.S. economy for the year 1992, with estimates of various green house gas emissions/dollar output of each commodity sector. In this dissertation, we use publicly available databases due to their advantages of large sample size, verifiability, transparency of methods and periodic updating by public agencies

(Joshi, 2000).

Generally, the impact themes covered include fertilizer use (as an indicator of the eutrophication potential), energy use, conventional air pollutants, green house gases and water use. However, in this study we only focus on green house gases. The values of output of the six-digit US input-output commodity (US-IO) sectors are from the benchmark input-output accounts for the US economy. This is a producer price model that indicates the wholesale value of output of each sector. Because roasted coffee almost exclusively consumes from its own commodity sector (green coffee) any detailed disaggregation models would also result in similar estimates. Thus, the aggregation of results from these stages provides a comprehensive life-cycle inventory.

2.5.3 EIO-LCA Analysis Results

Greenhouse Gas Emissions

We present the EIO-LCA analysis for the top ten sectors contributing greenhouse gases from the production of each sector needed in the roasted coffee supply chain. The greenhouse gases reported in this study are Global Warming Potential (GWP), carbon dioxide and nitrogen oxide emissions.

From Table 2.13 24.2% of GWP emissions come from the Electric services (utilities) sector at 276 MT of the total 1140 MT, 23.9 % of GWP emissions is from coffee fruits farming at 272 MT of the total 1140 MT, roasted coffee contributes 12.2% of GWP emissions at 139 MT of the total 1140 MT and trucking & courier services, except air contributing 10.4% of GWP emissions at 118 MT of the total 1140 MT.

Sectors	Direct Economic %	GWP MT (CO_2E)	Direct GWP MT (CO_2E)	Indirect GWP MT (CO_2E)
Electric services (utilities)	31	276	85.56	190.44
Fruits Farming	99.8	272	271.456	0.544
Roasted coffee	100	139	139	0
Trucking and courier services, except air	64.8	118	76.464	41.536
Nitrogenous and phosphatic fertilizers	0	36.5	0	36.5
Wholesale trade	68.2	36.1	24.6202	11.4798
Water transportation	71.6	28.1	20.1196	7.9804
Petroleum refining	9.96	25.7	2.55972	23.14028
Paper and paperboard mills	1.19	22	0.2618	21.7382
Air transportation	58.8	22	12.936	9.064
Total for all sectors	**71.7**	**1140**	**817.38**	**322.62**

Table 2.13: Top Ten Sectors Contributing Global Warming Potential (GWP) Emissions

Source: Author's own calculations from (EIO-LCA) US 1992 (485) model

Improvements in the coffee roasting sector may be directed at reducing the amount of electricity consumed in its facilities to address the GWP emissions. However, even such actions will still only target a small amount of the GWP emissions because the direct emissions from the electric services (utilities) sector due to the demand for power from the coffee roasting sector are only 85.56 MT. Most of GWP emissions from the Electric services (Utilities) sector are from indirect demand at 190.44 MT. There is need to rally supplier facilities (indirect demand) to collaborate in collectively reducing their electricity consumption or switch their electricity providers to alternative sources if the GWP emissions reduction is expected to have greater impact in the roasted coffee supply chain.

Coffee fruits farming, roasted coffee and trucking & courier services, except air have more GWP emissions from direct demand. Therefore, efforts to address GWP emissions should directly be focused on these sectors' facilities or activities to reduce the emissions.

Sectors	Direct Economic %	CO_2 MT	Direct CO_2 MT	Indirect CO_2 MT
Electric services (utilities)	31	247	76.57	170.43
Fruits Farming	99.8	241	240.518	0.482
Roasted coffee	100	125	125	0
Trucking and courier services, except air	64.8	106	68.688	37.312
Nitrogenous and phosphatic fertilizers	0	34.8	0	34.8
Wholesale trade	68.2	32.6	22.2332	10.3668
Water transportation	71.6	26.1	18.687	7.4124
Petroleum refining	9.96	24.7	2.4601	22.2398
Paper and paperboard mills	1.19	20.2	0.2403	19.9596
Air transportation	58.8	19.6	11.524	8.0752
Total for all sectors	**71.7**	**1020**	**731.34**	**288.66**

Table 2.14: Top Ten Sectors Contributing Carbon Dioxide Emissions

Source: Author's own calculations from (EIO-LCA) US 1992 (485) model

From Table 2.14 we observe that 24.2% of carbon dioxide emissions come from the electric services (utilities) sector at 247 MT of the total 1020 MT, 23.6% of carbon dioxide emissions is from coffee fruits farming at 241 MT of the total 1020 MT, roasted coffee contributes 12.3% of carbon dioxide emissions at 125 MT of the total 1020 MT and trucking & courier services, except air contributing 10.4% of carbon dioxide emissions at 106 MT of the total 1020 MT.

Improvements in the coffee roasting sector may be directed at reducing the amount of electricity consumed in its facilities to address the carbon dioxide emissions. However, even such actions will still only target a small amount of the carbon dioxide emissions because the direct emissions from the electric services (utilities) sector due to the demand for power from the coffee roasting sector are only 76.57 MT.

Most of carbon dioxide emissions from the electric services (utilities) sector are from indirect demand at 170.43 MT. So, getting supplier facilities (like the ones in the coffee fruit farming sector) to reduce their electricity consumption or switch their electricity provider to renewable sources could make a bigger difference in the overall CO_2 emissions. Coffee fruits farming, roasted coffee and trucking & courier services, except air have more carbon dioxide emissions from direct demand. Therefore efforts to address CO_2 emissions should be directed on these sectors' facilities or activities to reduce the environmental burdens.

Finally, Table2.15 shows that 27.3% of nitrous oxide emissions come from the coffee fruits farming sector at 29.5 MT of the total 108 MT, 26.9% of nitrous oxide emissions is from electric services (utilities) at 29 MT of the total 108 MT, roasted coffee contributes 11.9% of nitrous oxide emissions at 12.9 MT of the total 108 MT and trucking & courier services, except air contributing 10.8% of nitrous oxide emissions at 11.7 MT of the total 108 MT.

Coffee fruits farming, roasted coffee and trucking & courier services, except air have more nitrous oxide emissions from direct demand. Therefore efforts to address NO_2 emissions should be directed on these sectors' facilities or activities to reduce the environmental burdens.

Sectors	Direct Economic %	N_2O MT	Direct N_2O MT	Indirect N_2O MT
Fruits Farming	99.8	29.5	29.441	0.059
Electric services (utilities)	31	29	8.99	20.01
Roasted coffee	100	12.9	12.9	0
Trucking and courier services, except air	64.8	11.7	7.5816	4.1184
Nitrogenous and phosphatic fertilizers	0	1.68	0	1.68
Wholesale trade	68.2	3.38	2.30516	1.07484
Water transportation	71.6	1.99	1.42484	0.56516
Petroleum refining	9.96	0.99	0.098604	0.891396
Paper and paperboard mills	1.19	1.76	0.020944	1.739056
Air transportation	58.8	2.37	1.39356	0.97644
Total for all sectors	**71.7**	**108**	**77.436**	**30.564**

Table 2.15: Top Ten Sectors Contributing Nitrous Oxide Emissions

Source: Author's own calculations from (EIO-LCA) US 1992 (485) model

However, direct demand from electric services may not yield much reduction in nitrous oxide emissions since such actions will still only target a small amount of the nitrous oxide emissions as the direct demand from the electric services (utilities) sector due to the demand for power from the coffee roasting sector are only 8.99 MT.

Most of nitrous oxide emissions from the electric services (utilities) sector is from indirect demand at 20.01 MT. So, getting supplier facilities (like the ones in the coffee fruit farming sector) to reduce their electricity consumption or switch their electricity provider to renewable sources would make a bigger difference in the overall NO_2 emissions.

2.6 Summary and Conclusions

In Part I of this dissertation, we show how collective marketing efforts by small-scale coffee producers influence both coffee prices and buyer behavior. In particular, we examine how collective marketing by KCCE, a small-scale producers cooperative affects coffee prices at the Nairobi coffee auction. We find that while the competitively bid prices increase at the rate of $14.55 per 50 kg bag, the administered prices increase at a smaller rate of $4.088 per 50 kg bag. After combining the competitively bid and the administered coffee prices together, the overall results indicate that coffee prices increase at the rate of $6.602 per 50 kg bag. We interpret these results as evidence that the increase in coffee prices can be attributed to reduced transaction costs.

The relevant transaction costs in the Kenyan coffee market are costs of information, search, negotiation, screening, monitoring, coordination and enforcement costs. Further, the entry of KCCE into the auction market may have increased the small-scale producers' bargaining power because we find an increase in the administered coffee prices which generally are negotiated prices. At the auction 87% of the transactions constitute coffee sold at administered prices with competitively bid prices being 13% of the transactions.

Buyer behavior analysis investigates whether collective marketing positively influences buyer behaviour. We find that multinational buyers pay more for the competitively bid prices at a rate of $ 21.618 per 50 kg bag. Similarly, the multinational buyers pay more for administered prices at the rate of $20.416 per 50 kg bag. Combined there is an increase of $ 23.697 per 50 kg bag in the coffee prices that multinational buyers paid. We interpret these results as evidence that the buyer's search (product-information) costs and monitoring (quality and grade uncertainty) costs have been reduced by the presence of a collective marketing cooperative at the coffee auction.

Further, we provide estimates of the green house gas emissions in the coffee supply chain and identify the sectors in the coffee production life cycle where environmental improvements can easily be achieved. We show that for green house gases, the coffee fruit farming sector contributes 27.3% of nitrous oxide emissions, 23.6% of the carbon dioxide emissions and 23.9 % of GWP emissions ; electric services (utilities) sector contributes 24.2% of the carbon dioxide emissions, 24.2% of GWP emissions and 26.9% of nitrous oxide emissions; roasted coffee sector contributes 12.3% of the carbon dioxide emissions while the trucking & courier services, except air contributes 10.4% of the carbon dioxide emissions and 10.8% nitrous oxide emissions.

Last but not least, we show the environmental impacts can be classified into those that are primarily direct (directly from the sector) and those impacts that are primarily indirect (coming from suppliers and second or third tier suppliers). Improvements may be achieved by collaborating with supplier facilities (indirect demand) to reduce their electricity consumption or switch their electricity provider to alternative sources if carbon dioxide emissions reduction is expected to have greater impact in the coffee supply chain. In contrast, coffee fruit farming, trucking and courier services, except air and roasted coffee sectors have the most carbon dioxide emissions from direct demand. Therefore, environmental improvements in carbon dioxide emission reduction can easily be achieved by targeting these sectors directly as a first step towards supporting a sustainable coffee supply chain.

Chapter 3

PART II: Post-harvest Inventory Hedging Model For Price-Taker

Most of the literature related to small-scale producer agricultural marketing (e.g. Jayne et al., 2002; IFAD, 2003; Kherallah & Kirsten, 2002; and Dorward et al., 1998) attribute the problem of market access to price risk and uncertainty among others. Recent approaches to deal with price volatility in the coffee market use market-based solutions to hedge risks. For example, coffee roasters and traders depend upon futures markets and related hedging operations to manage their risk profile across market volatility in the coffee market. Yet, small-scale producers who arguably are most in need of market stability are ill-equipped to hedge or diversify their risk exposure. This is because they lack access to hedging tools, have limited understanding of futures markets and risk management coupled with insufficient capital to make initial hedges (Potts et al., 2007).

In 1999, the International Task Force (ITF) on commodity risk management in developing countries was constituted by the World Bank and other development partners to address commodity risk management markets in developing countries. The ITF conducted field studies to assess the feasibility of delivering risk-management products to producers or producer associations and found that nearly all coffee producers considered volatility of prices to be a greater risk than volatility in production (ITF, 2002a). In the context of long-term investments such as those required for perennial crops like coffee and the increased price risk faced by small-scale producers, collective action can reduce individual producer risk (Di Gregorio et al., 2004) through management of price variability in the coffee market.

This underscores the need for instruments to cope with price risk to manage the negative consequences of price variability for small-scale producers who are ill-equipped to hedge or diversify their risk exposure (Gemech et al., 2011). Therefore, innovative ways to manage price variability and its negative consequences for small-scale producers is a key issue for governments and policy-makers (Krivonos, 2004) and more research is needed to design strategies that can help small-scale producers cope with price risk as well as income variability.

3.1 Challenges in Kenya's Coffee Sector

In the case of small-scale coffee producers in Kenya, many do not well understand the market, how it works and why prices fluctuate; and they have little or no information on market conditions and prices. They lack market information, particularly with regards to price setting for their coffee at the auction. Consequently, small-scale coffee producers hold the least amount of bargaining power within the coffee supply chain while the miller/marketing agent is the most powerful actor in the domestic market.

As price takers the small-scale coffee producers are unable to negotiate effectively and have become susceptible to the inherent price volatility in the world coffee market. The real benefits have not been reaching the small-scale coffee producers and this has left them demoralized resulting in neglect of their coffee farms or diversification out of coffee farming to other crops such as bananas.

In addition, the coffee supply chain in Kenya further exposes the small-scale producers directly to price fluctuations without any control of the price risk. For example, the small-scale producers can only get paid after their coffee is sold to importers, further delaying the coffee payments after their coffee has been sold by the marketing agents. This is true because the producers maintain ownership of their coffee until it is sold to importers and have no control on the selling decision. Millers and marketing agents process and sell the coffee and charge a fee for their services. There are eight millers/coffee marketing agents in Kenya.

However, since the millers and marketing agents do not own the coffee, they cannot hold the coffee inventory and wait for a better price but have to sell all the harvest each season for whatever price offered. This is shown in figure 3.1 and we observe that the current strategy is to sell all the harvest available in each season. We call this practice the “selling-all” strategy.

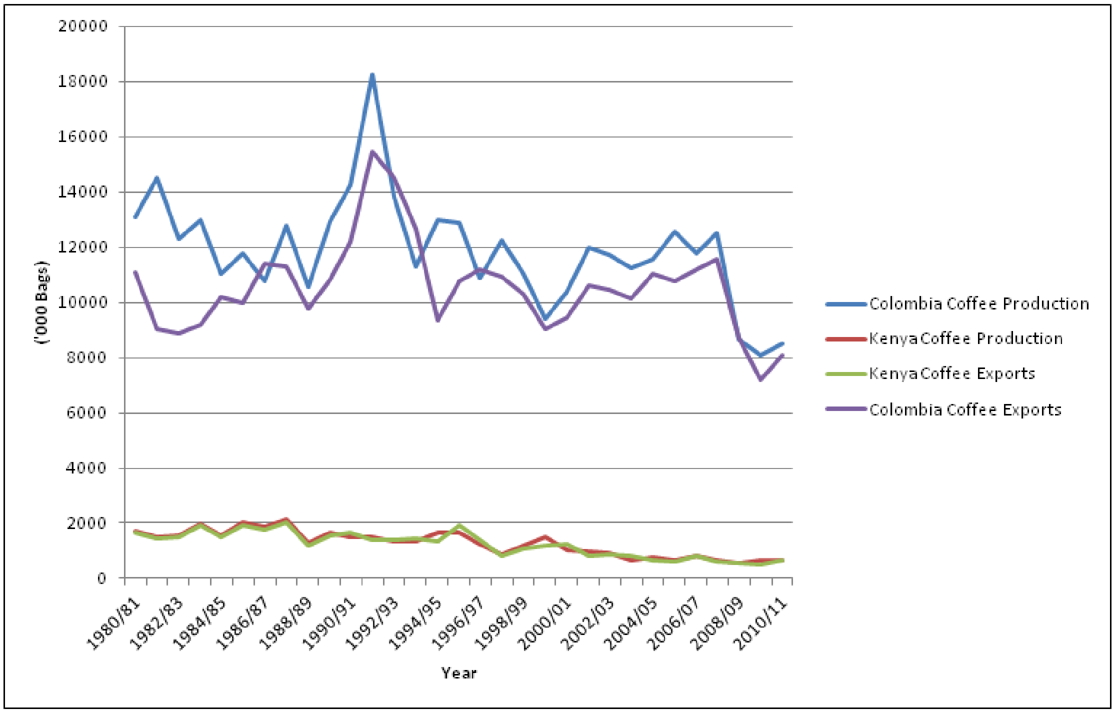


Figure 3.1: Exports vs. Production

Source: ICO Statistics

Declining Production and Exports

In Kenya, coffee ranks fourth in the total export earnings for the country and represents a very significant source of cash incomes for an estimated 700,000 small-scale producers. It is estimated that the coffee industry in Kenya creates over 100,000 jobs and supports millions of people (Nyangito, 2002) through its forward and backward linkages. Despite the pivotal role played by coffee in Kenya's economy, both production and export of coffee has been on a downward trend. During the past twenty years coffee production has declined by 68% in 10 years.

