EVALUATION AND MITIGATION OF GREENHOUSE GAS EMISSIONS FROM THE SMALLHOLDER COFFEE SUPPLY CHAIN IN KENYA

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Evaluation and Mitigation of Greenhouse Gas Emissions from the Smallholder Coffee Supply Chain in Kenya

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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DEDICATION

To my dear parents. Thank you for all the support and encouragement throughout the duration of my studies.

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LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COD	Chemical Oxygen Demand
EPA	Environmental Protection Agency
GHG	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
N_2O	Nitrous Oxide
SFL	Sustainable Food Laboratory
UNFCC	United Nations Framework Convention on Climate Change
SOM	Soil Organic Matter
PCF	Product Carbon Footprint
PCR	Product Category Rule

ABSTRACT

Coffee is an important crop to the Kenyan export portfolio yet little information exists on the carbon footprints of the Kenyan coffee supply chains. This especially with regards to small holder coffee production which contributes 66% of the total coffee produced in Kenya. This study sought to assess how small holder coffee production systems in Kenya contribute to climate change and how this can be mitigated. The study was carried out in Kiambu County where a smallholder cooperative society was selected. The selected cooperative society had three primary coffee processing factories from which 108 smallholder farmers were selected using a two-way stratified random sampling approach. Stratification was based on farmer production level in kilogram of cherry per tree and the processing factory to which they delivered the cherry. The farmers' yields were classified as 5kg/tree and above, 3-4.9 kg/tree and 0-2.9kg/tree for high, medium and low production levels, respectively. To quantify the GHG emissions, the Cool Farm Tool (CFT) was selected. Above ground carbon stock values for the selected coffee farms were computed using allometric models obtained from literature. The use of pumice and charcoal in mitigating greenhouse gases from the wastewater from coffee processing was as well investigated. The results of this study show that coffee product carbon footprints among small holder producers were dependent on the yield level and decreased with increase in production. The mean product carbon footprints obtained were 0.05kg CO_2e/kg cherry, 0.27kg CO_2e/kg cherry and 0.58 kg CO_2e/kg cherry for high, medium and low producers respectively. ANOVA results showed that at 99% confidence level there were highly significant differences in product carbon footprints for the production levels ($p<0.001$; $F_{calculated} = 19.35$; $F_{critical} = 3.09$) and a highly significant difference in emissions per acre of land for the production levels ($p<0.001$; $F_{calculated} = 4.702$; $F_{critical} = 3.09$). The main source of emissions at farm level was fertiliser use which accounted for 94% of the overall farm footprint. At processing level, the main source of emissions was coffee processing wastewater which accounted for 93% of the total processing emissions at the factory. The carbon footprint at the primary processing stage ranged from 2.4 kg CO_2e/kg parchment to 2.62 kgCO_2e/kg parchment. Soil carbon formed the largest stock in the farms

(15.28Mg/Ha), followed by shade tree biomass (9.32Mg/Ha) and finally coffee tree biomass (2.19Mg/Ha). Pumice and charcoal reduced the BOD levels in wastewater from coffee processing by 71.3 and 62.8% respectively.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

According to United Nations Framework Convention on Climate Change UNFCC (2002), climate change is a known and largely accepted reality, and the world's climate will continue to change as long as greenhouse gas (GHG) levels keep rising. It is the most serious environmental threat facing the planet today (Wright *et al.*, 2009). The effects of climate change are clearly perceivable, and are being felt worldwide. This is especially so for farmers who are dependent on climate for their livelihoods (Killian *et al.*, 2013). According to the Intergovernmental Panel on Climate Change (IPCC) global temperatures are recorded to have increased by 0.74°C during the 20th century (Rikxoort *et al.*, 2013a). Most scientists agree that this warming in recent decades has been caused by human activities, such as the burning of fossil fuel and biomass as well as deforestation, which have increased the amount of greenhouse gases in the atmosphere (Oreskes, 2004). Greenhouse gases are the major contributors to the change in climate (Wright *et al.*, 2009).

Agriculture, besides suffering from the effects of climate change also contributes significantly to the climate change effect itself (Pandey & Agrawal, 2014). Agriculture alone is responsible for 14 percent of global GHG emissions, mainly as a result of poor agricultural practices (EPA, 2007). When deforestation for farmland expansion and tree plantations is also considered, agriculture is estimated to account for 30 percent of total GHG emissions globally (IPCC, 2007; Jarvis *et al.,* 2013). Smallholder farmers are able to adapt annual cropping systems to counter the effect of varying climate but this is much difficult in the case of perennial systems, yet perennial cash crops such as coffee, tea and cacao support millions of livelihoods and have significant contributions to many countries' Gross Domestic Product (Laderach *et al.,* 2011). Focus needs to be made on adapting perennial cash crop systems to climate change.

After oil, coffee is the most important tropical commodity traded by developing countries worldwide (Austin, 2012; Davis *et al.,* 2012). For many developing countries, coffee is the primary export product (Salomone, 2003; Naakubuza *et al.,* 2005) and a vital contributor to foreign exchange earnings as it accounts for a substantial part of tax income and GDP (ICO, 2014). The production of coffee takes place exclusively in tropical countries with farmers residing in regions of Africa, Latin America, Southeast Asia and consumers living in Europe, North America and in rapidly developing areas of Asia (Austin, 2012; Naakubuza *et al.,* 2005). As a result of production on such a large scale, the coffee supply chain is an important contributor to global GHG emissions, and measures must be taken to reduce the amount of GHG contributed to the atmosphere from this sector.

In Kenya, coffee supports about 700,000 households representing approximately 4.2m or 10% of Kenyan population (Mithamo, 2013). The enterprise contributes about 6% of the total agricultural export earnings and up to 30% of the total labour force employed in Agriculture (Monroy *et al.*, 2013). Current annual earnings from coffee is about 19.5 billion Kenyan shillings (Kenya Economic Survey, 2015). The total area under coffee in Kenya is 109,800 Ha of which 78% is under smallholder production and the rest being under estates. The current production of coffee stands at 32,700 tonnes for smallholder farmers and 16,800 tonnes for estates, with yield levels of 383kg/ha and 680kg/ha for smallholders and estates, respectively (Kenya Economic Survey, 2015). As a result of this distribution, smallholder farmers form an important portion of the Kenyan coffee supply chain. Moreover, the low yield figures in the smallholder farms indicate a need for improved management practices in these farms.

Kenya produces almost exclusively washed Arabica Coffee of the Bourbon type, although there is a very small production of Robusta coffee that is grown in the low altitude areas (Monroy *et al.*, 2013). The productivity of Arabica is tightly linked to climate variability and is thus strongly influenced by natural climatic oscillations. In the coffee sector, the first signs that there is need for climate change mitigation in agricultural supply chains are visible (Haggar & Schepp, 2011). Decreased coffee production levels have been reported which have been attributed to depressed performance of both the long and short rains (Kenya Economic Survey, 2014). A study that assessed the impact of climate change on Kenya's coffee production zones (Sangana PPP, 2011; Haggar & Schepp, 2011) predicts a temperature increase of $1.0^{o}C$ by 2020 and $2.3^{o}C$ by 2050, combined with unpredictable precipitation. The suitability of coffee growing zones in Kenya is thus expected to decrease by approximately 30 percent in 2020 and by more than 30% in 2050 (Rikxoort *et al.*, 2013b). Besides suffering from the effects of climate change, coffee production also makes its contribution to greenhouse gas emissions throughout its supply chain (Killian *et al.,* 2013). There is therefore an increasing need for approaches to coffee farming that not only help farmers adapt to a changing climate but also minimize the contribution of coffee farming itself to climate change.

Studies regarding GHG emission in coffee supply chains (Tchibo, 2008; Noponen *et al.,* 2012; Coltro *et al.,* 2006; Killian *et al.,* 2013) indicate that there is a knowledge gap with regards to the influence of primary production on GHG emissions and the most suitable climate change mitigation options for smallholder farmers. In an attempt to fill this gap, the main purpose of this study was to determine the carbon footprint of a Kenyan small holder coffee production system. The study sought to identify 'hot spots' of GHG emissions in the small holder coffee supply chain, in order to determine where mitigation efforts should be focused, and to evaluate alternatives of mitigation efforts and their impact on the carbon footprint. To meet these objectives, the study focused on different stages of the primary coffee supply chain: at farm level, in the wet mills, and during the process of transportation to the dry mill.

1.2 Problem Statement

Smallholder coffee producers face major challenges to meet livelihood needs due to their small value shares in the coffee supply chain and volatile market prices now compounded with climate change (Rahn *et al.,* 2014; Laderach *et al.,* 2011). Climate change threatens to become an environmental disaster for small holder coffee farmers (ITC, 2010). Besides suffering from climate change, coffee production contributes to climate change by the release of greenhouse gases during production (Rikxoort *et al.,* 2013a). The first step to mitigating climate change is quantification of the contribution of this enterprise to climate change. There is therefore an increasing need for approaches to coffee farming and processing that not only help farmers adapt to a changing climate but also minimize the contribution of coffee farming itself to climate change.

Although much work is ongoing with reference to climate change and coffee (Rikxoort *et al.,* 2013a; Tchibo 2008; Killian *et al.,* 2013; Noponen *et al.,* 2012) there still exist knowledge gaps that prevent stakeholders along coffee supply chains to make informed decisions in defining high-impact climate change mitigation strategies. These knowledge gaps concentrate around the carbon footprint determination process. A clear baseline for GHG emissions in the Kenyan small holder supply chain is necessary to facilitate subsequent mitigation strategies.

1.3 Objectives

1.3.1 Main Objective

The main objective of this study was to assess greenhouse gas emissions from the smallholder coffee supply chain and the potential for mitigation.

1.3.2 Specific Objectives

1. To evaluate greenhouse gas emissions from smallholder coffee producers in Kiambu County.
2. To determine the amount of biomass and soil carbon stocks in the small holder coffee farms and the potential for carbon sequestration.
3. To investigate the use of pumice and charcoal in the reduction of greenhouse gas emissions from wastewater from coffee processing.

1.4 Research Questions

1. What is the carbon footprint of smallholder farmers in Kiambu County?
2. How much carbon are smallholder farmers storing in the soil and in plant matter?
3. Can pumice and charcoal be used to reduce emissions from primary processing of coffee?

1.5 Justification

Small holder coffee producers in developing countries such as Kenya lack the organisational capacity to handle complex data collection and GHG emission calculations along their part of the supply chain. As this study is conducted with small holder coffee producers, it can contribute to the development of methods that will work in the smallholder farming context. This study makes use of the Cool Farm Tool which is a user friendly carbon accounting tool that is fairly accurate and less time consuming thus making it ideal for use with smallholder farmers. Small holder coffee production varies greatly from farm to farm therefore mitigation options that may be suitable for one farm may not be suitable for another. A deeper understanding of the production systems is paramount to outlining suitable mitigation practices.