Coffee was the top foreign exchange earner in Kenya accounting for over 10% of the total export earnings during the 1970s and 1980s. In 1998, the sector contributed 11.07% to export earnings. Recently, coffee production and export have been sharply declining and in 2008 the sector contributed a mere 3.27% making coffee rank fourth after tourism, tea and horticulture in export earnings. The export of Kenya's coffee has been decreasing (see Figure 3.2) while the world market share declined from around 3% in 1980s to 0.6% in 2008. The decline of the coffee industry has a disastrous impact on the sustainable livelihood of coffee producers in Kenya and millions of people who directly or indirectly depend on the coffee sector.

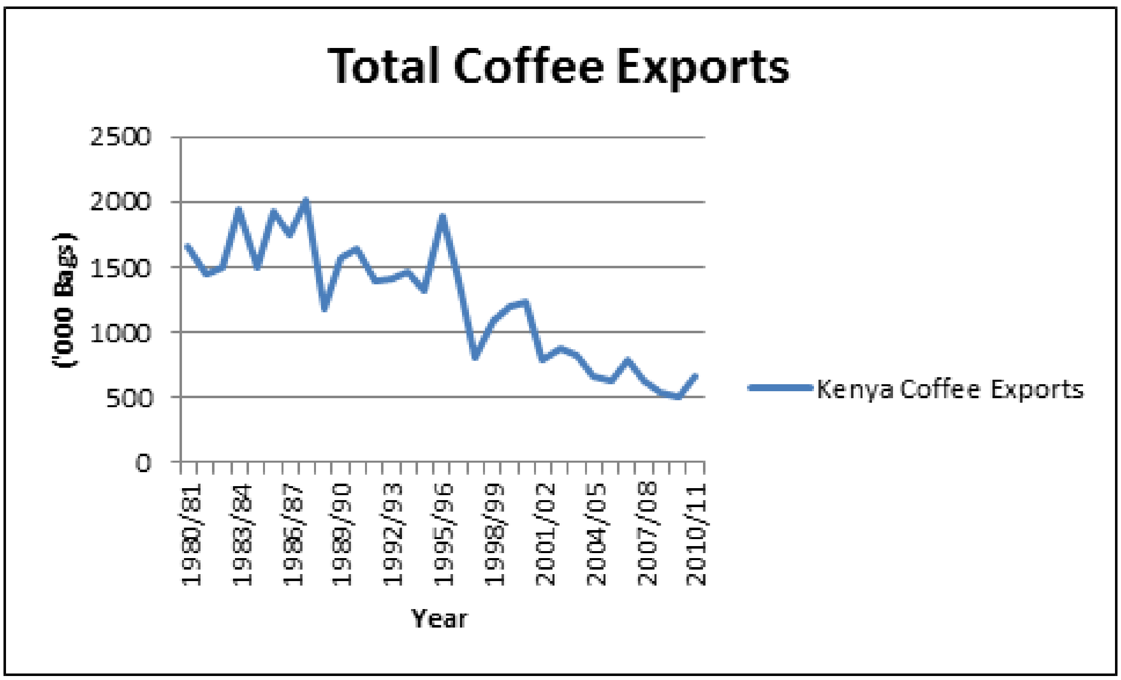


Figure 3.2: Kenya Coffee Exports (1980-2010)

Source: ICO Database Statistics

The supply chain works as follows: In each season, coffee cherries are harvested by producers and handed in to cooperative factories for primary processing. At the primary processing stage the coffee cherries are converted into parchment coffee which is then delivered to coffee millers and converted into green coffee beans. The green coffee beans are graded, warehoused and marketed by marketing agents and finally exported by traders/importers.

3.2 Objective and Main Results

We analyze the extent of post-harvest marketing and inventory-hedging strategy benefits for the small-scale producers in Kenya. The strategy involves costs, so the benefits of inventory hedging need to be evaluated in order to assess its usefulness for small-scale coffee producers. Specifically, we attempt to justify the benefits of post-harvest inventory management by producer organizations such as KCCE based on real-world data, by answering two fundamental questions: (1) What is the value of the inventory-hedging strategy for the small-scale producers? (2) How can KCCE manage post-harvest inventory to hedge the price variation?

To this end, we consider the Kenya coffee supply chain as a whole, including the small-scale producers, cooperatives and KCCE, in a dynamic post-harvest inventory model with random supply and price. We first conduct an empirical study of the Kenya coffee supply chain to fully define our mathematical model. Then we characterize the optimal inventory policy for a variety of cost functions, such as linear, linear plus fixed, concave and convex, for carrying and selling inventory. For convex cost functions, the optimal policy is found to be a selling-down-to policy. For other cost functions, the optimal policy is a selling-all-or-retaining-all policy. For linear cost functions, we further derive closed-form recursive equations to calculate the optimal cut-off price and the optimal discounted profit. We also show that the optimal cut-off prices and discounted profits converge in an infinite time horizon, and derive closed-form expressions for the limits. Finally, we apply the analytical results to the real-world data and quantify the impact of the inventory-hedging strategy. The results show that judiciously retaining inventory for a potentially higher price in the future can significantly outperform the current selling-all strategy.

This part of the dissertation is organized as follows. The next section reviews the literature and in subsequent sections the modeling assumptions are briefly described and justified in an empirical study; the mathematical model and the optimal policy is then presented; the closed form analysis for the carryover levels is presented and a comparison is made of the inventory-hedging model with the current practice (sell-all policy). Finally, numerical experiments based on real world data from Kenya's coffee industry and KCCE is presented to quantify the difference between the two models. Implications are given in the concluding remarks section.

3.3 Literature Review

Our work is related to post-harvest inventory management in the agricultural economics literature, and inventory and risk management in the operations management literature.

Gustafson (1958) introduces dynamic programming to problems of grain storage and discusses the optimal stockpiling rules. The paper takes the perspective of governmental agencies and seeks the objective of maximizing net benefit to the general public by evening out year-to-year supplies. Price is not considered in this model. We refer to Wright (2001) for a review on follow-up works.

This problem is similar to the water storage problem in a dam due to the random exogenous supply and relatively constant consumption, see Prabhu (1998) for a review on dam models. Alaouze, Sturgess and Watson (1978) take the seller's perspective and studies a dynamic programming model for Australian wheat assuming that Australia is a price taker with a limited storage capacity. They solved the model based on empirical data using value iteration. Knapp (1982) generalizes Alaouze, et al., (1978) by considering trade and borrowing in presence of foreign exchange issues.

Berg (1987) considers both risk-neutral and risk-averse farmers for grain carryover problems. Assuming risk neutrality and a general cost function, the paper studies the class of selling-all-or-retaining-all policies and provides a recursive procedure to calculate the best cut-off prices. For risk-averse farmers, the paper shows that spreading sales out over the storage season can be a better policy than selling-all-or-retaining-all. Blakeslee (1997) considers risk-averse model for wheat storage, and uses Taylor-series to approximate the expected utility functions. Lai, Myers and Hanson (2003) confirms the result of Berg(1987) for risk-averse farmers under a more general price distribution.

Tronstad and Taylor (1991) studies a risk-neutral dynamic model to make grain storage decisions and futures market transactions by taking nonlinear tax issues into account. However, because of the large number of factors considered in the model, the resulting decision rule is difficult to characterize and calculate. Fackler and Livingston (2002) considers a dynamic farm marketing model in continuous time by modeling price process by a one-factor Ito diffusion process. The paper shows that the optimal policy is an selling-all-or-retaining policy where the optimal cut-off price can be solved by a partial differential equation.

For risk-neutral models, the only result to date on the optimal inventory policy is by Fackler and Livingston (2002) which considers a continuous-time model and linear profits. It is not known what policy is optimal in discrete time models even for the linear cost functions, let alone real-world complexities such as convex, concave, linear plus fixed cost functions and storage capacity constraints. Although Berg (1987) studies the selling-all-retaining-all policy in discrete time, it does not show whether the policy is optimal among all policies. Indeed, the selling-all-or-retaining-all policy may not be optimal for nonlinear cost functions.

This dissertation contributes to the literature in two ways: Analytically, we provide a comprehensive characterization of the optimal policy for all aforementioned cost functions and constraints in a risk-neutral discrete-time model with either independent or dependent price processes. We show that the selling-all-retaining-all policy is optimal not only for linear cost functions but also for a wide-range of nonlinear cost functions such as linear plus fixed and concave cost functions. However, this policy may not be optimal for convex cost function and systems with capacity constraints. For linear cost functions and independent price process, we further derive closed-form expressions for the optimal cut-off price and total discounted profit in both finite and infinite time horizons. Our equations of the finite horizon simplify those of Berg (1987) by directly connecting the price in one season to the price in the next without calculating the cost-to-go functions. Our result of the infinite time horizon is new. Empirically, we study Kenya's coffee supply chain, apply our analytical results to this real-world practice and demonstrate the impact of the inventory-hedging strategy.

Inventory hedging is studied in the operations management literature for mitigating risks in manufacturing systems. For these systems, the uncertainty mainly comes from demand, and inventory is often used as safety-stock to buffer against potential demand surges. For instance, Abhyankar and Graves (2001) study a manufacturing system facing highly variable and non-stationary demand and develop a hedging policy against such uncertainties by building a safety stock in the material pipeline.

The inventory control problems associated with agricultural products share certain commonalities, such as unpredictable supply, random price and unlimited demand (if the player is a price taker). These features distinguish these problems from those found in typical manufacturing industries where demand and price may be random but external supply is unlimited. These differences lead to different models: for agriculture products, one typically has supply as an exogenous random variable while the demand to be satisfied is a decision variable. In contrast, for manufacturing products one typically has demand as an exogenous random variable while the supply is a decision variable. Thus, it often makes sense to hold inventory and lose sales simultaneously for agriculture products but not for manufacturing products.

Although problems of agricultural and manufacturing industries require different models, the research methodology, e.g., stochastic dynamic programming, remains the same. We refer the readers to Zipkin (2000) and Porteus (2002) for reviews of the inventory control literature for manufacturing industries.

The general idea of hedging the risk by controlling inventory and capacity has been explored quite extensively in the operations management literature, we refer the reader to van Mieghem (2003), Chen, et al., (2007) and Choi, et al., (2010) for recent reviews on both static and dynamic models. Various risk aversion measures are investigated, and operational strategies such as resource diversification, operations flexibility and demand pooling are studied to reduce the profit variance and mitigate risk, see, e.g., van Mieghem (2007) and Tomlin and Wang (2005). Again, while these studies are grounded on manufacturing products and the decisions are on supply, our study is based on agriculture products and the decisions are on demand to be satisfied.

3.4 Empirical Study: Kenya Coffee Sector

In this section, we first conduct an empirical study on the entire Kenya coffee supply chain to support the argument that Kenya is a price taker in the world coffee market.

Next, we conduct an empirical study on KCCE's weekly sales at the auction to show that KCCE is also a price taker at the national coffee market. The empirical studies then help to define our model in §3.5. We also estimate the price and production processes for Kenya coffee, as well as the cost functions and the time discounted factor.

Kenya Coffee Price Time Series

We first characterize the price process for Kenya coffee which is classified by the International Coffee Organization (ICO) as Colombian Milds and sold as such. The price series data analyzed here is the monthly "Colombian Milds selling prices" published by ICO from crop year 1989/90 to 2007/08. The price is in U.S. cents per lb. Because Kenya coffee has one main harvest season each year, we average the monthly prices over a crop-year to obtain a series of annual coffee prices.

Descriptive statistics shows that the price has a mean of 111 cents and a standard deviation of 37 cents. To study the price process, we use a simple least-square regression which yields the following model:

$$P_t \; = \; 41.162 + 0.65 P_{t+1} + \epsilon_t, \tag{3.1}$$

where periods are backward indexed and the R-square is 0.408.

To further test the strength of the first-order auto-correlation, we use the Q-statistic introduced by Box and Pierce (Pindyck and Rubinfeld 1998) to test the following hypothesis.

Null hypothesis: the first-order auto-correlation coefficient of prices is zero.

Alternative hypothesis: the first-order auto-correlation coefficient of prices is NOT zero.

We shall reject the null if the Q-statistic is greater than the critical 5-percent level for a chi-square distribution. In our case, the Q-statistic is 8.392 and the critical value is 3.84, so we reject the null hypothesis and conclude that the first-order auto-correlation coefficient in the coffee price data is not zero at the 5-percent level of significance. We also tested higher order (2nd and 3rd) auto-correlations but didn't find strong enough evidence to show that they are not zero.

Next, we estimate the probability distribution of the residuals ϵ_t. The descriptive statistics show that ϵ_t has a standard deviation of 29 cents. We further test the following hypothesis,

Null hypothesis: the residuals ϵ_t have a normal distribution.

Alternative hypothesis: the residuals ϵ_t do not have a normal distribution.

We test this hypothesis using the Shapiro-Wilk Normality test (Ugarte, Militino and Arnholt 2008, pg 461) and the Jarque Bera test (Pindyck and Rubinfeld 1998, pg 47) at the 5-percent level of significance. Our calculations show that the Shapiro-Wilk Normality test and Jarque Bera test yield statistically insignificant p-values of 0.1074, and 0.3802 respectively. Therefore, we fail to reject the null hypothesis at the 5-percent level of significance, and conclude that the residuals follow a normal distribution.

Kenya Coffee Production Time Series

The annual coffee production data analyzed is collected from the Coffee Board of

Kenya (CBK) annual reports for the crop years from 1989/90 to 2007/08. Descriptive statistics show that the annual production has a mean of 40495 tons and a standard deviation of 14555 tons. To study the auto-correlation of the production data, we use a simple least-square regression which shows the R-square to be 0.221.

To further test the strength of the first-order auto-correlation in annual production data, we use the Q-statistic by Box and Pierce (Pindyck and Rubinfeld, 1998) to test the following hypothesis.

Null hypothesis: the first-order auto-correlation coefficient of production is zero.

Alternative hypothesis: the first-order auto-correlation coefficient of production is NOT zero.

Similar to the price process, we shall reject the null if the Q-statistic is greater than the critical 5-percent level. In this case, the Q-statistic is 3.29 and the critical value is 3.84, so we fail to reject the null hypothesis and conclude that the first-order auto-correlation coefficient in the production data is zero. We also tested higher order auto-correlations (2nd and 3rd) but obtain the same result.

We now estimate the probability distribution of the annual production by testing the following hypothesis.

Null hypothesis: The production data follows a normal distribution.

Alternative hypothesis: The production data does not follow a normal distribution.

We test this hypothesis by the Shapiro-Wilk Normality test and the Jarque Bera Test at 5-percent level of significance. Our calculation shows that these tests yield statistically insignificant p-values of 0.971 and 0.135 respectively. Therefore, we fail to reject the null hypothesis and conclude that the production data follows a normal distribution. Based on these statistical evidence, we can reasonably conclude that the coffee production is independent across crop years.

Kenya Coffee Price vs. Kenya Coffee Production

We now study the dependence between price and production for Kenya coffee. Their correlation coefficient is 0.10 and a scatter plot of price and production is shown in figure 3.3. To further test the strength of the correlation, we use the following hypothesis.

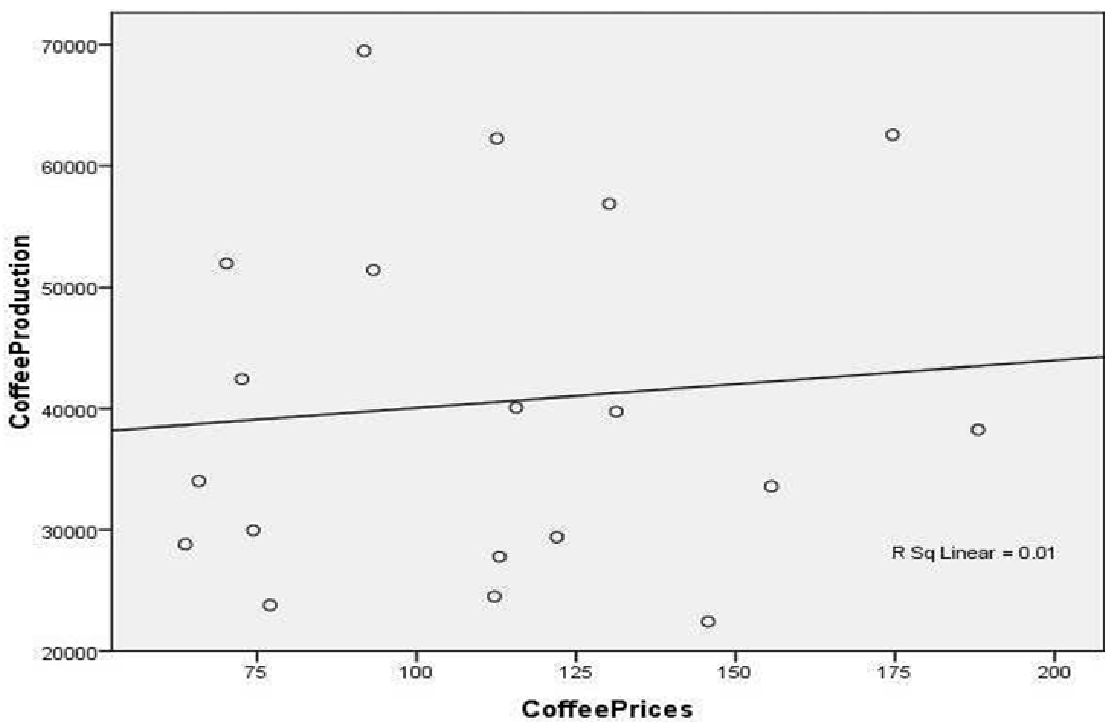


Figure 3.3: Kenya coffee price vs. Kenya coffee production

Null hypothesis: The correlation coefficient between price and production is zero.