Adoption of the proposed wastewater treatment system will provide wet mills with a pathway of reducing the emissions from released effluent. The use of locally available adsorbents would be ideal for Kenyan coffee cooperatives. This study will also be beneficial to various coffee cooperative societies and smallholder farmers in Kiambu County and other locations engaged in coffee growing. This is because the project identifies key sources of GHG emissions and provides measures that should be adopted in the agricultural practices in order to eliminate or reduce the amount and level of GHG emissions. The study as well seeks to foster agricultural resilience amongst small holder farmers through improvement of agronomic practices.

1.6 Scope of the Study

This study involved the calculation of carbon footprints from coffee at farm level and at primary processing level. Data was therefore collected from the selected coffee farms and wet mills. The carbon footprint boundary was set at growing coffee in smallholder farming systems to wet processing in the mills ending at parchment delivery to the dry mill. For the carbon foot print determination, materials that contributed less than 1% to the carbon footprint were excluded in the study. Management changes that occurred more than 20 years prior to the assessment were excluded in accordance with IPCC guidelines. Energy use that was directly linked to the coffee production process was also excluded.

1.7 Limitations of the Study

Due to financial constraints, the study was limited to one coffee producing area. Allometric equations were not developed on site as destructive sampling of coffee trees from smallholder producers was not possible, however the allometric equations selected were as close as possible to the production systems studied. Wastewater sampling from the three wet mills was done once due to time constraints and the seasonality of coffee processing.

CHAPTER TWO

LITERATURE REVIEW

2.1 Climate Change and Agriculture

Climate change is widely recognized as one of the most serious environmental threats facing our planet today (Wright *et al.*, 2009). It refers to a deviation from the long-term weather patterns (Mithamo, 2013) and is characterized by an increase in temperature, and a change in rainfall patterns and quantities in different parts of the world (Haggar & Schepp, 2011). All Global circulation models (GCMs) show that mean temperatures will increase and there will be changes in precipitation regimes (Laderach *et al.,* 2011). The major driver of these changes in weather patterns is the accumulation of GHG in the atmosphere (Laderach *et al*., 2011). Forecasts about future annual warming for Africa range between 0.2°C and just over 0.5°C per decade (Masiga, 2013). Climate models forecast that East Africa is likely to experience a 5 – 20% increase in rainfall from December to February and 5 –10% decrease in rainfall from June to August by 2050 (Masiga, 2013). Sectors that are dependent on climate and environmental stability will therefore be affected by these predicted changes.

One of the economic sectors that will be most affected is agriculture which is also greatly dependent on environmental stability and natural resources (Killian *et al.*, 2013). Laderach *et al.,* (2011) point out that the impacts of climate change are likely to vary across geographical regions and between different agro ecological systems. In addition to crop losses from the increased incidence of natural disasters such as floods, droughts, fires and others, agricultural systems will need to cope with changing rainfall regimes, geographical shifts in the occurrence of pests and diseases, temperature stress and loss of climatic suitability (Jarvis *et al.*, 2013). The tropics are expected to experience decreased crop yields of 10-30% (Jarvis *et al.*, 2013). Agriculture's position in the climate change equation is unique; it is simultaneously a highly vulnerable and culpable sector with regard to its significant contribution to anthropogenic emissions and also a sector with enormous potential for mitigating anthropogenic climate change (Jarvis *et al.,* 2013)

Studies have shown that the agricultural sector contributes significantly to anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Pye-Smith, 2011; IPCC, 2007). Richards (2013) argues that attention has been directed towards climate change by focusing on carbon dioxide yet this is not the only contributor towards greenhouse gases since methane and nitrous oxide are the largest proportions of agricultural GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) estimates that agriculture accounts for about one fifth of the annual increase in GHG (Cole *et al*., 1997). Land-use changes related to agriculture especially in the tropics, including biomass burning and soil degradation, are also major contributors of GHG (IPCC, 2007). Agriculture produces 47 percent of the total global methane emissions and 58 percent of the total global nitrous oxide emissions (Pye-Smith, 2011). On the other hand, carbon sequestration in agricultural soils could potentially offset 5‑15% of global fossil fuel emissions (Lal, 2004), not to mention the mitigation power of deforestation reduction and fertilizer and irrigation optimization through sustainable intensification practices. Figure 2.1 illustrates the contribution of Agriculture to GHG emissions in the atmosphere.

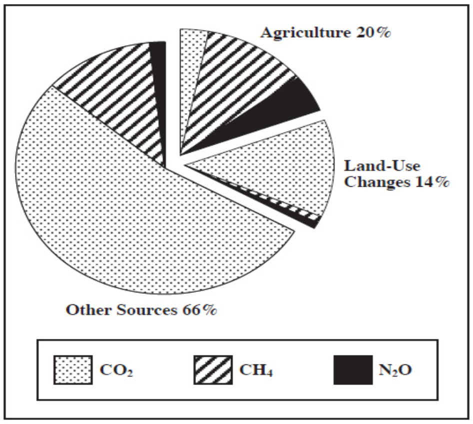

Figure 0.1: Proportions of the Annual Increase in Global GHG Attributable to Agriculture and Agriculture-Related Land-Use Change (Source: Wright *et al.*, 2009)

Many farmers continuously vary the varieties of annual crops grown, selecting them based on several criteria including sustenance, market dynamics, productivity, and cultural preferences (Laderach, *et al.,* 2011). In view of the short growth cycle of annual crops, in many cases substitutions can be made with a minimum costs, thus farmers have the capacity to make changes that will likely outstrip the speed of climate change such as changing crop varieties, crop types and planting dates. Laderach *et al.* (2011) points out that whilst attention needs to be paid to adapting annual cropping systems to future changes in climate, more urgent action is required to address these issues as they apply to high-value perennial cropping systems. Cash crops such as coffee have large impacts on national economies through their contribution to countries' GDP and supporting millions of livelihoods (Killian, *et al.,* 2013; Salomone, *et al.,* 2003). Concerns over the future suitability of high value perennial crops in the producing regions have arisen. In this regard, Haggar and Schepp (2011) suggested that as the climate becomes warmer in Kenya the current coffee producing areas will be rendered unsuitable in the near future. The suitability of coffee growing zones in Kenya is expected to decrease by approximately 30% in 2020 and by over 50%in 2050 (Laderach *et al.,* 2011). There is need to look into ways of adapting these coffee systems to the changing climate as well as find ways in which they can contribute to climate change mitigation.

2.2 Coffee in Kenya

The coffee industry is a crucial sector to the Kenyan economy. Coffee is the fifth foreign exchange earner after tourism, tea, horticulture and remittances from Kenyans in the diaspora (KIPPRA, 2013; Mithamo, 2013). Annual coffee earnings have ranged from 18.5 to19.5 billion shillings between the years 2013 and 2015. Kenya is ranked the 17th largest coffee producer globally (Hoebink *et al.,* 2014). Kenyan coffee is not only used in its pure form but is also popular to create blends for the market thus the global demand for Kenyan coffee has meant that the industry plays a significant part in the country's economy (Hoebink *et al.*, 2014).

The Kenyan coffee sector is characterised by two types of farms: plantations also termed estates and cooperatives. The plantation sub-sector consists of about 454 farms, with large estates cultivating about 24,605 ha. The cooperative sub-sector is made up of 422 cooperative unions, representing about 570,824 smallholder farmers who cultivate about 85,106 ha, equivalent to about 0.2 hectares a per farmer (Hoebink *et al.,* 2014) under rain fed farming system. Only some large-scale farmers and estates irrigate their coffee and have 'stable' access to financial services. The current annual coffee production stands at 32,700 tonnes for smallholder farmers and 16,800 tonnes for estates. Coffee supports a livelihood of 700,000 smallholder farmers representing 3.5m direct dependants organised with producer cooperatives which produce 60% of the Kenyan coffee and large scale estates producing the remaining 40% (Kimemia, 2013). Coffee incomes have been invested in the economy, mainly in the rural areas bringing considerable rural development in terms of improvement of farm income, employment and food security. Over the years, coffee has contributed towards poverty alleviation especially among the small holder farmers because it has a medium to high potential for agriculture growth and medium potential for poverty reduction.

The main coffee producing regions in Kenya are on deep, fertile acidic volcanic soils found in the highlands between 1400-2100 meters above sea level (Monroy *et al.,* 2013). These regions produce high quality milder coffee *Arabica* L. that is known for its intense flavor, full body and pleasant aroma. The climate in these regions is mild, with an average temperature of less than 19°C and an annual precipitation of at least 1000mm (Kiseve, 2012). Most coffee is grown in the triangular area between Mt. Kenya, the Aberdare Range and Machakos which is essentially in the larger Central and Eastern provinces. This area accounts for over 70% of Kenya's coffee production (Hoebink *et al.,* 2014).

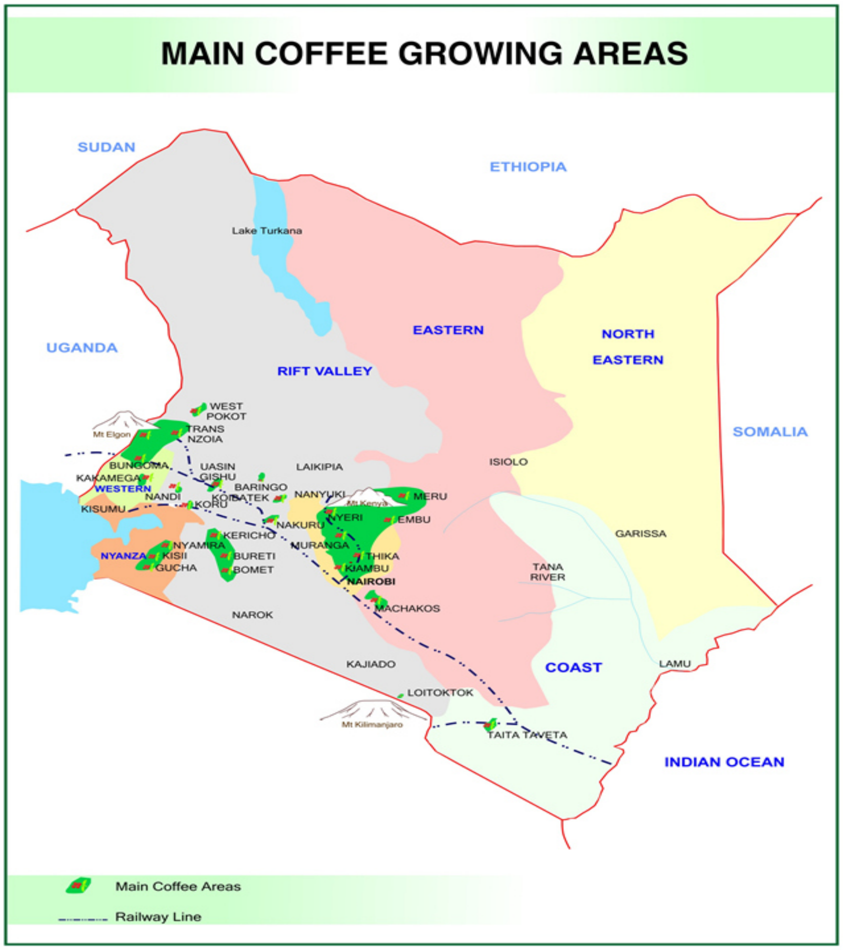

Figure 0.2: Kenya's Coffee Growing Regions (Source: Coffee Board of Kenya 2015)

Coffee in Kenya enjoys a three months dry period during which the flower buds are dormant. The flower bud dormancy is broken by a slight decrease in temperature, received rainfall or irrigation (Gathaara, 1998). As a result there are two coffee seasons in Kenya referred to as early and late crop, resulting from the two commonly experienced rainfall seasons, short and long rains respectively, occurring in October-December and April-May respectively (Kiseve, 2012). The main crop ripens from October until December in most coffee producing districts in Kenya while the second and smaller flowering comes with the short rains and is picked starting from early June.