Alternative hypothesis: The correlation coefficient between price and production is NOT zero.

We test this hypothesis using the Pearson product-moment correlation coefficient (Sheskin, 2000 pg 766). Specifically, for approximately normally distributed data, the sampling distribution of Pearson's correlation coefficient approximately follows Student's t-distribution. The decision rule is to reject the null hypothesis if the t-statistic is less than the critical value of 2.093 at the 5-percent level of significance (for our case). Our calculation shows that the t-statistic is 2.110 and thus we fail to reject the null hypothesis and conclude that there isn't a significant correlation between coffee prices and coffee production.

We also test the correlation between coffee production and the lagged coffee prices and find that their correlations are not significant as well. From the foregoing statistical evidence, we may reasonably conclude that the price for Kenya's coffee is independent of Kenya's available coffee for sale. Intuitively, this statement makes sense as the price is determined by the total export in the world commodity market, of which Kenya's share is insignificant at 1-3%. This fact renders Kenya a price taker.

KCCE Price Time Series

We now characterize the price process for KCCE which they received at the coffee auction. The price series data analyzed here is the weekly auction prices received by KCCE crop year 2009/10 to 2010/11. The price is in U.S. dollars per 50 kg bag. Descriptive statistics shows that the price has a mean of \$352 and a standard deviation of \$94.2123.

Using regression analysis, we find the price (in \$) follows an AR(1) process as shown:

$$P_t \;=\; 165.4 + 0.6886 P_{t+1} + \epsilon_t, \tag{3.2}$$

where periods are backward indexed and the R-square is 0.56.

To further test the strength of the first-order auto-correlation, we use the Q-statistic introduced by Box and Pierce (Pindyck and Rubinfeld, 1998) to test the following hypothesis.

Null hypothesis: the first-order auto-correlation coefficient of auction prices is zero.

Alternative hypothesis: the first-order auto-correlation coefficient of auction prices is NOT zero.

We shall reject the null if the Q-statistic is greater than the critical 5-percent level for a chi-square distribution. In our case, the Q-statistic is 4.5063 and the critical value is 3.84, so we reject the null hypothesis and conclude that the first-order auto-correlation coefficient in the coffee price data is not zero at the 5-percent level of significance. We also tested higher order 2nd (4.6186) and 3rd (6.3924)) auto-correlations but didn't find strong enough evidence to show that they are not zero.

KCCE Coffee Exports Time Series

The weekly coffee export data analyzed is collected from the coffee auction for the crop years from 2009/10 to 2010/11. Descriptive statistics shows that the weekly exports have a mean of 26.41 bags and a standard deviation of 23.961 bags. To study the auto-correlation of the export data, we use a simple least-square regression as shown: which shows the.

$$Q_t \; = \; 145.4 + 0.1611\, Q_{t+1} + \epsilon_t, \tag{3.3}$$

where periods are backward indexed and the R-square is 0.023.

Based on these statistical evidence, we can reasonably conclude that the coffee exports are independent across weeks and therefore the i.i.d model is appropriate.

KCCE Coffee Price vs. KCCE Coffee Exports

We now study the dependence between price and exports for KCCE coffee. Their correlation coefficient is 0.169 and a scatter plot of price and export is shown in Figure 3.4. A regression between exports and selling price shows a $R^2 = 0.03$ for the linear model and $R^2 = 0.05$ for the log linear model. To further test the strength of the correlation, we use the following hypothesis.

Null hypothesis: The correlation coefficient between price and exports is zero.

Alternative hypothesis: The correlation coefficient between price and exports is NOT zero.

We test this hypothesis using the Pearson product-moment correlation coefficient (Sheskin 2000, pg 766). Specifically, for approximately normally distributed data the sampling distribution of Pearson's correlation coefficient approximately follows Student's t-distribution. The decision rule is to reject the null hypothesis if the t-statistic is less than the critical value of 1.96 at the 5-percent level of significance (for our case). Our calculation shows that the t-statistic is 2.739 and thus we fail to reject the null hypothesis and conclude that there isn't a significant correlation between coffee prices and coffee

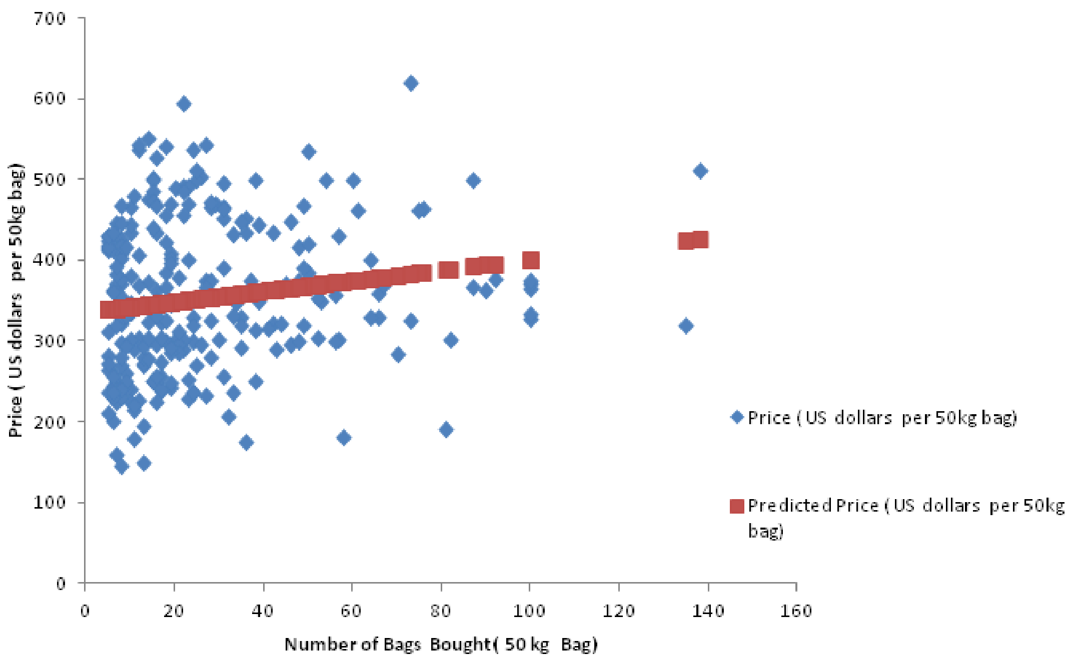


Figure 3.4: KCCE Price vs. Exports (January 2010-November 2010)

exports for KCCE.

We also test the correlation between coffee exports and the lagged coffee prices and find that their correlations are not significant as well. From the foregoing statistical evidence, we may reasonably conclude that the price for KCCE's coffee is independent of KCCE's available coffee for export. Intuitively, this statement makes sense as the price is determined by the total exports in the coffee auction market and KCCE is just but one of the many marketing agents in the Kenya coffee supply chain. KCCE is a price taker at the coffee auction with an insignificant market share of less than 10%.

Costs and Other Parameters

In Kenya, once coffee stocks are sold they cannot be replenished until the next harvest hence the irreversibility assumption by Fackler and Livingston (2002) holds here. The time discounted factor reflects the time value of money. There is a variable cost associated with marketing and selling the coffee in Kenya, including taxes and fees, it amounts to 4.1% of gross sales. This is shown in Table 3.1. The holding costs are assumed to be storage costs and the opportunity cost of capital which is the interest income that one could have earned if the coffee was sold and the receipts were invested in assets such as government bonds. We do not consider the costs of processing coffee as they remain the same regardless of the sales and inventory decisions of the Kenya coffee supply chain.

Marketing cost	**Rate**
Coffee Board of Kenya Levy (tax)	1% of the gross sales
Coffee Research Foundation Levy	2% of the gross sales
Local government cess (tax)	1% of the gross sales
Auctioneer (Marketing agent) fees	0.10 % of gross sales
Source: Coffee Board of Kenya Reports	
Opportunity cost of capital	**Interest Rate**
Treasury Bill(3-month)	2.1%
Treasury Bill(6-month)	2.199%
Treasury Bill(One year)	3%
Source: Central Bank of Kenya (August 2010)	

Table 3.1: Selling Costs

3.5 Mathematic Model

Based on the empirical study in §3.4, we make the following assumptions.

Assumption 3.1

1. *The harvest in a period/season is independent of harvests in previous periods/seasons.*

2. *Kenya/KCCE is a price taker, that is, the price is independent of coffee available for sales in all periods/seasons.*

This assumption implies that the coffee price does not depend on coffee production and its sales decisions. In addition, the demand for coffee can be assumed unlimited at the price. We must point out that the price taker assumption is often made in the literature, see, e.g., Alaouze et al., (1978); Berg (1987) and Fackler & Livingston (2002). For obvious reasons, the price and harvest of coffee at each season must be positive.

We assume that the coffee (green beans or parchment) can be carried for an indefinite time. We also assume that the decision makers are risk neutral. For inventory carried over from one season to the next, we assume an inventory carrying cost per season.

Following convention, we consider a planning horizon of T seasons with a backward index $t = 0, 1, 2, ..., T$ where $t = 0$ is the last season and $t = T$ is the first season.

- P_t: the price (a random variable) for Kenya's coffee at season t, $P_t > 0$; we denote its realization by p_t.

- Q_t: Kenya coffee supply/harvest (a random variable) at season t, $Q_t > 0$.

- I_t: coffee inventory available for sale at the end of season t.
- x_t: the amount of coffee sold at the end of season t.
- y_t: the coffee inventory carried over from season t to season $t-1$.
- $H_t(y_t)$: holding cost function for coffee carried over from season t to season $t-1$.
- c_t: variable cost for sales transaction at season t.
- K_t: fixed cost for sales transaction at season t.
- β: time discounted factor.

We assume the following sequence of events: At the end of season t, coffee harvest Q_t in this season is realized which is q_t. The total coffee available for sales is $I_t = y_{t+1} + q_t$. The sales decision, x_t, is made, and the leftover inventory (if any) $y_t = I_t - x_t$ is carried to the next season. In the last season, we assume that all inventory available must be sold.

Instead of x_t, we use y_t as decision variables. Let $V_t(I_t, p_t)$ be the optimal total discounted supply chain profit from season t to the end of the planning horizon with an initial coffee inventory I_t and a price p_t at season t.

$$V_t(I_t, p_t) = \max_{0 \le y_t \le I_t} \{(p_t - c_t)(I_t - y_t) - H_t(y_t) + \beta E[V_{t-1}(y_t + Q_{t-1}, P_{t-1})|p_t]\}, \quad (3.4)$$

$$V_0(I_0, p_0) = p_0 * I_0, \quad (3.5)$$

where the expectation is taken with respect to Q_{t-1} and P_{t-1}.

3.6 Linear Cost Functions and Independent Price

In this section, we consider independent price process $\{P_t\}$, and $H_t(y_t) = h_t y_t$, $c_t = 0$, $K_t = 0$ for all t, where h_t is the inventory carrying cost per unit per season. We first characterize the optimal selling/inventory policy and derive closed-form expressions for the policy and the total discounted profit in a finite time horizon. Then, we study the problem in an infinite time horizon.

3.6.1 Optimal Policy

By Eqs. (3.4)-(3.5),

$$V_t(I_t, p_t) = p_t \cdot I_t + \max_{0 \le y_t \le I_t} \{-(p_t + h_t) \cdot y_t + \beta E[V_{t-1}(y_t + Q_{t-1}, P_{t-1})]\}, \tag{3.6}$$

$$V_0(I_0, p_0) = p_0 * I_0. \tag{3.7}$$

To identify the structure of the optimal selling policy, we define

$$g_t(y_t, p_t) = -(p_t + h_t) * y_t + \beta E[V_{t-1}(y_t + Q_{t-1}, P_{t-1})] \tag{3.8}$$

and

$$G_t(I_t, p_t) = \max_{0 \le y_t \le I_t} g_t(y_t, p_t). \tag{3.9}$$

Lemma 3.1 *$V_t(I_t, p_t)$ is concave in I_t for $I_t \ge 0$ and for all $t = 0, 1, 2, ..., T$.*

Proof. Clearly, $V_0(I_0, p_0) = p_0 * I_0$ is concave in I_0 for $I_0 \ge 0$. Suppose $V_{t-1}(I_{t-1}, p_{t-1})$ is concave in I_{t-1}, we now show that $V_t(I_t, p_t)$ is concave in I_t. $V_{t-1}(I_{t-1}, p_{t-1})$ being concave in I_{t-1} implies that $E[V_{t-1}(y_t + Q_{t-1}, P_{t-1})]$ is concave in y_t, which further implies that $g_t(y_t, p_t)$ is concave in y_t for $y_t \geq 0$. Let $s_t \geq 0$ be the point that maximizes $g_t(y_t, p_t)$ for all $y_t \geq 0$. Clearly, y_t is a function of p_t. But for simplicity, we suppress the dependence in the notation. Thus,

$$G_t(I_t, p_t) = \begin{cases} g_t(I_t, p_t) & \text{if} \quad I_t \leq s_t, \\ g_t(y_t, p_t) & \text{if} \quad I_t > s_t. \end{cases} \tag{3.10}$$

Clearly, $G_t(I_t, p_t)$ is concave in I_t for $I_t \geq 0$. Therefore, $V_t(I_t, p_t) = p_t * I_t + G_t(I_t, p_t)$ is concave in I_t for $I_t \geq 0$. □

By Lemma 3.1, it is straightforward to identify the structure of the optimal selling policy, as follows.

Theorem 3.1 *The optimal selling policy for the problem defined in Eqs. (3.6)-(3.7) is a "sell-down-to" policy, where at season $t \neq T$, it is optimal to set the inventory carried over to season $t-1$, y_t, to*

$$y_t = \begin{cases} I_t & \textit{if} \quad I_t \leq s_t, \\ s_t & \textit{if} \quad I_t > s_t, \end{cases} \tag{3.11}$$

where $g_t(y_t, p_t)$ researches its maximum at s_t.

That is, it is optimal to bring inventory down to s_t if available inventory is higher than this level. Otherwise, one should carry all available inventory to the next season. We call s_t the optimal sell-down-to level.

We now study the impact of system parameters p_t and h_t on the optimal selling policy. By Eq. (3.8), we note that increasing p_t or h_t reduces the first derivative of $g_t(\cdot)$ (with respect to y_t) and thus results in smaller s_t. In view of $x_t = I_t - y_t$, we conclude the sensitivity of y_t and x_t in the following proposition.

Proposition 3.1 *The optimal selling-down-to level, s_t, is decreasing in p_t and h_t. The optimal selling volume, x_t, is increasing in I_t, p_t and h_t.*

3.6.2 Closed-Form Expressions

Now we derive a closed-form expression for y_t^* and for $V_t(I_t, p_t)$. We work backwards by first looking at season $t = 1$. By Eqs. (3.6)-(3.7), we must have

$$\begin{aligned} V_1(I_1, p_1) &= p_1 \cdot I_1 + \max_{0 \le y_1 \le I_1} \{-(p_1 + h_1) \cdot y_1 + \beta E[P_0(y_1 + Q_0)]\}, \\ &= p_1 \cdot I_1 + \max_{0 \le y_1 \le I_1} \{-(p_1 + h_1 - \beta E[P_0]) \cdot y_1 + \beta E[P_0] E[Q_0]\}. \end{aligned}$$

The second equality holds because we assume price and supply to be independent (see Assumption 3.1). Clearly, y_1^* can be determined as follows,

$$y_1^* = \begin{cases} 0 & \text{if} \quad p_1 \ge \beta E[P_0] - h_1, \\ I_1 & \quad \text{Otherwise.} \end{cases} \tag{3.12}$$

So the optimal policy is a selling-all-or-retaining-all policy which depends on the cut-off price defined as

$$p_1^* = \beta E[P_0] - h_1. \tag{3.13}$$

The optimal discounted profit $V_1(I_1, P_1)$ can be expressed as follows:

$$\begin{aligned} V_1(I_1, p_1) &= \max\{p_1, \beta E[P_0] - h_1\} I_1 + \beta E[P_0] E[Q_0] \\ &= \max\{p_1, p_1^*\} I_1 + (p_1^* + h_1) E[Q_0]. \end{aligned} \tag{3.14}$$

Now consider $t = 2$,

$$\begin{aligned} V_2(I_2, p_2) &= p_2 \cdot I_2 + \max_{0 \le y_2 \le I_2} \{-(p_2 + h_2) \cdot y_2 \\ &+ \beta E[\max\{P_1, p_1^*\}](y_2 + E[Q_1]) + \beta(p_1^* + h_1)E[Q_0]\}. \end{aligned}$$

It is easy to see that in this season, the optimal policy is still a selling-all-or-retaining-all policy, where

$$y_2^* = \begin{cases} 0 & \text{if} \quad p_2 \ge \beta E[\max\{P_1, p_1^*\}] - h_2, \\ I_2 & \quad \text{Otherwise.} \end{cases} \tag{3.15}$$

Define the cut-off price as

$$p_2^* \;=\; \beta E[\max\{P_1, p_1^*\}] - h_2,$$

where the expectation is taken with respect to P_1. $V_2(I_2, p_2)$ can be written as follows.

$$V_2(I_2, p_2) \;\; = \max\{p_2, p_2^*\}I_2 + (p_2^* + h_2)E[Q_1] + \beta(p_1^* + h_1)E[Q_0].$$

In general, we consider any season $t > 0$, suppose there exists a cut-off price p_t^* so that $y_t^* = 0$ if $p_t \ge p_t^*$, and $y_t^* = +\infty$ otherwise. We also assume $V_t(I_t, p_t) = \max\{p_t, p_t^*\}I_t + (p_t^* + h_t)E[Q_{t-1}] + \beta(p_{t-1}^* + h_{t-1})E[Q_{t-2}] + \ldots + \beta^{t-1}(p_1^* + h_1)E[Q_0]$ (this is clearly true for $t = 1, 2$). Now we consider season $t + 1$ as follows.

$$\begin{aligned} V_{t+1}(I_{t+1}, p_{t+1}) &= p_{t+1} \cdot I_{t+1} + \max_{0 \le y_{t+1} \le I_{t+1}} \{-(p_{t+1} + h_{t+1}) \cdot y_{t+1} \\ &\quad + \beta E[\max\{P_t, p_t^*\}](y_{t+1} + E[Q_t]) + \beta(p_t^* + h_t)E[Q_{t-1}] + \ldots \\ &\quad + \beta^t(p_1^* + h_1)E[Q_0]\}. \end{aligned}$$

Clearly, y^*_{t+1} can be determined as follows,

$$y^*_{t+1} = \begin{cases} 0 & \text{if} \quad p_{t+1} \geq \beta E[\max\{P_t, p^*_t\}] - h_{t+1}, \\ I_{t+1} & \text{Otherwise,} \end{cases} \tag{3.16}$$

Define the cut-off price as

$$p^*_{t+1} \;=\; \beta E[\max\{P_t, p^*_t\}] - h_{t+1}, \forall t \leq T-1, \tag{3.17}$$

we can write $V_{t+1}(I_{t+1}, p_{t+1})$ as follows,

$$\begin{aligned} V_{t+1}(I_{t+1}, p_{t+1}) \;&=\; \max\{p_{t+1}, p^*_{t+1}\}I_{t+1} + (p^*_{t+1} + h_{t+1})E[Q_t] \\ &\quad + \beta(p^*_t + h_t)E[Q_{t-1}] + \ldots + \beta^t(p^*_1 + h_1)E[Q_0]. \end{aligned} \tag{3.18}$$

We note that Eqs. (3.16)-(3.17) also hold for $t = 0$ if we set $p^*_0 = 0$, and Eq. (3.18) holds for $t = 0$. Note that the cut-off price p^*_{t+1} is independent of the state variables I_{t+1} and p_{t+1}.

3.6.3 Steady-State Analysis

In this section, we consider stationary parameters, that is, $h_t = h$, for all t and prices in all seasons are i.i.d. random variables, i.e., P_t equals to P in distribution for all t. We first derive steady-state limit for the optimal cut-off price, then steady-state limit for the optimal total discounted profit.

Because of the stationary parameters, the recursive equation for p^*_t can be written as follows,

$$p^*_{t+1} \;=\; \beta E[\max\{P, p^*_t\}] - h.$$

Define

$$L(x) \;=\; \beta E[\max\{P, x\}] - h.$$

Clearly, $L(x)$ is non-decreasing and convex in x because the function $\max\{p, x\}$ is non-decreasing and convex in x for each realization of $P = p$. Because the domain of P is finite, $\lim_{x\to+\infty} \frac{dL(x)}{dx} = \beta$. If $L(0) = \beta E[P] - h \geq 0$, then there is a unique intersection between $y = L(x)$ and $y = x$ (see Figure 3.5); that is, there is a unique solution to $x = L(x)$. Denote the solution to be p^*, clearly, $p^* \geq \beta E[P] - h$.

If $L(0) = \beta E[P] - h < 0$, then $p_1^* = L(0) < 0$ and there is no solution for $x = L(x)$. In addition, we must have $p_t^* = L(0) < 0$ for any $t \geq 2$ (by Eq. (3.17) and the non-negativity of P). Intuitively, $L(0) < 0$ means that it is too expensive to carry inventory even for one season and so the optimal policy is to sell all available inventory at each season.

So $L(0) < 0$ is a degenerate special case, and the case of $L(0) = \beta E[P] - h \geq 0$ is more interesting and relevant. We shall assume $L(0) \geq 0$ for the rest of this paper.

$$\begin{aligned} p_1^* \;&=\; \beta E[P] - h \;=\; L(0) \\ p_2^* \;&=\; L(p_1^*) \;\geq\; L(0) \;=\; p_1^*, \end{aligned}$$

where the inequality follows the non-decreasing property of $L(x)$. We continue in this fashion by assuming $p_t^* \geq p_{t-1}^*$ for any $t > 1$, then

$$p_{t+1}^* = L(p_t^*) \geq L(p_{t-1}^*) = p_t^*,$$

which implies that as T increases, p_t^* is increasing. Consequently, it is easy to show,

$$p_{t+1}^* - p_t^* \;=\; \beta E[\max\{P, p_t^*\} - \max\{P, p_{t-1}^*\}] \;\leq\; \beta(p_t^* - p_{t-1}^*). \tag{3.19}$$

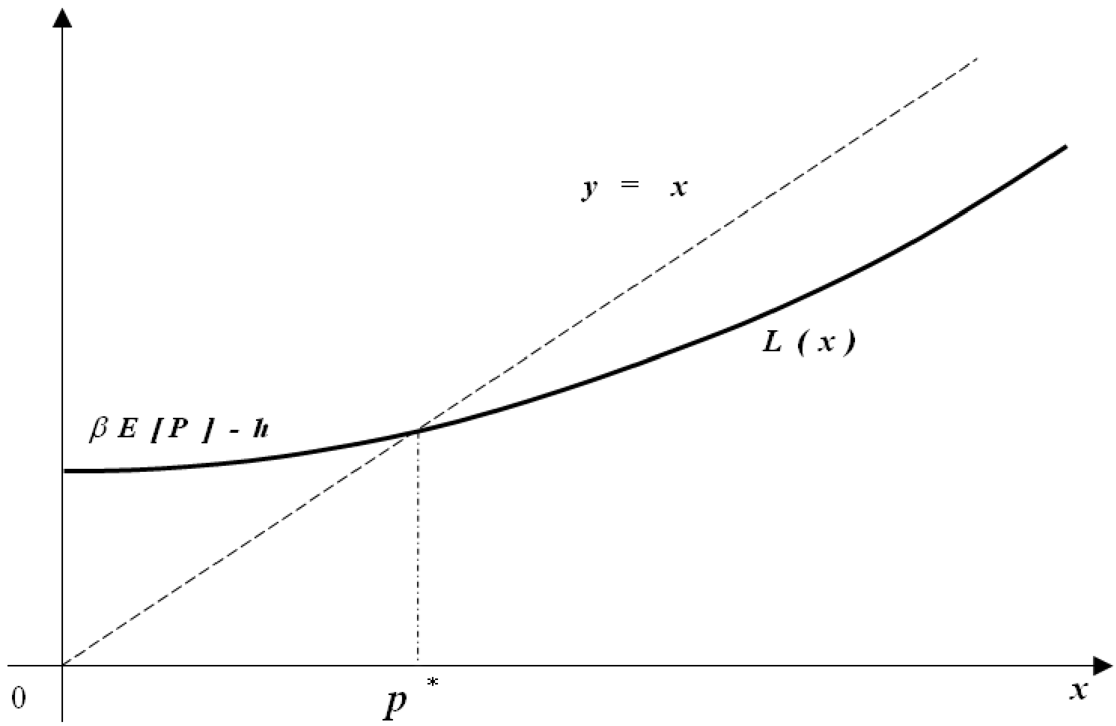


Figure 3.5: The intersection between $y = L(x)$ and $y = x$.

Thus $y = L(x)$ is a Banach contraction mapping because $\beta < 1$ (Dugundji and Granas 2010, pg 9). By Banach fixed point theorem, as $t \to +\infty$, p_t^* increases and converges to p^*, where p^* is determined by

$$p^* \; = \; L(p^*) \; = \; \beta E[\max\{P, p^*\}] - h. \tag{3.20}$$

We note that p^* depends only on β, h and the price distribution but not on distribution of supply Q_t (we do not even require Q_t to be specific form, e.g., i.i.d here).

The result of $\beta E[P] - h = p_1^* \leq \ldots \leq p_t^* \leq p_{t+1}^* \to p^*$ has an important practical implication: the more seasons in the future that one plans to sell, the higher the cut-off price should be because one has a better chance of getting a good price in the future. We can use $p^* - (\beta E[P] - h)$ to characterize the impact of carry-over between an indefinite future horizon and one season left before selling all.

To derive the limit for the optimal discounted profit in an infinite time horizon, we require that Q_t are i.i.d. random variables, i.e., Q_t equals to S in distribution for all t. By Eq. (3.18), we know that for $t \geq 0$,

$$\begin{aligned} V_{t+1}(I,p) &= \max\{p, p^*_{t+1}\}I + (p^*_{t+1} + h)E[Q] \\ &\quad +\beta(p^*_t + h)E[Q] + \ldots + \beta^t(p^*_1 + h)E[Q]. \end{aligned}$$

Define,

$$\begin{aligned} U_{t+1}(I,p) &= \max\{p, p^*\}I + (p^* + h)E(Q) \\ &\quad +\beta(p^* + h)E(Q) + \ldots + \beta^t(p^* + h)E(Q) \\ &= \max\{p, p^*\}I + (p^* + h)E(Q)\frac{1-\beta^{t+1}}{1-\beta}. \end{aligned} \tag{3.21}$$

Their difference can be written as follows,

$$\begin{aligned} \Delta_{t+1} &= U_{t+1}(I,p) - V_{t+1}(I,p) \\ &= (\max\{p, p^*\} - \max\{p, p^*_{t+1}\})I + E[Q][(p^* - p^*_{t+1}) + \beta(p^* - p^*_t) + \\ &\quad \ldots + \beta^t(p^* - p^*_1)]. \end{aligned}$$

By Eq. (3.19),

$$\begin{aligned} p^* - p^*_{t+1} &= p^* - p^*_{t+2} + p^*_{t+2} - p^*_{t+1} \\ &= p^* - p^*_{t+n} + p^*_{t+n} - p^*_{t+n-1} + \ldots + p^*_{t+2} - p^*_{t+1}, \text{ for } n > 1 \\ &\leq p^* - p^*_{t+n} + \frac{(p^*_{t+2} - p^*_{t+1})(1-\beta^{n-1})}{1-\beta}, \text{ for } n > 1. \end{aligned}$$

Let $n \to \infty$ and note that $p^*_{t+n} \to p^*$, we arrive at

$$\begin{aligned} p^* - p^*_{t+1} &\leq \lim_{n\to\infty} \left[p^* - p^*_{t+n} + \frac{(p^*_{t+2} - p^*_{t+1})(1-\beta^{n-1})}{1-\beta} \right] \\ &= \frac{p^*_{t+2} - p^*_{t+1}}{1-\beta}. \end{aligned}$$

Thus,

$$\begin{aligned} \Delta_{t+1} &\leq (\max\{p, p^*\} - \max\{p, p^*_{t+1}\})I \\ &\quad + E[Q]\left[\frac{p^*_{t+2} - p^*_{t+1}}{1-\beta} + \beta \frac{p^*_{t+1} - p^*_t}{1-\beta} + \ldots + \beta^t \frac{p^*_2 - p^*_1}{1-\beta} \right] \\ &\leq (\max\{p, p^*\} - \max\{p, p^*_{t+1}\})I + E[Q]\beta^t \frac{p^*_2 - p^*_1}{1-\beta}(t+1) \\ &\to 0 \text{ as } t \to \infty, \end{aligned}$$

where the second inequality follows Eq. (3.19), and the convergence result follows by the fact that $p^*_t \to p^*$ as $t \to \infty$. In summary, we have,

$$\lim_{t\to\infty} V_t(I, p) = \lim_{t\to\infty} U_t(I, p) = \max\{p, p^*\}I + (p^* + h)E[Q]/(1-\beta). \tag{3.22}$$

3.7 Extensions

It is straightforward to incorporate $c_t > 0$ in Eqs. (3.4)-(3.5) by redefining $P'_t = P_t - c_t$ to be the price. In what follows, we discuss convex cost functions (e.g., convex $H_t(\cdot)$), storage capacity constraints, concave cost functions, linear $H_t(\cdot)$ and a fixed sales cost $K_t > 0$, and a class of dependent price processes.

3.7.1 Convex Cost Functions and Storage Capacity Constraints

We consider two cases with the first case being convex $H_t(\cdot)$ while everything else remains the same as in §3.6. In this case, the single-period cost function, $-p_t y_t - H_t(y_t)$ is concave. It is straightforward to check that Lemma 3.1 and Theorem 3.1 hold. Because of the concavity of the single-period cost function, it may be optimal to sell a portion of the available inventory and retain the rest in a season.

The second case is the problem analyzed in §3.6 but with a storage capacity constraint, $y_t \leq C_t$. Eqs.

$$\begin{aligned} V_t(I_t, p_t) &= p_t \cdot I_t + \max_{0 \leq y_t \leq \min\{I_t, C_t\}} \{-(p_t + h_t) \cdot y_t \\ &\quad + \beta E[V_{t-1}(y_t + Q_{t-1}, p_{t-1})]\} \end{aligned} \tag{3.23}$$

$$V_0(I_0, p_0) = p_0 \cdot I_0. \tag{3.24}$$

Theorem 3.2 *For the problem defined in Eqs. (3.23)-(3.24), $V_t(I_t, p_t)$ is concave in I_t for all $t \geq 0$.*

Proof. By Eq. (3.24), $V_0(I_0, p_0)$ is concave in I_0. Now suppose $V_{t-1}(I_{t-1}, p_{t-1})$ is concave in I_{t-1}, then $-(p_t + h_t) * y_t + \beta E[V_{t-1}(y_t + Q_{t-1}, P_{t-1})]$ is concave in y_t. Further, in veiw of Lemma 5.1, we conclude function $V_t(I_t, p_t)$ is concave. The proof is now completed. □

In view of Theorem 3.1, Theorem 3.2 implies that with a storage capacity constraint, the optimal policy is a selling-down-to policy which may suggest to sell only a portion of the available inventory and retain the rest.

3.7.2 Concave Cost Functions

Let $H_t(\cdot)$ be concave and everything else be the same as in §3.6. In this case, the single-period cost function, $-p_t y_t - H_t(y_t)$ is convex. We have the following theorem.