2.2.1 Smallholder Coffee Production

Of the 109800 ha of land currently under coffee, 78% is under smallholder production with 66% of the total coffee produced annually being from smallholder farmers (Kenya Economic Survey, 2015). Because of the production on such a large scale, smallholder coffee farmers form an important component of the Kenyan coffee supply chain. The smallholder coffee production system in Kenya comprises of 'full sun' coffee with a few shade trees included in some farms (Rikxoort *et al.,* 2013b). The coffee system is part of a mixed cropping system containing food crops and small numbers of livestock. In some farms fruit trees such as banana, avocado and macadamia are grown alongside the coffee trees to supplement incomes from coffee. Farm level activities for smallholder coffee farmers include pruning, handling and desuckering, hand and chemical weeding, fertilizer application, spraying, manure application, mulching and picking (Odhiambo *et al.,* 1996). There are significant differences in the level and frequency of these activities both across regions and different farm sizes (Odhiambo *et al.,* 1996).

Harvesting of coffee entails picking only the red ripe cherries. The cherry is then transported to wet mills owned by the cooperative societies where it is sorted to remove green, overripe and diseased cherries then weighed and pulped to remove the outer skin (Mutua, 2000). Coffee processing in Kenya is done using the wet method which makes use of water at the pulping stage through to the fermentation and washing stage (Mureithi, 2008). After pulping, the cherries are sorted through water density separation into 3 grades and the beans are fermented for 12 to 72 hours, after which they are thoroughly rinsed and then soaked for 16 hours, followed by more rinsing and finally sun-drying to 12-15% (wet basis) moisture on raised screen beds (Mutua, 2000; Hoebink *et al.,* 2014). The parchment is moved to conditioning bins before being transported to dry mills. Milling plant operations involve pre-cleaning, which removes light material such as wool and papers, de-stoning which removes of heavy material that may be present in the coffee. Other milling plant operations are hulling which remove parchment/husks on the coffee, polishing or the removal of the silver skin/seed coat, and finally grading into classes based on sieve sizes (Hoebink *et al.,* 2014). The coffee is then packed in sacks and transported to the warehouse in readiness for marketing.

2.2.2 Challenges Facing Small Holder Coffee Production in Kenya

According to Hoebink *et al.,* (2014), the greatest problem faced by Kenyan coffee farmers is the low profit obtained due to low prices. Coffee production costs have escalated in the recent past due to major increases in the cost of purchased farm inputs. These rising production costs against a decline in prices make it difficult for farmers to break even (Kegode, 2005). Coffee like other agricultural goods is a seasonal product requiring investments prior to harvest and revenue returns. Smallholders with a low capital and savings base frequently rely on advances and credit to supply requisite pre-harvest inputs and living expenses (Gathura, 2013). As a result of this, the considerable time lag between coffee delivery to the mills and payment for coffee discourages farmers.

Population pressures lie at the heart of the land management challenges in Kenya. Most of agriculture is concentrated in the high and medium areas thus there are too many people trying to make a living on too small areas of land. Agricultural productivity, economic development, human development and standards of education and health have improved very little, certainly not enough to keep in pace with the growth in population. Land is almost at a point where any major change in weather and climate could have a catastrophic impact on human lives.

The growing conditions for coffee in East Africa have become more unpredictable in the last ten years. Rains are starting late, delaying crop planting and resulting in late coffee flowering and berry ripening (Salami *et al.,* 2010). This means delays for farmers' income from their coffee. Rains are also falling more heavily in intense cloud bursts, causing localized flooding, flattening crops and knocking coffee cherries off coffee bushes. Pests and diseases are a growing concern for coffee farmers (Jaramillo *et al.,* 2011). Shifting weather and climate are bringing new coffee boring insects such as thrips, new fungal infections such as coffee rust infection (Salami *et al,* 2010). Less predictable weather conditions also make it difficult to spray against these blights. Farmers spend a large amount of time, money and effort spraying against coffee berry disease and pests.

2.2.3 Effects of Climate Change on Coffee Production

The scenarios on climate change of the IPCC predict that dry seasons are to become even drier and precipitation is predicted to reduce in some areas up to 30%, and to be distributed less regularly (Rikxoort *et al.*, 2013a). Consequently, the optimal climate conditions for Arabica coffee cultivation in most of the current production regions are likely to change (Camargo, 2009). In Kenya, coffee production areas are predicted to shift upwards towards the mountain (Rikxoort *et al.,* 2013a). A similar shift is also expected in Arabica producing areas of Uganda (Jassogne *et al.,* 2013).