Theorem 3.3 *If $H_t(\cdot)$ is concave for all $t > 0$, then $V_t(I_t, p_t)$ is convex in I_t, and the optimal policy at season t is a selling-all-or-retaining-all policy for all $t > 0$.*

Proof. By Eq. (3.6),

$$V_t(I_t, p_t) \;=\; p_t * I_t + \max_{0 \le y_t \le I_t} \{-p_t y_t - H_t(y_t) + \beta E[V_{t-1}(y_t + Q_{t-1}, p_{t-1})]\}. \quad (3.25)$$

Suppose $V_{t-1}(I_{t-1}, p_{t-1})$ is convex in I_{t-1} (clearly true for $V_0(I_0, p_0) = p_0 I_0$), then $-p_t y_t - H_t(y_t) + \beta E[V_{t-1}(y_t + Q_{t-1}, P_{t-1})]$ is convex in y_t. Because the maximization over a convex function must be achieved at the end points, thus the optimal solution to Eq. (3.25) must be a selling-all-or-retaining-all policy, where

$$\begin{aligned} V_t(I_t, p_t) \;&=\; p_t * I_t + \max\{-H_t(0) + \beta E[V_{t-1}(Q_{t-1}, P_{t-1})] \\ &\quad -p_t I_t - H_t(I_t) + \beta E[V_{t-1}(I_t + Q_{t-1}, P_{t-1})]\}. \end{aligned}$$

Because the maximum of a constant and a convex function is also a convex function, $V_t(I_t, p_t)$ must be convex in I_t. □

3.7.3 Fixed Cost $K_t > 0$ and Linear $H_t(\cdot)$

Define $\delta(x)$ to be the Dirac function where $\delta(0) = 0$ and $\delta(x) = 1$ for $x > 0$. With a fixed transaction cost K_t for sales at each season, the cost function $h_t y_t + \delta(I_t - y_t) K_t$, although still concave, is not continuous, and thus merits a special attention. Eqs. (3.6)-(3.7) become

$$\begin{aligned} V_t(I_t,p_t) &= \max_{0\le y_t\le I_t}\{p_t(I_t-y_t)-\delta(I_t-y_t)K_t-h_ty_t \\ &+ \beta E[V_{t-1}(y_t+Q_{t-1},P_{t-1})]\} \\ &= \max\{-h_tI_t+\beta E[V_{t-1}(I_t+Q_{t-1},P_{t-1})],p_tI_t-K_t \\ &+ \max_{0\le y_t<I_t}\{-(p_t+h_t)y_t+\beta E[V_{t-1}(y_t+Q_{t-1},P_{t-1})]\}\}, \qquad (3.26) \\ V_0(I_0,p_0) &= p_0I_0-K_0. \qquad (3.27) \end{aligned}$$

We have the following proposition.

Proposition 3.2 *If $H_t(y_t)=h_ty_t$ and $K_t\ge 0$ all $t\ge 0$, then $V_t(I_t,p_t)$ is convex in I_t, and the optimal policy at season t is a selling-all-or-retaining-all policy for all $t>0$.*

Proof. Suppose $V_{t-1}(I_{t-1},p_{t-1})$ is convex in I_{t-1} (clearly true for $V_0(I_0,p_0)$, see Eq. (3.27), since $I_0\ge Q_0>0$), then clearly $-(p_t+h_t)y_t+\beta E[V_{t-1}(y_t+Q_{t-1},P_{t-1})]$ is convex in y_t and $-h_tI_t+\beta E[V_{t-1}(I_t+Q_{t-1},P_{t-1})]$ is convex in I_t. In view of Eq. (3.26), because the maximization over a convex function must be achieved at the end points, the maximization over $0\le y_t<I_t$ must be achieved at either $y_t=0$ or $y_t=I_t-\epsilon$ where $\epsilon\to 0$. Due to the fixed cost K_t, the solution $y_t=I_t$ must be superior to any $y_t=I_t-\epsilon$. So the optimal policy is still a selling-all-or-retaining-all policy and

$$V_t(I_t,p_t)=\max\left\{\begin{array}{l} -h_tI_t+\beta E[V_{t-1}(I_t+Q_{t-1},P_{t-1})], \\ p_tI_t-K_t+\beta E[V_{t-1}(Q_{t-1},P_{t-1})] \end{array}\right\}.$$

Because both terms inside the max operator are convex in I_t, and so $V_t(I_t,p_t)$ is convex in I_t. □

To illustrate the impact of the fixed cost, we derive the optimal policy and the optimal discounted profit for $t = 1$. Following a similar procedure as in §3.6.2 (we omit the details), we arrive at

$$V_1(I_1, p_1) \;=\; \max\{p_1 I_1 - K_1, p_1^* I_1\} + \beta E[P_0]E[Q_0] - \beta K_0, \tag{3.28}$$

where p_1^* is defined in Eq. (3.13), and the optimal policy is

$$y_1^* = \begin{cases} 0 & \text{if } [p_1 - p_1^*]I_1 \geq K_1, \\ I_1 & \text{Otherwise.} \end{cases}$$

We can see here that to sell all, it requires not only $p_1 > p_1^*$ as in Eq. (3.12), but also requires p_1 to be sufficiently greater than p_1^* so as to cover the fixed cost K_1. Note that the cut-off price here is $p_1^* + K_1/I_1$ which depends on the available inventory I_1.

Theorem 3.4 *For all period t, if $H_t(y) = h_t y$ and there is positive fixed cost $K_t > 0$, then $V_t(I_t, p_t)$ has the following expression*

$$V_t(I_t, p_t) = p_t I_t - K_t + \Big[(p_t^* - p_t) \cdot I_t + K_t + \beta[T_{t-1}(I_t) - T_{t-1}(0)]\Big]^+ + A_t \tag{3.29}$$

where for $t > 0$

$$A_t \;=\; \Sigma_{i=0}^{t-1}\beta^{i+1}\Big[\mathbf{E}[P_i]\mathbf{E}[Q_i] - K_i + T_{t-1}(0)\Big]; \tag{3.30}$$

$$T_t(y) \;=\; \mathbf{E}\Big[(p_t^* - P_t)(y + Q_t) + K_t + \beta[T_{t-1}(y + Q_t) - T_{t-1}(0)]\Big]^+, \tag{3.31}$$

and $A_0 = 0$, $T_0(y) = 0$ for any $y \geq 0$.

Further, the optimal decision is to sell all if and only if

$$(p_t^* - p_t) \cdot I_t + K_t + \beta[T_{t-1}(I_t) - T_{t-1}(0)] > 0; \tag{3.32}$$

otherwise retain all.

Proof. We prove the result via induction.

For period $t = 1$, $A_1 = 0$ and $T_0(y) = 0$. Then Eq. (3.28) justifies the results.

Next, assume the results hold for $t > 1$. Then Eq. (3.26) can be written as

$$V_{t+1}(I_{t+1}, p_{t+1}) = \max \left\{ \begin{array}{l} p_{t+1}I_{t+1} - K_{t+1} + \beta \mathbf{E}[V_t(Q_t, P_t)], \\ \\ -h_{t+1}I_{t+1} + \beta \mathbf{E}[V_t(I_{t+1} + Q_t, P_t)] \end{array} \right\}.$$

Substituting Eq. (3.29) into the equation above yields

$$\begin{aligned} & V_{t+1}(I_{t+1}, p_{t+1}) = \\ & \max \Big\{ p_{t+1}I_{t+1} - K_{t+1} + \beta \mathbf{E}\Big[(p_t^* - p_t)Q_t + K_t + \beta[T_{t-1}(Q_t) - T_{t-1}(0)]^+\Big], \\ & -h_{t+1}I_{t+1} + \beta \mathbf{E}\Big[(p_t^* - p_t)(I_{t+1} + Q_t) + K_t + \beta[T_{t-1}(I_{t+1} + Q_t) - T_{t-1}(0)]^+\Big]\Big\} + \beta A_t. \end{aligned}$$

Note that the expectation terms on the right hand side of the equation above can be expressed by $T_t(\cdot)$ according to Eq. (3.31). Hence

$$V_{t+1}(I_{t+1}, p_{t+1}) = \max \Big\{ p_{t+1}I_{t+1} - K_{t+1} + \beta T_t(0), -h_{t+1}I_{t+1} + \beta T_t(I_{t+1}) \Big\} + A_{t+1}.$$

The above equation can be readily written as Eq. (3.29), which completes the proof. Finally, the necessary and sufficient condition given by Eq. (3.32) readily follows from Eq. (3.29). □

3.7.4 Markov-Modulated Price Process

Define W_t to be a random vector of state variables that characterize the world dynamics of coffee trade. We relax the independent price assumption by assuming that (P_t, W_t)

follows an irreducible discrete-time Markov chain with a finite number of states. Let w_t be a realization of W_t. Eqs. (3.6)-(3.7) can be written as,

$$\begin{aligned} V_t(I_t, p_t, w_t) &= p_t * I_t + \max_{0\leq y_t \leq I_t} \Big\{ -(p_t + h_t) * y_t \\ &+ \beta E[V_{t-1}(y_t + Q_{t-1}, P_{t-1}, W_{t-1}) \Big| (p_t, w_t)] \Big\}, \qquad (3.33) \\ V_0(I_0, p_0, w_0) &= p_0 * I_0, \qquad (3.34) \end{aligned}$$

where the expectation is taken with respect to Q_{t-1}, P_{t-1} and W_{t-1} conditioning on (p_t, w_t). Even with dependent prices, the results in §3.6.1-3.6.2 still hold except that the optimal policy and the cut-off price at season $t-1$ now depend on the state variables (p_{t+1}, w_{t+1}). Specifically,

$$p^*_{t+1}(p_{t+1}, w_{t+1}) = \beta E\Big[\max\{P_t, p^*_t(P_t, W_t)\}\Big| (p_{t+1}, w_{t+1})\Big] - h_{t+1}. \qquad (3.35)$$

In the special case of auto-correlated prices, $P_t = a + bP_{t+1} + \epsilon_t$,

$$\begin{aligned} p^*_1(p_1) &= \beta E[P_0|p_1] - h_1 \\ p^*_{t+1}(p_{t+1}) &= \beta E[\max\{P_t, p^*_t(P_t)\}|p_{t+1}] - h_{t+1}. \end{aligned}$$

The optimal discounted profits, Eqs. (3.14) and (3.18), can be written as

$$\begin{aligned} V_1(I_1, p_1) &= \max\{p_1, p^*_1(p_1)\}I_1 + (p^*_1(p_1) + h_1)E[Q_0] \\ V_{t+1}(I_{t+1}, p_{t+1}) &= \max\{p_{t+1}, p^*_{t+1}(p_{t+1})\}I_{t+1} + (p^*_{t+1}(p_{t+1}) + h_{t+1})E[Q_t] \\ &+\beta(E[p^*_t(P_t)|p_{t+1}] + h_t)E[Q_{t-1}] + \dots \\ &+\beta^t(E[p^*_1(P_1)|p_{t+1}] + h_1)E[Q_0]. \end{aligned}$$

3.8 Optimal Inventory Hedging vs. No Hedging

In this section, we compare the effectiveness of the inventory-hedging strategy with the no hedging strategy of selling-all each season. We provide some analytical results in §3.8.1-3.8.2, and a numerical study based on real-world data in §3.8.3.

3.8.1 An Analytical Comparison

We consider the base model in §3.6. By Assumption 3.1, the total discounted profit of the selling-all strategy is $\sum_{t=0}^{T} \beta^t E[P_{T-t}]E[Q_{T-t}]$. Without loss of generality, we assume zero initial inventory at $t = T$. Under the inventory-hedging strategy, the optimal discounted profit is $E[V_T(Q_T, P_T)]$. By Eqs. (3.17)-(3.18),

$$\begin{aligned} E[V_T(Q_T, P_T)] &= E[\max\{P_T, p_T^*\}]E[Q_T] + (p_T^* + h_T)E[Q_{T-1} \\ &\quad + \beta(p_{T-1}^* + h_{T-1})E[Q_{T-2}] + \ldots + \beta^{T-1}(p_1^* + h_1)E[Q_0] \\ &= E[\max\{P_T, p_T^*\}]E[Q_T] + \beta E[\max\{P_{T-1}, p_{T-1}^*\}]E[Q_{T-1}] \\ &\quad + \beta^2 E[\max\{P_{T-2}, p_{T-2}^*\}]E[Q_{T-2}] + \ldots + \beta^T E[P_0]E[Q_0] \end{aligned} \tag{3.36}$$

So

$$\begin{aligned} &E[V_T(Q_T, P_T)] - \sum_{t=0}^{T} \beta^t E[P_{T-t}]E[Q_{T-t}] = \\ &\sum_{t=0}^{T-1} \beta^t \Big(E[\max\{P_{T-t}, p_{T-t}^*\}] - E[P_{T-t}] \Big) E[Q_{T-t}] \geq 0. \end{aligned} \tag{3.37}$$

Not surprisingly, the "inventory-hedging" strategy always outperforms the "selling-all" strategy in expected profit.

For stationary parameters, we can derive even simpler expression for the gap between the "inventory-hedging" strategy and the "selling-all" strategy in the long-run. By Eq. (3.22),

$$\lim_{T\to\infty} E[V_T(Q_T,P_T)] - \lim_{T\to\infty}\sum_{t=0}^{T}\beta^t E[P]E[Q] \;=\; (E[\max\{P,p^*\}]-E[P])E[Q]/(1-\beta). \tag{3.38}$$

For independent price processes with a normal distribution, we can simplify the calculation as follows, Let $P_t \sim \text{normal}(\mu_t,\sigma_t)$, $f_t(x)$ be its probability density function and Z be a standard normal random variable, then

$$\begin{aligned} E[\max\{P_t,p_t^*\}] &= \int_0^{p_t^*} p_t^* f_t(x)dx + \int_{p_t^*}^{\infty} x f_t(x)dx \\ &= p_t^*\text{Prob}\{P_t<p_t^*\} + \sigma_t\int_{\frac{p_t^*-\mu_t}{\sigma_t}}^{\infty} z\phi(z)dz + \mu_t\text{Prob}\{P_t>p_t^*\} \\ &= \mu_t + (p_t^*-\mu_t)\text{Prob}\{Z<\frac{p_t^*-\mu_t}{\sigma_t}\} + \sigma_t\phi(\frac{p_t^*-\mu_t}{\sigma_t}), \end{aligned} \tag{3.39}$$

where $\phi(x) = \frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}}$. Because $P_t > 0$, we must also have

$$\begin{aligned} E[\max\{P_t,p_t^*\}] - E[P_t] &= \int_{-\infty}^{p_t^*}(p_t^*-x)f_t(x)dx \\ &= (p_t^*-\mu_t)\text{Prob}\{Z<\frac{p_t^*-\mu_t}{\sigma_t}\} + \sigma_t\phi(\frac{p_t^*-\mu_t}{\sigma_t}). \end{aligned} \tag{3.40}$$

For autocorrelated price processes, we have

$$\begin{aligned} E[V_T(Q_T,P_T)] = \quad & E[\max\{P_T,p_T^*(P_T)\}]E[Q_T] + \\ & \beta E[E[\max\{P_{T-1},p_{T-1}^*(P_{T-1})\}|P_T]]E[Q_{T-1}] + \\ & \beta^2 E[E[\max\{P_{T-2},p_{T-2}^*(P_{T-2})\}|P_T]]E[Q_{T-2}] + \ldots + \\ & \beta^T E[E[P_0|P_T]]E[Q_0], \end{aligned} \tag{3.41}$$

and

$$E[V_T(Q_T,P_T)] - E[\sum_{t=0}^{T}\beta^t P_{T-t}Q_{T-t}] =$$
$$\sum_{t=0}^{T-1}\beta^t E\Big[E[\max\{P_{T-t}, p^*_{T-t}(P_{T-t})\} - P_{T-t}|P_T]\Big]E[Q_{T-t}] \geq 0,$$

where the outside expectation is taken with respect to P_T.

3.8.2 A Special Case - Constant Price

To see the impact of price volatility, we consider the base model in §3.6 and a special case where P_t is a constant p for all seasons. By Eqs. (3.6)-(3.7),

$$\begin{aligned} V_1(I_1,p) &= p*I_1 + \max_{0\leq y_1\leq I_1}\{-(p+h_1)*y_1 + \beta E[p*(y_1+Q_0)]\} \\ &= p*I_1 + \max_{0\leq y_1\leq I_1}\{-(p+h_1-\beta p)*y_1 + \beta p*E[Q_0]\}. \end{aligned}$$

Clearly, $y_1^* = 0$. Suppose $y_\tau^* = 0$ for $\tau = t-1, t-2, ..., 0$, then

$$\begin{aligned} V_t(I_t,p) &= p*I_t + \max_{0\leq y_t\leq I_t}\{-(p+h_t)*y_t + \beta E[V_{t-1}(y_t+Q_{t-1},p)]\} \\ &= p*I_t + \max_{0\leq y_t\leq I_t}\{-(p+h_t-\beta p)*y_t + p\sum_{\tau=1}^{t}\beta^\tau E[Q_{t-\tau}]\}. \end{aligned}$$

It is easy to see that $y_t^* = 0$. By induction, $y_t^* = 0$ for all $t = 0,1,2,...,T$. Thus if there is no price volatility, it is optimal to sell all available inventory in each season.

3.8.3 Numerical Studies

In this section, we quantify the difference between the "inventory-hedging" strategy and the "sell-all" strategy for three cases: (1) the entire Kenya coffee supply chain, (2) the producer organization KCCE under i.i.d. price process and (3) the producer organization KCCE under AR(1) price process.

Kenya Coffee Supply Chain

By §3.4, the marginal distribution of the price (in cents) is normal(111, 37). The price (in cents) follows an AR(1) process $P_t = a + bP_{t+1} + \epsilon_t$, where $a = 41.2$, $b = 0.65$ and ϵ_t follows a normal(0, 29) distribution. The total Kenya coffee production (in tons) in a season follows normal(40495, 14555). The time discounted factor $\beta = 0.966$ and the selling variable cost is 4.1% of the selling price. We estimate the inventory holding cost per season, h_t, to be 10% of the average price (adjusted by the selling variable cost), which is 10.6 cents/lb/year.

Rather than computing the gap, $E[V_T(Q_T, P_T)] - \sum_{t=0}^{T} \beta^t E[P_{T-t}]E[Q_{T-t}]$, for any T, we focus on $T = 1$ which serves as a lower bound for the gaps of $T > 1$ (see Eq. (3.37)). Specifically, we compute the gap $E[V_1(Q_1, P_1)] - E[P_1 Q_1 + \beta P_0 Q_0]$.

$$\begin{aligned} E[V_1(Q_1, P_1)] &= E[\max\{P_1, p_1^*(P_1)\}]E[Q_1] + (E[p_1^*(P_1)] + h_1)E[Q_0] \\ &= E[\max\{P_1, \beta(a + bP_1) - h_1\}]E[Q_1] + \beta E[a + bP_1]E[Q_0] \\ &= \$206,428,699, \end{aligned}$$

and

$$E[P_1 Q_1 + \beta P_0 Q_0] = \$186,834,169.$$

Thus the gap (additional expected profit) is $19,594,530 or 10.49% of the expected profit of the selling-all strategy in these two years.

KCCE with i.i.d. Price Process

We now quantify the difference between the optimal inventory hedging policy (the selling-all-retaining-all strategy – “SARA”) and the selling all (“SA”) strategy for the KCCE. In particular, we apply KCCE’s weekly selling quantity and the corresponding prices at the Nairobi Coffee Exchange (auction) from January 1, 2010 to November 9, 2010. Secondly, we assume the price process is i.i.d. with a marginal distribution of normal(352.3, 94.1) (in US $ for a 50kg bag of coffee). We obtain a time discounted factor $\beta = 0.9984$ from the 3 month treasury bill issued by the Central Bank of Kenya and for the inventory holding cost we consider the possible values, $h = 0, 1, 2, \cdots, 10$ and then compute the cut-off price dynamically.

We observe that the optimal cut-off prices increase in the number of periods left and as h decreases. Therefore, for the i.i.d. price processes, the weekly cut-off price is exponentially approaching its stationary cut-off price and the higher the holding cost, the lower the cut-off price. See figure 3.6.

Next, we perform a sensitivity analysis of the cut-off prices and the results are given in Figure 3.7. We make three observations: First, the cut-off price decreases in h, but not significantly. Second, the cut-off price increases in β, but not significantly. And finally, the cut-off price could be above or below the average price. This leads us to conclude that the likelihood to Retain-All if the price is stationary decreases in h and increases in β.

Finally, to assess the performance of the SARA policy, we consider (1) *Expected NPV*:

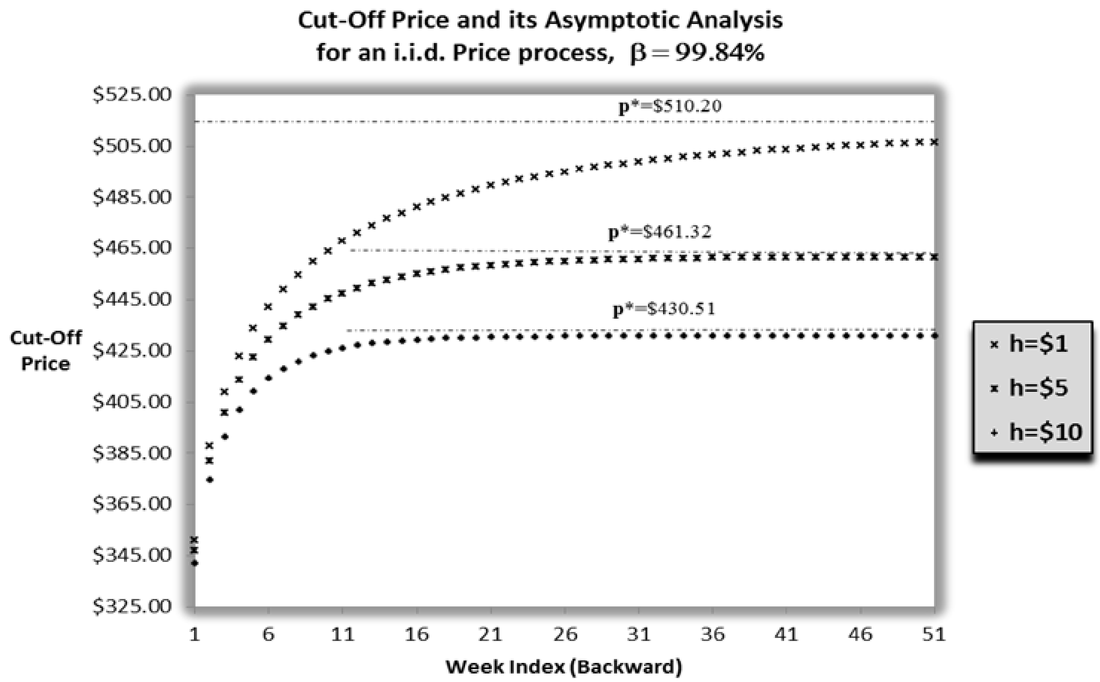


Figure 3.6: Cut-off Prices

the expected net present value of the profits over the periods assessed in November-2010 given the uncertainty of the future periods, and (2) *Sample-Path NPV*: the net present value of profits over the periods while the uncertainty is dynamically realized. We perform a simulation of 10^6 replications.

Table 3.2 displays the NPV values and improving percentage for various holding costs, where $improving\% = SARA/(SARA - SA) \times 100\%$. It shows that the NPV of the "SARA" policy decreases in $\$h$, while that of "SA" does not vary much since there is no left inventory to carry over. Further, the improving% ranges between 19.73% and 15.99% and is decreasing in $\$h$. Thus, less holding cost comes with large improvements by the optimal "SARA" policy as seen in Table 3.2. Thus, we conclude that the inventory

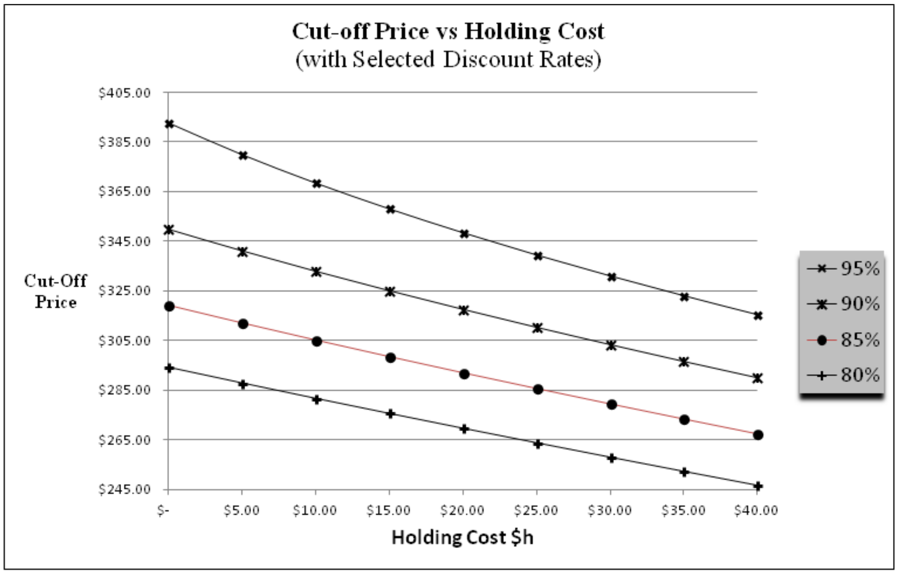


Figure 3.7: Cut-off Price vs Holding Cost

hedging strategy may outperform the sell-all strategy quite significantly.

KCCE with AR(1) Price Process

We now consider the AR(1) price process for KCCE and apply the optimal "SARA" policy to KCCE's weekly exports and selling prices to see the performance of the policy. By Section 3.4 Eq. (3.2), we know the price process follows $P_t = 165.4 + 0.6886P_{t+1} + \epsilon_t$, where ϵ_t $normal(0, 46.5)$. Let h =\$2/bag/week, $\beta = 99.84\%$. We assume the following sequence of the events in each week: First, we observe the market price. Then we update the price distribution for all future weeks. Next we calculate the cut-off prices for the current week and all future weeks. Finally, we compare the cut-off price of the current week with the actual price and make a decision by the "SARA" policy. Table 3.3 shows an example starting from the week of 11/16/2010 with an observed price of

Expected Profit	h = $0	$1	$2	$3	$4	$5	$6	$7	$8	$9	$10
SARA	597,478	595,542	593,588	591,834	589,764	587,905	585,826	583,988	582,500	580,592	578,803
SA	499,030	499,056	498,937	499,151	499,035	499,171	499,014	499,029	498,976	499,074	498,993
Improvement % (SARA−SA)/SA	**19.73%**	**19.33%**	**18.97%**	**18.57%**	**18.18%**	**17.78%**	**17.40%**	**17.02%**	**16.74%**	**16.33%**	**15.99%**

Table 3.2: Comparing SARA and SA Expected Profits

$348.14, where we show that had KCCE used the optimal "SARA" policy, it could have improved its NPV of profit by 26.35% as compared its current selling all (SA) strategy.

Week Index		Weeks to Go							
		1	**3**	**4**	**9**	**10**	**12**	**13**	**15**
	Price	**$348.14**	**$366.98**	**$352.99**	**$434.90**	**$490.63**	**$515.86**	**$590.04**	**$540.87**
1	**$348.14**	**$567.43**	$570.84	$572.36	$570.73	$562.67	$550.54	$526.53	$0.00
3	**$366.98**		**$565.49**	$568.32	$567.83	$560.80	$549.15	$525.65	$0.00
4	**$352.99**			**$563.68**	$564.44	$558.58	$547.49	$524.58	$0.00
9	**$434.90**				**$542.41**	$543.14	$535.99	$517.27	$0.00
10	**$490.63**					**$550.09**	$541.68	$521.25	$0.00
12	**$515.86**						**$541.24**	$522.51	$0.00
13	**$590.04**							**$555.32**	$0.00
15	**$540.87**	Period T, Realized Price							
Optimal Strategy		**RA**	**RA**	**RA**	**RA**	**RA**	**RA**	**SA**	**SA**

Table 3.3: Cut-off Prices (Periodically Updated)

In addition, the table 3.4 shows a range of holding costs and the improving percentage of the SARA policy.

$h	NPV of SA	NPV of SARA	Improvement%
$0.00	$649,298.25	$827,672.79	**27.47%**
$1.00	$649,298.25	$823,995.86	**26.91%**
$2.00	$649,298.25	$820,318.93	**26.34%**
$3.00	$649,298.25	$816,642.00	**25.77%**
$4.00	$649,298.25	$812,965.07	**25.21%**
$5.00	$649,298.25	$809,288.14	**24.64%**
$6.00	$649,298.25	$805,611.21	**24.07%**
$7.00	$649,298.25	$801,934.29	**23.51%**
$8.00	$649,298.25	$798,257.36	**22.94%**
$9.00	$649,298.25	$794,580.43	**22.38%**
$10.00	$649,298.25	$790,903.50	**21.81%**

Table 3.4: Cut-off Prices Performance

3.9 Concluding Remarks

In this study, we provide decision support and justification for KCCE's initiative. Under this initiative, one can control coffee inventory sold each week and carry the rest to future weeks for a potentially better price – the inventory-hedging strategy. Based on an empirical study, we construct a post-harvest dynamic inventory model with random exogenous supply and price. We characterize the optimal control policy and derive closed-form expressions for the policy and the optimal discounted profit. Comparing to the current practice that sells all inventory in each season, we show that the inventory-hedging strategy can increase the profitability of the supply chain and that of KCCE significantly.

Chapter 4

PART III: Post-harvest Inventory Hedging Model For Price-Maker

4.1 Colombia Coffee Growers Federation (CCGF)

Colombian coffee producers organized themselves into the Colombian Coffee Growers Federation (CCGF) way back in 1927. In Colombia there are 570,000 coffee producers and 91% of these are small-scale producers. Unlike Kenya, the federation comprises both small-scale and large-scale producers and handles large volumes of coffee. This means CCGF can achieve economies of scale and is also able to influence world prices. This makes Colombia a price maker.

CCGF has built up markets based on its reputation for quality after creating the Juan Valdez trademark in 1959 helping establish the Colombian coffee brand. According to

Bentely and Baker (2000), Colombian coffee sells at a premium of about 20% with 35% of the coffee being sold as unblended roasts (100% Colombian). This is something that other coffee producing countries have not been able to match. Thus, CCGF is able to sign large contracts with big roasting companies the way small firms (exporters) could never do (Bates, 1997).

CCGF established a coffee fund whose main purpose is to buy the coffee harvest from the coffee producers. However, CCGF does not have a monopoly to buy or export coffee, and private dealers control about half the Colombian coffee market which gives the federation some healthy competition. The coffee fund consists of contributions from both coffee producers and consumers and levies on coffee exports. The fund supports coffee producers by providing a domestic minimum price for a stable income. The coffee producers are guaranteed the minimum coffee price by covering the difference when the price of Colombian coffee falls below it in international coffee market. Currently, the coffee producers in Colombia receive about 95% of the world price for their harvest in the form of a cheque that can be cashed the same day.

CCGF manages price fluctuations on the world market by buying more coffee when prices are low and letting private buyers buy more coffee when prices are high. Therefore, when prices are high CCGF saves money in the coffee fund which is later used to manage price fluctuations by keeping prices from falling too low. When prices are low, CCGF stores coffee in its warehouses to sell when world prices recover.

Nonetheless, an increase in price volatility implies greater uncertainty about future prices. Therefore, increased price volatility will affect even Colombian producers as it reduces the accuracy of their forecasts of future prices, exposing them to higher levels of price risk. Aftet the ICA breakdown in 1989, there was a considerable fall in CCGF's income. For example in 1996 the annual income was about $140 million, having fallen from levels of over $200 million per annum achieved in the last few years of the ICA (Gemech et al., 2011).

4.2 Objectives and Main Results

In this part of the dissertation, we seek to answer two basic questions in CCGF's inventory-hedging strategy based on real-world data: (1) How much coffee should CCGF sell in any one season and what is the value of such an inventory-hedging strategy? (2) How should post-harvest inventory be managed to hedge the coffee price variation?

To this end, we consider the Colombia coffee supply chain, including the small-scale producers and CCGF as a whole, in a dynamic post-harvest inventory model with random supply and constant price elasticity. We first conduct an empirical study of the Colombia coffee supply chain to fully define our mathematical model. Then we characterize the optimal inventory policy for a variety of cost functions, such as linear and linear plus fixed, for carrying and selling inventory.

For linear selling cost functions, the optimal policy is found to be a selling-down-to policy. If there is a fixed selling cost, the optimal policy is a selling-down-to (S, s) policy. We also show that the optimal policies depend on initial inventory level. Finally, we apply the analytical results to the real-world data and compare the performance of the optimal policy to the benchmark of selling-all policy. Thus, we quantify the inventory-hedging strategy on the Colombia coffee supply chain.

The agriculture economics literature has not yet addressed the price-maker models and the inventory pricing models (see, e.g., Chen et al. 2007) developed in operations management literature focus on manufacturing products with fundamentally different assumptions, see Section 3.3. This part of the dissertation is organized as follows. In subsequent sections, the modeling assumptions are described; the mathematical model and the optimal policy is then presented; and a comparison is made between the optimal inventory-hedging policy and the benchmark (the sell-all policy). Finally, numerical experiments based on real world data from CCGF is presented to quantify the difference between the two policies. Implications are given in the concluding remarks section.

4.3 CCGF: Price Maker Model

In this section, we consider the producers or their association as a price maker. Specifically, the market price denoted by P_t is random pertaining to the market uncertainty and its distribution is essentially determined by the selling quantity x_t. We use p_t to denote its realization. The revenue of selling x_t is random and can be expressed as $R_t(x_t, P_t(x))$. We further denote $R_t(x) = \mathbf{E}_P[R_t(x, P_t(x))]$.