Temperature and rainfall conditions are considered to be important factors in defining potential coffee yield (Haggar & Schepp, 2011; Ridely, 2010). The Arabica coffee plant responds sensitively to increasing temperatures, specifically during blossoming and fructication (Camargo, 2009). A relatively high air temperature during blossoming, especially if associated with a prolonged dry season, may cause abortion of flowers (Camargo, 2009). In addition, higher temperatures improve living conditions for pests and diseases (Jaramillo *et al.*, 2011). Increasing pest attacks lead to the loss of quality of the coffee beans or even the destruction of yield and plants (Haggar & Schepp, 2011). Rainfall is the most restrictive factor in coffee growing regions, and both the total annual rainfall, and monthly distributions of precipitation are important (Ridley, 2010). A soil water deficit decreases the biological and economic productivity of coffee, by lowering the quantity and quality of the yield (Camargo, 2009).

The already perceived and future predicted impacts of climate change on coffee production will threaten small scale farmers as they are at risk of losing their yield and family income. Moreover, all actors of the value chain, including the consumer, will be affected (Haggar & Schepp, 2011). Reduction of areas suitable for coffee production as a result of unsuitable weather conditions will influence the world coffee market and will increase pressure on the price. More coffee may need to be grown under irrigation thereby increasing pressure on scarce water resources. All the foregoing will increase the cost of production whereas in the future, fewer parts of the world may be suitable for coffee production (Rikxoort *et al*, 2013a)

2.3 Contribution of Coffee to Greenhouse Gas Emissions

Apart from being highly vulnerable to climate change, coffee production also contributes to the increase of GHGs in the atmosphere. Like most agricultural commodities, GHG emissions occurring in the primary coffee supply chain arise from the production and application of fertilizers and organic manure, the use of pesticides, crop residue, field energy use and transportation.

2.3.1 Crop Nutrition

The application of fertilizers causes N_2O and induced CO_2 emissions. GHG emissions from N fertilizer production are mainly from two sources. These are CO_2 from the use of fossil energy sources (mainly natural gas) as feedstock and fuel in ammonia synthesis and N_2O emitted from nitric acid production (Wood & Cowie, 2004; Dolejsi, 2010). Two categories of soil N_2O emissions result from fertiliser and manure use: direct emissions from N-fertilisation of soils, and indirect emissions resulting from leaching and volatilisation of deposited N. The rate of N_2O emissions depends mostly on the availability of mineral N source, meaning directly related to the rate of fertilization (Granli & Bockman, 1994). The method of fertilizer application also influences the amount of emitted GHG's. This is illustrated by Hultgreen and Leduc (2003) who demonstrated that there is a trend for higher emissions of N_2O when urea was broadcast rather than banded, and when urea was placed mid-row, rather than side-banded. The efficient use of fertiliser is central to both a productive coffee farm and a coffee farm wanting to contribute to climate change mitigation. There is need to relate the input levels for small holder systems with yields and their contribution to GHG emissions.

2.3.2 Crop Protection

The GHG emissions related to crop protection in coffee production with pesticides are directly related to the energy required for the production of the active ingredients in these pesticides. The production of pesticides is a major worldwide contributor to GHG emissions (Bellarby *et al*., 2008). Thus, reducing pesticide use also directly reduces GHG emissions. Rao *et al*., (2010) points out that agro forestry systems use naturally less pesticides because the production system itself has an improved pest resistance. Rao *et al.,* (2010) argue that the reason pest incidence is less in agro forestry systems is because the balance between insect pests and predators is maintained to a greater extent. It is therefore necessary to understand the extent of pesticide use in small holder coffee farms and to examine the effect of integrated pest management strategies on reduction of the carbon footprint.

2.3.3 Primary Processing

Primary processing of coffee is done either by the dry method or wet method. The dry processing method consists of removing (de-pulping) the skin, pulp and hull of the coffee cherry (Rikxoort *et al.,* 2014). The first step is de-pulping after which the coffee is usually spread on drying beds and sun-dried. The wet processing method starts similar as in the dry process with de-pulping the harvested cherries during which electricity, fossil fuels and water are used depending on the deployed machinery. The second step consists of the fermentation of the de-pulped coffee cherries (Von Enden, 2002) and is done by soaking the de-pulped cherries in big tanks. When the fermentation is finalized the fermented beans are washed to remove residues and remaining mucilage layers. After this final washing the beans are dried (Von Enden, 2002).

Kenyan smallholder farmers have their coffee processed using the wet method. Wet processing is believed to deliver higher quality coffee compared to the dry process since small amounts of off-flavours are generated in this process which gives the coffee a better taste and body (Calvert, 1998). However, the environmental impact of wet processing of coffee is considerable. The main pollution in coffee waste water stems from the organic matter set free during pulping when the mesocarp is removed and the mucilage texture surrounding the parchment is partly disintegrated (Mburu *et al.,* 1994). Methane emissions from wastewater are primarily a function of how much organic content is present in the wastewater and how the wastewater is treated. Methane is produced by the anaerobic decomposition of organic matter, as measured by the biochemical oxygen demand (BOD) of the wastewater. Values for BOD are up to 20,000 mg/l for effluents from pulpers and up to 8,000 mg/l from fermentation tanks (Von Enden & Calvert, 2002). The BOD should be reduced to less than 200 mg/l before let into natural waterways (Calvert 1998). Resistant organic materials which can only be broken down by chemical means indicated by the Chemical Oxygen Demand (COD) make up around 80% of the pollution load and are reaching 50,000 mg/l and more The material making up the high COD can be taken out of the water as precipitated mucilage solids. Problems occur through large amounts of effluents disposed into watercourses heavily loaded with organic matter. (Von Enden & Calvert 2002). The amount of CH_4 emitted is related to the amount of wastewater produced and wastewater treatment system in place. Most studies in Kenya have not included the contribution of coffee processing wastewater to the overall footprint