Assumption 4.1 *For any period t, $R_t(x)$ is increasing and concave (or linear), and satisfies*

$$\lim_{x\to\infty} R_t(x)/x \quad \leq \quad p_t; \tag{4.1}$$

$H_t(y)$ is increasing and convex (or linear), and satisfies

$$\lim_{y\to\infty} H_t(y)/y \quad \leq \quad h_t. \tag{4.2}$$

4.4 Constant Elasticity of Supply

In economics, *elasticity* is defined as the degree to which a variable (i.e., demand or supply) curve reacts to a change in another variable (e.g., price). Elasticity varies among products because some products may be more essential to the consumer. Products that are necessities are less sensitive to price changes because consumers would continue buying these products despite price increases.

Constant Elasticity Supply function has been adopted in some economics literature [cf. Perloff (2010)]. The general constant elasticity of supply function is $x = a \cdot p^b$, where $a > 0$ is a constant and $b \geq 0$ is the elasticity. For the case with $b = 0$, the supply quantity is constant and it is zero elastic of price which is referred to as *perfectly inelastic*. If $0 < b < 1$, it is called *inelastic*, while $b > 1$ is referred to as *elastic*.

We mention that, being analogous to the constant elasticity supply function, the constant elasticity of demand function is widely adopted in studies of joint price and inventory decisions. We refer the reader to Wang, *et al.* (2004) and Petruzzi and Dada (1999) for reviews and extensions.

Assumption 4.2 *In coffee business, we assume that coffee's price is constantly elastic* *of supply, which is given as*

$$P_t(x_t) = a \cdot x_t^{-b} + \epsilon_t, \tag{4.3}$$

where $a > 0$, $b > 0$ and ϵ_t is normally distributed with zero mean and standard deviation $\sigma_t > 0$.

By Section 4.3, $R_t(x)$ is the expected profit of selling x amount of coffee during period t. For the case with a constant elasticity b, we have the expected revenue of selling x as

$$R_t(x) = \mathbf{E}[R_t(x, P_t(x))] = a \cdot x^{1-b}. \tag{4.4}$$

4.5 The Multi-Period Model

Instead of selling quantity x_t, we use y_t as decision variables. Let $V_t(I_t)$ be the optimal total discounted supply chain profit from season t to the end of the planning horizon with an initial coffee inventory I_t at season t. Accordingly, we have the following dynamic programming model, for $0 < t \leq T$,

$$g_t(I_t, y_t) = R_t(I_t - y_t) - H_t(y_t) + \beta_{t-1}\mathbf{E}[V_{t-1}(y_t + Q_{t-1})], \tag{4.5}$$

and

$$V_t(I_t) = \max_{0 \leq y_t \leq I_t} g_t(I_t, y_t), \tag{4.6}$$

where $V_0(y_1) = R_0(y_1)$. Note that for any $I_t > 0$, $R_t(I_t - y_t, p_t) - H_t(y_t)$ is decreasing in y_t, while $\mathbf{E}[V_{t-1}(y_t + Q_{t-1})]$ is increasing. Nonetheless, the monotonicity of $g_t(I_t, y_t)$ is unclear.

4.5.1 Zero Fixed Cost

If there is no fixed cost for transaction (selling), then we have the following result.

Lemma 4.1 *For any period $t = 0, 1, 2, ..., T$, under Assumption 4.1, if $K_t = 0$, then*

(1) function $g_t(I_t, y_t)$ is concave in (I_t, y_t) for $0 \leq y_t \leq I_t$;

(2) function $V_t(I_t)$ is increasing and concave in $I_t \geq 0$.

Proof. We prove the results by induction.

(a) It is evident that $V_0(I_0) = R_0(I_0)$ is increasing and concave in $I_0 \geq 0$. Therefore, for period $t = 1$, we have

$$g_1(I_1, y_1) = R_1(I_1 - y_1) - H_1(y_1) + \beta\mathbf{E}[R_0(y_1 + Q_0)],$$

which implies $g_1(I_t, y_t)$ is increasing in I_t for any y_t. Taking the second derivative test on $g_1(I_1, y_1)$, one can easily show its Hessian matrix is negative definite. Therefore, part (1) holds for $g_1(I_1, y_1)$. Since $V_1(I_1) = \max_{0 \leq y_1 \leq I_1} g_1(I_1, y_1)$, the increasing property of $V_1(I_1)$ follows from the facts that both g_1 and the max operation increase in I_1. In view of Lemma 5.1, $V_1(I_1)$ is also concave.

(b) Now assume statements (1)-(2) hold for period $t - 1$ and all the periods thereafter. Then by statements (1) and (2), for any given $I_t > 0$, by Eq. (4.5), $g_t(I_t, y_t)$ is increasing in I_t and jointly concave in (I_t, y_t) since $V_{t-1}(\cdot)$ is concave and $R_t(I_t - y_t) - H_t(y_t)$ is also concave by assumption. Hence, the increasing property of $V_t(\cdot)$ follows from the facts that both g_t and the max operation increase in I_t. Furthermore, it is readily shown that $V_t(\cdot)$ is concave in view of Lemma 5.1.

Finally, the proof is complete based on arguments (a) and (b) above. $\square$

By Lemma 4.1, it is straightforward to identify the structure of the optimal selling policy, as follows.

Theorem 4.1 *The optimal selling policy for the problem defined in Eqs. (3.8)-(4.6) is a "sell-down-to-S" policy, where at season $t > 0$, it is optimal to set the inventory carried over to season $t-1$, y_t, to*

$$y_t^*(I_t) = \begin{cases} I_t & \text{if} \quad I_t \leq S_t(I_t), \\ S_t & \text{if} \quad I_t > S_t(I_t), \end{cases} \tag{4.7}$$

where the "sell-down-to" level $S_t(I_t)$ is dependant on I_t and $g_t(I_t, y_t)$ researches its maximum at $S_t(I_t)$.

That is, it is optimal to bring inventory down to $y_t^*(I_t)$ if available inventory is higher than this level. Otherwise, one should carry all available inventory to the next season. We refer to $S_t(I_t)$ as the *optimal sell-down-to level* which is a function of the available inventory I_t in general at the beginning of period t.

To study the sell-down-to level, S_t, for given $I_t > 0$, we take the first order derivative of function $g_t(I_t, y_t)$ with respect to $0 \leq y_t \leq I_t$.

$$\partial g_t(I_t, y_t)/\partial y_t = -R_t'(I_t - y_t) - H_t'(y_t) + \beta_{t-1}\mathbf{E}\Big[V_{t-1}'(y_t + Q_{t-1})\Big] \tag{4.8}$$

Proposition 4.1 *The optimal selling-down-to level, $S_t(I_t)$ is increasing in I_t.*

Proof. By Eq. (4.8), S_t can be identified by

$$R_t'(I_t - S_t) = -H_t'(S_t) + \beta_{t-1}\mathbf{E}[V_{t-1}'(S_t + Q_t)] \tag{4.9}$$

If I_t increases, then the left side of the equation above decreases accordingly by Assumption 4.1. To sustain the equality, S_t should increase such that the right side decreases, which completes the proof. $\square$

4.5.2 Positive Fixed Cost

If there is a positive fixed cost $K_t > 0$ for transaction (selling) in each period, we have the following dynamic programming formulation.

$$g_t(I_t, y_t) = R_t(I_t - y_t) - K_t \cdot \delta(I_t - y_t) - H_t(y_t) + \beta_{t-1}\mathbf{E}\Big[V_{t-1}(y_t + Q_{t-1})\Big] \tag{4.10}$$

and

$$V_t(I_t) = \max_{0 \le y_t \le I_t} g_t(I_t, y_t). \tag{4.11}$$

In the sequel, we shall apply K-concavity approach to derive the optimal solution. Interested readers are referred to Appendix for a brief review of K-concavity.

Lemma 4.2 *(Positive Fixed Cost)*

For any period $t = 1, 2, ..., T$*, under Assumption 4.1, if* $0 < \beta_{t-1} \cdot K_{t-1} \le K_t$*, then*

(1) function $g_t(I_t, y_t)$ *is* K_t*-concave in* $0 \le y_t \le I_t$*;*

(2) function $V_t(I_t)$ *is increasing and* K_t*-concave in* $I_t \ge 0$*, and* $\lim_{I_t \to \infty} V_t(I_t)/I_t = 0$.

Proof. We prove the results by induction.

(a) It is evident that $V_0(I_0) = R_0(I_0) - K_0\delta(I_0)$ is K_0-concave in $I_0 \ge 0$ since $R_0(\cdot)$ is concave. Therefore

$$\hat{g}_1(I_1, y_1) = R_1(I_1 - y_1) - H_1(y_1) + \beta_0 \mathbf{E}[V_0(I_0)|p_t] \tag{4.12}$$

is $\beta_0 K_0$-concave, which implies

$$g_1(I_1, y_1) = \hat{g}_1(I_1, y_1) - K_1 \cdot \delta(I_1 - y_1)$$

is $K_1 = \max\{K_1, \beta K_0\}$-concave. Hence, $V_1(\cdot)$ is K_1-concave.

(b) Now assume statements (1) and (2) hold for period $t > 1$ and all the periods thereafter. Then by statements (1) and (2), we have

$$\hat{g}_{t+1}(I_{t+1}, y_{t+1}) = R_{t+1}(I_{t+1} - y_{t+1}) - H_{t+1}(y_{t+1}) + \beta_t \mathbf{E}\Big[V_t(y_{t+1})|p_t\Big] \tag{4.13}$$

is $\beta_t K_t$-concave, which implies

$$g_{t+1}(I_{t+1}, y_{t+1}) = \hat{g}_{t+1}(I_{t+1}, y_{t+1}) - K_{t+1} \cdot \delta(I_{t+1} - y_{t+1})$$

is $K_{t+1} = \max\{K_{t+1}, \beta_t K_t\}$-concave. Hence, $V_{t+1}(\cdot)$ is K_{t+1}-concave.

Finally, the combination of (a) and (b) concludes the induction and completes the proof. $\square$

By Lemma 4.2, it is straightforward to identify the structure of the optimal selling policy as follows.

Theorem 4.2 *The optimal selling policy for the problem defined in Eqs. (4.10)-(4.11) is a "(S_t, s_t) sell-down-to" policy, where $0 < s_t(I_t) < S(I_t)$ and at period $t \neq T$, it is optimal to set the inventory carried over to season $t-1$ as*

$$y_t^*(I_t) = \begin{cases} I_t & \text{if} \quad I_t \leq S_t(I_t), \\ s_t(I_t) & \text{if} \quad I_t > S_t(I_t), \end{cases} \tag{4.14}$$

where $g_t(y_t, p_t)$ reaches its maximum at $s_t(I_t)$ and $S_t = \sup\{y|y \geq s_t, g_t(y) = g_t(s_t) - K_t\}$.

That is, it is optimal to bring inventory down to S_t if available inventory is higher than s_t. Otherwise, one should carry all available inventory I_t to the next period.

4.6 Optimal Inventory Hedging vs. No Hedging

In this section, we quantify the difference between the "*sell-down-to* " (sell-down-to) strategy and the "*selling-all* " (sell-all) strategy for the Colombian coffee supply chain. In particular, we first apply the historical data from July 2006 through July 2010 to construct the constant elasticity model between price and selling quantity. Secondly, according to the constant elasticity relationship we apply the optimal *sell-down-to* policy to the real business from December 2010 through April 2011 to see the performance of the policy. For the inventory holding cost we consider the possible values, $h = 0, 1, 2, \cdots, 5$.

4.6.1 Constant Supply Elasticity of Colombia Coffee

We collect CCGF's monthly selling price and quantity data from 7/2006 to 7/2010. Taking the vehicle of regression, we find that the export price has a constant elasticity as presented below with $R^2 = 54.63\%$,

$$p(x) = 952918 \times x^{-0.624}.$$

Figure 4.1 depicts the production-price data and the regression of the constant elasticity function.

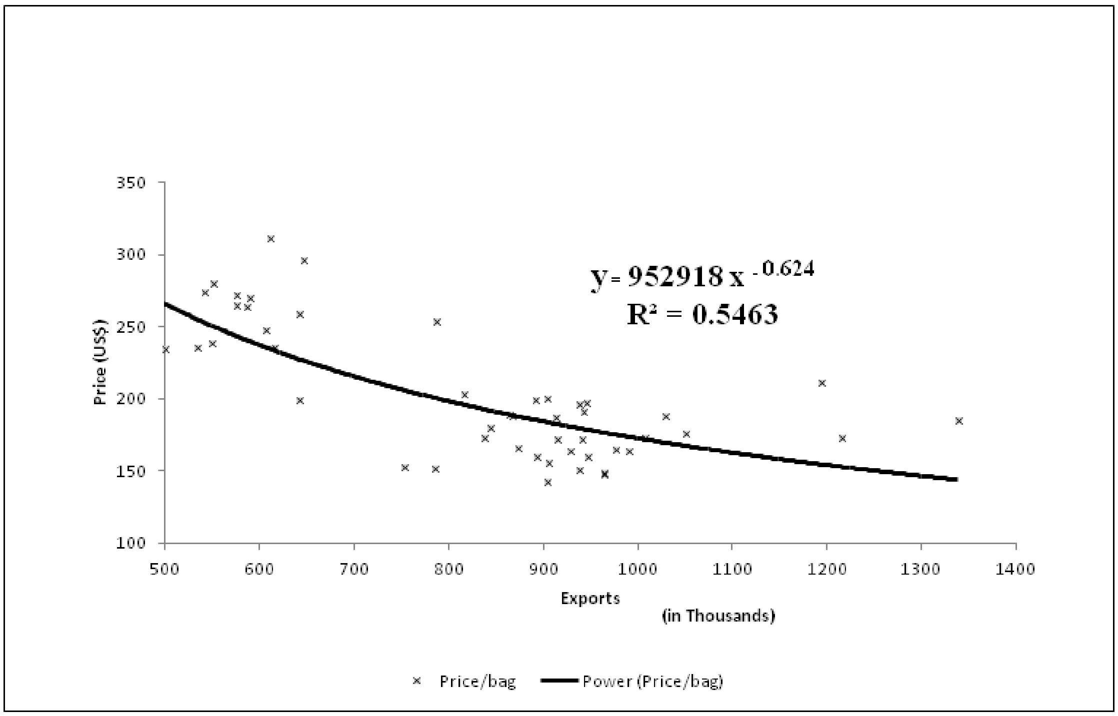


Figure 4.1: Production and Price of Columbia Coffee (July 2006-July 2010)

Figure 4.2 depicts the optimal selling-down-to levels and the corresponding optimal profits for initial inventory levels 10000, 13000 and 16000. It shows that the profit-to-go $V_1(I_1)$ is concave in I_1 and there is a unique optimum for each initial inventory level.

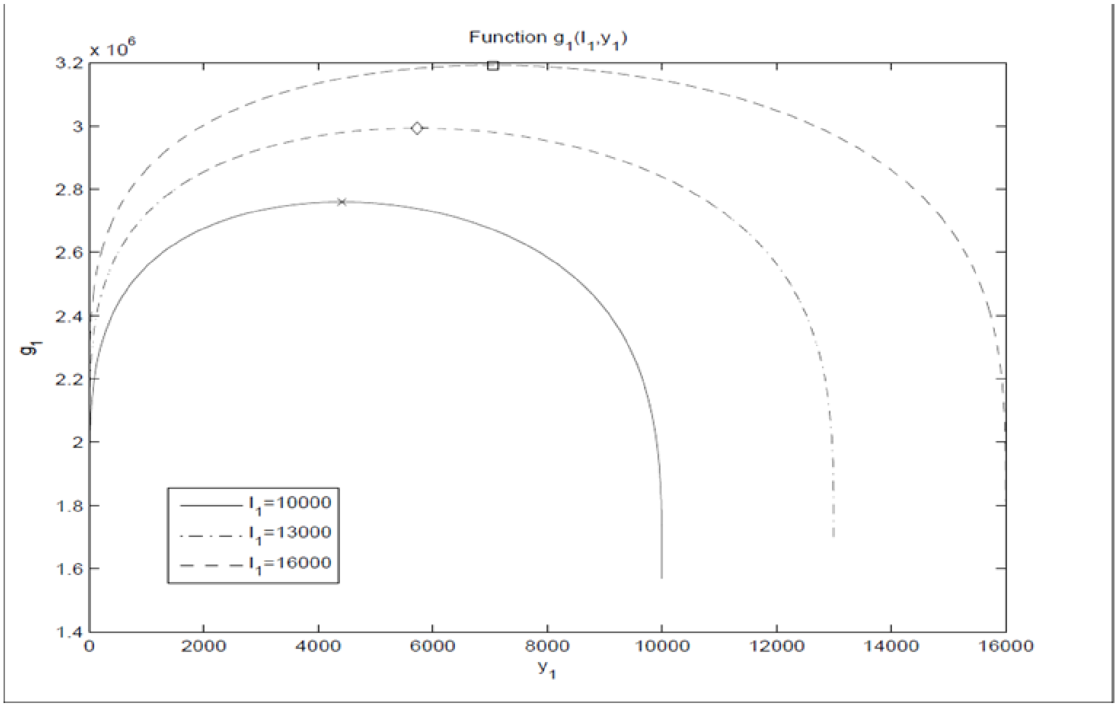


Figure 4.2: Function $g_1(y_2, y_1)$

4.6.2 Numerical Studies

With the constant supply elasticity obtained in §4.6.1, we consider monthly transactions for the period from Dec-2010 to Apr-2011 and assume the initial inventory in Dec-2010 is zero. For the *sell-down-to* policy, the dynamic selling-down-to levels for each month are given in Table 4.1. It shows that the selling-down-to levels decreases in \$$h$. Further, it is optimal to even out the sales in periods.