2.4 Quantification of GHG Emissions from Coffee

2.4.1 Methodologies for GHG Quantification

The amount of GHG emissions emitted during the life cycle of a given commodity is expressed as the carbon footprint (Wiedmann & Minx, 2008). A carbon footprint offers a simple mode of communication about climate responsibility of different entities between people, scientists and policy makers (ITC, 2012). There are two approaches to carbon foot print determination process namely whole farm approach and life cycle analysis. Whole farm approach measures a farm's overall annual GHG emissions and is a useful calculation for individual farm benchmarking purposes (ITC, 2012). These calculations highlight 'hot spots' or areas where GHG reductions might be made. Life cycle analysis measures the GHG emissions associated with a specific product throughout its lifecycle i.e. from cradle to grave. Carbon footprints can be calculated directly using equations proposed by IPCC and specific emission factors or by using tools that have in-built models for GHG quantification.

Various studies have been carried out to quantify GHG emissions resulting from coffee production, using various methodologies. The amount of greenhouse gases released during the coffee lifecycle vary with production systems, processing methods, the boundaries of the footprints and methodologies used. Salomone (2003) used a Life Cycle Assessment (LCA) to quantify the effect of coffee production on the environment. He established that more than 80 percent of the GHG emissions in the researched supply chain are attributed to the consumption of coffee. The study was largely based on a general coffee production system and not taking into account different farming systems. In addition only the dry processing method and average fertilisation scenarios have been used by the author. Consequently, the study is not able to attribute levels of GHG emissions to different coffee production systems and bring forward context specific climate change mitigation focus points on farm level.

Killian *et al.* (2013) evaluated the carbon footprint of Costa Rica coffee supply chain using PAS 2050 as a guide. This study showed that the highest source of emissions were from coffee cultivation mainly as a result of inorganic fertilisers. This study however did not take into consideration carbon stock in coffee and shade tree biomass thus leaving out a major component of GHG sinks in the coffee ecosystem.

Humbert *et al.* (2009) also used LCA to determine the environmental impact of associated with spray dried soluble coffee over its entire life cycle and compared it with drip filter coffee. The study showed that the cultivation, processing and packaging stage are each responsible for approximately 10% of the total energy used. In determining the contribution of the cultivation phase to the global warming score, they considered a N_2O emission factor of 0.07kg N emitted as N_2O per kg of N fertilizer input in the field. They thus did not include the effect of crop residues and the variation in direct and indirect N_2O emissions in different farms.

Tchibo (2008) set out to calculate the product carbon footprint of a Rainforest Alliance certified coffee product. All stages of the lifecycle were reviewed, especially with regard to the key sources of CO_2 emissions, known as hot spots. The study revealed that the carbon footprint of the coffee product researched is 8.4kg CO_2e per kg coffee produced, processed and consumed. The conclusions from the study were that the coffee chain has two major hot spots; cultivation and coffee preparation by the consumer. The study revealed that the use of agrochemicals is contributing most to GHG emissions on coffee production level. However, only one farm was researched in this study and this happened to be a coffee plantation. How the data from this single plantation relates to the numerous other coffee production systems and especially smallholder farming remains unclear. The emissions of CH_4 occurring during coffee fermentation and the generation and discharge of wastewater was left out, as well as ability of the coffee farming system to sequester carbon in the soil and plants.

2.4.2 GHG Quantification Tools

Numerous GHG quantification tools and models are available with a very wide range of application. Most models do not reach further than quantifying the fossil fuel use from transport activities, households, offices and small businesses among other sources (Amani & Scheifer, 2011). Quantifying emissions from agricultural processes requires different measures. This is a consequence of the complex emission sources such as soil released N_2O from fertilizer application, CH_4 emissions connected to the generation and discharge of wastewater and carbon sequestration in on-farm biomass and soils (Amani & Scheifer, 2011; Rikxoort *et al.,* 2013a). Optimally all these emission and sequestration factors are taken into account to determine the total CO_2e figures from farming systems as accurate as possible.

The datasets used within the various calculators vary significantly because of differences in the quality of data used and how emissions are estimated (Colomb *et al.,* 2012). Depending on the aim of the user, each calculator tries to find the best compromise between user-friendliness, time consumption and result accuracy. As long as GHG assessment is mostly voluntary and limited economic return is expected, cost and skill requirements for using GHG calculators should remain limited. The IPCC has published guidelines on the methods that should be used for estimating greenhouse gas emissions by sources and removal by sinks (IPCC 2006). These guidelines are known as ‘2006 IPCC Guidelines’ and are recognized and agreed globally. There are 3 ‘tiers’ of data recognized by the 2006 IPCC Guidelines; tier 1 data is country specific but based on global activity, it is the default factor for an emission source and contains a lower level of accuracy as figures are more general. Tier 2 data is country/region or farming system specific and therefore more accurate and applicable. Finally tier 3 data is high resolution data, possibly farm specific and is therefore the most accurate form of data. It is particularly important to know what level of data is used to allow for better comparison and proper accounting.