To assess the performances of *sell-down-to* policy, we consider (1) *Expected NPV*: the expected net present value of the profits over the periods assessed at the beginning of Dec-2010 given the uncertainty of the future periods, and (2) *Sample-Path NPV*:

Table 4.1: Optimal Selling-Down-to Levels ($\times$1000 bags)

Months	**Harvest** (1000 bags)	**\$h** $0	\$1	\$2	\$3	\$4	\$5
1 (Dec-2010)	1164	300	300	300	300	200	200
2 (Jan-2011)	908	400	400	300	200	200	200
3 (Feb-2011)	764	200	200	100	100	0	0
4 (Mar-2011)	779	100	100	0	0	0	0
5 (Apr-2011)	523	0	0	0	0	0	0

the net present value of profits over the periods while the uncertainty is dynamically realized. Table 4.2 displays the NPV values and improving% for various holding costs, where $improving\% = SDT/(SDT - SA) \times 100\%$. It shows that the NPV of *sell-down-to* policy decreases in $\$h$, while that of *selling-all* does not vary since there is no left inventory to carry over. Further, the improving% is decreasing in $\$h$ and improvement is marginal in the range of around 0.1% to 0.8%.

4.6.3 Case: No Harvest in the Last Month

Previously, we assume the harvest in the last month, i.e., April 2011 is realized and all the inventory is sold at the end. In this subsection, we assume the harvest in the last month is not materialized. In this case, Table 4.3 displays the optimal selling-down-to levels for selected $\$h$, and Table 4.4 presents the improving% of *sell-down-to* over *selling-*

Table 4.2: Optimal Net Present Value (×$1000)

NPV	**SDT/SA**	**$h**					
		$0	$1	$2	$3	$4	$5
Expected	SDT	$832,318	$831,771	$831,331	$830,955	$830,612	$830,333
	SA	$829,237	$829,237	$829,237	$829,237	$829,237	$829,237
	Improving%	0.37%	0.31%	0.25%	0.21%	0.17%	0.13%
Sample-Path	SDT	$834,845	$833,852	$830,667	$829,971	$829,414	$829,016
	SA	$828,239	$828,239	$828,239	$828,239	$828,239	$828,239
	Improving%	0.80%	0.68%	0.29%	0.21%	0.14%	0.09%

all policy. Again, the selling-down-to levels decrease in $h, but more quantity is carried over to the April-2011 for more revenue compared with that in Table 4.1. Importantly, the improving% is around 13%-16% in this case because more inventory is carried over to sell in the last month.

4.6.4 Impact of Initial Inventory

In the prior numerical studies in §4.6.2-4.6.3, the initial inventory in Dec-2010 is assumed to be zero. In this subsection, we experiment with some selected levels of initial inventory to see the impact of initial inventory on the improving percentage. In particular, we set the initial inventory levels to be 0, 500, 1000 and 1500 (× 1000 bags).

For each initial inventory level, Table 4.5 displays the NPV of *sell-down-to* policy compared with *selling-all* policy for selected $h. It shows that Improving% is sensitive to

Table 4.3: Optimal Selling-Down-to Levels (×1000 bags)

Months	Harvest (1000 bags)	$h					
		$0	$1	$2	$3	$4	$5
1 (Dec-2010)	1164	500	400	400	400	400	300
2 (Jan-2011)	908	700	600	600	600	600	500
3 (Feb-2011)	764	700	600	600	600	500	500
4 (Mar-2011)	779	700	600	600	600	600	600

initial inventory, because the optimal *sell-down-to* policy suggests to carry more inventory to the future periods if there is more initial inventory available. In addition, it shows that the improving% is not sensitive to $\$h$.

4.7 Concluding Remarks

In this study, we provide decision support for CCGF. We find that one can control the coffee inventory sold each month and carry the rest to future months for a potentially better price – the inventory-hedging strategy. Based on an empirical study, we construct a post-harvest dynamic inventory model with random exogenous supply and constant elasticity price functions. We characterize the optimal control policy under various cost functions.

We then compare to a benchmark that sells all inventory in each season/month. We

Table 4.4: Optimal Net Present Value (×$1000)

NPV	**SDT/SA**	**$h**					
		$0	$1	$2	$3	$4	$5
Expected	SDT	$766,565	$764,860	$763,254	$761,753	$760,331	$758,992
	SA	$664,384	$664,384	$664,384	$664,384	$664,384	$664,384
	Improving%	15.38%	15.12%	14.88%	14.66%	14.44%	14.24%
Sample-Path	SDT	$796,284	$793,439	$791,255	$789,070	$786,546	$784,888
	SA	$690,377	$690,377	$690,377	$690,377	$690,377	$690,377
	Improving%	15.34%	14.93%	14.61%	14.30%	13.93%	13.69%

show that the inventory-hedging strategy can increase the profitability of the supply chain and that of CCGF but not significantly. In this study, we find that for the price maker it is not a "selling-all or retaining all" policy and the optimal carry over quantity depends on the available inventory, the chance of a higher or lower harvest in the next period and the inventory carrying cost. We have empirically studied Colombia's coffee export vs. price and quantified the impact of the optimal selling strategy for CCGF.

Table 4.5: Optimal Net Present Value (×$1000)

Initial Inventory (×1000 bags)	**SDT/SA**	**$h** $0	$1	$2	$3	$4	$5
0	SDT	$834,845	$833,852	$830,667	$829,971	$829,414	$829,016
	SA	$828,239	$828,239	$828,239	$828,239	$828,239	$828,239
	Improving%	0.80%	0.68%	0.29%	0.21%	0.14%	0.09%
500	SDT	$872,640	$868,713	$866,749	$863,330	$862,079	$860,996
	SA	$855,778	$855,778	$855,778	$855,778	$855,778	$855,778
	Improving%	1.97%	1.51%	1.28%	0.88%	0.74%	0.61%
1,000	SDT	$907,887	$903,358	$898,883	$896,438	$894,449	$890,285
	SA	$878,644	$878,644	$878,644	$878,644	$878,644	$878,644
	Improving%	3.33%	2.81%	2.30%	2.03%	1.80%	1.32%
1,500	SDT	$940,999	$934,020	$930,739	$927,445	$922,617	$919,950
	SA	$898,472	$898,472	$898,472	$898,472	$898,472	$898,472
	Improving%	4.73%	3.96%	3.59%	3.22%	2.69%	2.39%

Chapter 5

Conclusion

5.1 Summary and Conclusions

In Part I of this dissertation, we show how collective marketing efforts by small-scale coffee producers influence both coffee prices and buyer behavior. In particular, we examine how collective marketing by KCCE, a small-scale producers cooperative, affects coffee prices at the Nairobi coffee auction. We find that while the competitively bid prices increase at the rate of $14.55 per 50 kg bag, the administered prices increase at a smaller rate of $4.088 per 50 kg bag. After combining the competitively bid and the administered coffee prices together, the overall results indicate that coffee prices increase at the rate of $6.602 per 50kg bag. We interpret these results as evidence that the increase in coffee prices can be attributed to reduced transaction costs, increased information sharing between buyer and seller and increased bargaining power for the producers.

Regarding buyer behavior analysis, we investigate whether collective marketing positively influences buyer behaviour. We find that multinational buyers pay more for the competitively bid prices at a rate of \$ 21.618 per 50 kg bag. Similarly, the multinational buyers pay more for administered prices at the rate of \$20.416 per 50 kg bag. Combined there is an increase of \$ 23.697 per 50kg bag in the coffee prices that multinational buyers paid. We interpret these results as evidence that the buyer's search (product-information) costs and monitoring (quality and grade uncertainty) costs have been reduced by the presence of a collective marketing cooperative at the coffee auction.

Further, we demonstrate why taking a life cycle perspective of the coffee supply chain is essential and why efforts to reduce green house gas emissions in the coffee supply chain may not be targeting areas where the most effects are created. We conclude in this part that it is essential for vulnerable small-scale coffee producers in Kenya and elsewhere, whose livelihoods will be most affected by climate change, to use the results of this study to identify adaptation pathways for efficient coffee production systems.

In Part II of this dissertation, we provide decision support and justification for KCCE's post-harvest marketing and inventory hedging strategy. We find that under such an initiative, one can control coffee inventory sold each week and carry the rest to future weeks for a potentially better price – the inventory-hedging strategy. The trade-off for the price taker is that KCCE can either sell now or sell later. However, even if selling now means that there is no inventory to be carried over to the next period, one must accept the current price. For the selling later decision, one has to carry inventory but may get a better price in the future.

In Part III of this dissertation, we provide decision support and justification for

CCGF's post-harvest marketing and inventory hedging strategy. We find that under such an initiative, one can control coffee inventory sold each month and carry the rest to future months for a potentially better price incase of a potential supply shortage in the future – the inventory-hedging strategy. Similar to the price taker case, there is a trade-off for the price maker in that CCGF can either sell more or sell less. However, even though selling more now means that there is less inventory to be carried over to the next period, we may reduce the current price. For the selling less decision, one has to carry more inventory to the next period but may increase the current price.

The results of the research should be quite easily transferable to other small-scale producers and producer organizations in the global coffee supply chain in any coffee producing country.

5.2 Future Research Directions

Some interesting areas for further research arose when conducting this study. First, it would be interesting to extend the price taker model to include financing issues as well as risk aversion. Furthermore, investigating the win-win strategy between producer organizations and small-scale producers to maximize the total profit, minimize the risk and achieve fair sharing would be an interesting topic to study.

Second, for the price maker models we assume an i.i.d. harvest process. One question remains: what if we assume an auto-correlated process for the harvests? Does the selling-down-to optimal policy remain optimal if the underlying harvest process is auto-correlated?

Finally, the focus of this study has been on post-harvest marketing and inventory decisions. However, it would be important to continue research on what critical success factors constitute best practices for producer organizations in agricultural supply chains. Extending the theory of new institutional economics in a comparative study of the responses by different coffee producing countries to the tremendous changes that the global coffee supply chain has undergone in the past decades would be interesting to pursue. Similarly, the EIO-LCA model focused on green house gas emissions but it would be important to also investigate the water and energy use in the coffee supply chain and develop strategies that can reduce the associated negative environmental effects.

Appendix

The following Lemma is frequently applied in the proofs through the paper.

Lemma 5.1 *Given a function $\theta(x, y)$ defined on the product space $\mathbf{R} \times \mathbf{R}$, assume that for any $x \in \mathbf{R}$, there is an associated convex set $C(x) \in \mathbf{R}$ and $\mathbf{C} = \{(x, y)|y \in C(x), x \in \mathbf{R}\}$ is convex. If $\theta(x, y)$ is concave and the function*

$$\Theta(x) \ = \sup_{y \in C(x)} \theta(x, y),$$

is well defined, then $\Theta(x)$ is also concave in $x \in \mathbf{R}$

Proof. In line with Proposition 2.2.15 of Simchi-Levi *et al.* (2004, pg24), we consider any $x_1 \neq x_2$ and $0 \leq \lambda \leq 1$. Let $\Theta(x_1) = \theta(x_1, y_1)$ and $\Theta(x_2) = \theta(x_2, y_2)$ where $y_i \in C(x_i)$, $i = 1, 2$. Since $\mathbf{C}$ is convex, $(\lambda x_1 + (1 - \lambda)x_2, \lambda y_1 + (1 - \lambda)y_2) \in \mathbf{C}$. Hence, $\lambda y_1 + (1 - \lambda)y_2 \in C(\lambda x_1 + (1 - \lambda)x_2)$. Furthermore,

$$\begin{aligned} \Theta(\lambda x_1 + (1 - \lambda)x_2) &\geq \theta(\lambda x_1 + (1 - \lambda)x_2, \lambda y_1 + (1 - \lambda)y_2) \\ &\geq \lambda\theta(x_1, y_1) + (1 - \lambda)\theta(x_2, y_2) \\ &= \lambda\Theta(x_1) + (1 - \lambda)\Theta(x_2), \end{aligned}$$

where the first inequality holds by the definition of $\Theta(\cdot)$, and the second inequality comes from the concavity of $\theta(x, y)$. The proof is now completed. □

Review for K-Convexity

In the following, we provide a brief review for K-convexity. For details, we refer the reader to Simchi-Levi (2007) and Ross (1970).

Definition 5.1 *A real-valued function $f(\cdot)$ is called K-convex for $K \geq 0$, if for any $x_1 \leq x_2$, and $\lambda \in [0, 1]$,*

$$f((1 - \lambda)x_1 + \lambda x_2) \leq (1 - \lambda)f(x_1) + \lambda f(x_2) + \lambda K. \tag{5.1}$$

Below we summarize major properties of K-convex functions.

Lemma 5.2 *(a) A real-valued convex function is also 0-convex and hence K-convex for all $K \geq 0$. In general, a K_1-convex function is also a K_2-convex function for $K_1 \leq K_2$.*
(b) If $f_1(x)$ and $f_2(x)$ are K_1-convex and K_2-convex respectively, then for $\alpha, \beta \geq 0$, $\alpha f_1(x) + \beta f_2(x)$ is $(\alpha K_1 + \beta K_2)$-convex.
(c) If $f(x)$ is K-convex and Z is a random variable, then $\mathbf{E}[f(x - Z)]$ is also K-convex, provided $\mathbf{E}[|f(x - Z)|] < \infty$ for all x.
(d) Assume that f is a continuous K-convex function and $f(x) \to \infty$ as $|x| \to \infty$. Let S be a minimum point of $f(x)$ and s be any element of the set

$$\{x|x \leq S, f(x) = f(S) + K\},$$

then the following results hold:

(i) $f(S) + K = f(s) \leq f(x)$ *for all* $x \leq s$.

(ii) $f(x)$ *is non-increasing for* $x \leq s$.

(iii) $f(x) \leq f(y) + K$ *for all* $s \leq x \leq y$

(e) If $f(x)$ *is a* K*-convex function, then function*

$$g(y) = \min_{x \geq y} \{Q \cdot \delta(x - y) + f(x)\},$$

is $\max\{Q, K\}$*-convex.*

Review for K-Concavity

In the following, we provide a brief review for K-concavity.

Definition 5.2 *A real-valued function* $f(\cdot)$ *is called* K*-concave for* $K \geq 0$*, if for any* $x_1 \leq x_2$*, and* $\lambda \in [0, 1]$*,*

$$f((1 - \lambda)x_1 + \lambda x_2) \geq (1 - \lambda)f(x_1) + \lambda f(x_2) - \lambda K. \tag{5.2}$$

Below we summarize major properties of K-concave functions.

Lemma 5.3 *(a) A real-valued concave function is also 0-convex and hence* K*-concave for all* $K \geq 0$*. In general, a* K_1*-concave function is also a* K_2*-concave function for* $K_1 \leq K_2$*.*

(b) If $f_1(x)$ *and* $f_2(x)$ *are* K_1*-concave and* K_2*-concave respectively, then for* $\alpha, \beta \geq 0$*,* $\alpha f_1(x) + \beta f_2(x)$ *is* $(\alpha K_1 + \beta K_2)$*-concave.*

(c) If $f(x)$ *is* K*-concave and* Z *is a random variable, then* $\mathbf{E}[f(x - Z)]$ *is also* K*-concave, provided* $\mathbf{E}[|f(x - Z)|] < \infty$ *for all* x*.*

(d) Assume that $f(x)$ *is a continuous* K*-concave function and* $f(x) \to -\infty$ *as* $|x| \to \infty$*. Let* S *be a maximum point of* $f(x)$ *and* s *be*

$$s = \inf\{x | x \geq S, f(x) = f(S) - K\},$$

then the following results hold:

(i) $f(S) - K = f(s) \geq f(x)$ *for all* $x \geq s$.

(ii) $f(x)$ *is non-increasing for* $x \geq s$

(iii) $f(x) \geq f(y) - K$ *for all* $s \leq x \leq y$.

(e) If $f(x)$ *is a* K*-concave function, then function*

$$g(y) = \max_{x \leq y} \{Q \cdot \delta(y - x) + f(x)\},$$

is $\max\{Q, K\}$*-concave.*

(f) If $f(x)$ *is a* K*-concave function, then function* $-f(x)$ *is* K*-convex.*

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