Table 0.1: GHG Calculators and Models Used in the Agriculture Sector

Calculator/ Model	Methodology	Gases covered	Scope
CALM calculator	IPCC tier 1	CH_4, CO_2, N_2O	Regional (U.K)
EX-ACT carbon tool	IPCC tier 1	CH_4, CO_2, N_2O	Global
CFF carbon calculator	IPCC tier 1 and tier 2	CH_4, CO_2, N_2O	Regional (U.K)
DAYCENT model	Model simulations	N_2O, CO_2	Global
DNDC model	Model simulations	CH_4, CO_2, N_2O	Regional (U.S)
Cool Farm Tool	IPCC tier 1 and tier 2	CH_4, CO_2, N_2O	Global

2.4.3 The Cool Farm Tool

The Cool Farm Tool (CFT) was developed by the University of Aberdeen, and has been used in a multi-company project on agricultural climate change mitigation coordinated by The Sustainable Food Lab. CFT recognizes context specific factors that influence GHG emissions such as: geographic and climate variations, soil characteristics and management practices at farm level (Hillier et al., 2011). The model delivers output in tonnes CO_2e/ha and kg CO_2e/kg of product so that the performance of production systems both in terms of land-use efficiency and efficiency per unit product can be assessed. The calculator is a free and open source tool, and enables users to carry out a footprint calculation on a ‘product’ or enterprise basis (Hillier *et al*, 2011).

The tool allows the user to select variables that they can influence to reduce their carbon footprint. Such variables could include tillage changes - this allows a 'what if' approach, allowing farmers to see how changes in certain practices would impact GHG emissions. CFT is fairly straight forward to use providing the required data is readily available. A 'whole farm' calculation requires computation to be done for each enterprise, which can be time consuming. This calculator takes the estimates of technical potential to the farm and uncovers what is practical and pragmatic from a farmer and field perspective.

The CFT calculates the GHG emissions from fuel and electricity use utilizing IPCC default values, soil carbon sequestration based on an empirical model which was developed from the results of several published studies and built from over 100 global datasets. The allometric equation model developed by Segura *et al* (2006) for *Coffea Arabica* and a wide variety of shade trees has been used for determination of carbon stock from above and below ground biomass. Emissions from pesticide production are computed using IPCC default values while N_2O emissions from fertilizer application are computed based on an empirical model built from an analysis of over 800 global datasets. These datasets refine gross IPCC Tier I estimates of N_2O emission by factoring in the guiding drivers of N_2O emissions such as climate, soil texture, soil carbon and soil ph.

The CFT uses several empirical sub-models to estimate the overall GHG emissions; machinery emissions - simplified model derived from ASABE, GHG emissions from fertilizer production, nitrous oxide emissions from fertilizer application (Bouwman *et al*., 2002), changes in soil C based on IPCC methodology as in Ogle *et al*. (2005) and finally effect of manure application on soil C based on Smith *et al* (1997).

There are seven input sections of the calculator, which are in separate Excel Worksheet that relate to: General Information: year, production area, location, product and climate, Crop management: crop protection, residue management, agricultural operations, fertilizer use, Sequestration: biomass above the ground, land management and use, Livestock: management of manure, Field energy use:

irrigation, primary processing: storage, factory, Transport: rail, road and air. Results from Cool Farm Tool provide credible information on carbon footprint. An insight is obtained regarding the various environmental operations and aids in optimizing management decisions on the farm.

2.5 Carbon Stocks and Carbon Sequestration in Coffee Farms

Apart from greenhouse gas emissions another aspect of the climate impact of coffee production is the amount of standing carbon stock and carbon sequestered in the coffee farms (Rikxoort *et al.*, 2014). Although unshaded coffee plantations sequester carbon in coffee plants, inclusion of shade trees in these systems increases their carbon concentrations (Anim-Kwapong, 2009; Bellarby *et al*., 2008). In most studies carbon stocks are often measured as biomass above ground defined as shade trees, coffee shrubs and litter and biomass below ground, defined as soil organic carbon and carbon stored in root biomass (Segura *et al*, 2006).

According to Albrecht and Kandji (2003) biomass equations form a basis for estimating carbon sequestration in forest and agro forestry systems. Biomass is frequently estimated by employing allometric models, which express the tree biomass as a function of easily measurable variables such as diameter at breast height, dbh, total height, h and basal area, BA (Segura *et al*, 2006). These models can be locally developed by destructive sampling, derived from literature for supposedly comparable forest types or estimated from fractal branching analysis. Allometric models have mainly been developed for their application in natural forests and forest plantations. Segura *et al* (2006) developed allometric models for coffee grown with shade trees. These models have been used in the CFT to determine carbon stocks and carbon sequestered by the coffee trees. The models predict plant biomass based on diameter at breast height (1.3m from ground level) and coffee stem diameter at a height of 15 cm from ground level and plant height.

For cases where equations have not been developed at the sites, the equations proposed Brown (1997) can be used. These equations are based on diameter at breast height, height of tree and the density of the wood. The CFT uses these allometric equations as proposed by IPCC to determine the biomass stored in other tree types apart from coffee, such as tropical moist and wet hardwoods, tropical and temperate pines as well as palm trees. However, the use Brown's equations was found to overestimate the actual biomass of trees (Ketterings *et al.,* 2001; van Noordwijk *et al.,* 2002) which shows the need to develop species-specific and site-specific equations that yield more reliable estimates of the characteristics of species of trees in East Africa's systems. A number of allometric equations have been developed for forests and agroforestry systems in East Africa which would give better estimates of biomass in these systems.

Soils contain about twice the amount organic carbon in the atmosphere. As a result, small changes in the soil organic content pool could have dramatic impacts on the concentration of CO_2 in the atmosphere (Nemoto, 2010). Conversion of land from natural to agricultural systems, agricultural activities and livestock farming enhance soil degradation, decrease soil organic carbon content, and reduce biomass production and biomass return to the soil (Lal, 2002; Nemoto, 2010). These effects become a cause of greenhouse gas emission from the soil.

Soil management in agriculture plays an important role in the mitigation of greenhouses gases. Furthermore, agronomists have recognized the benefits of maintaining and increasing soil organic matter, which adds to soil fertility, water retention, and long-term sustained crop productivity (Nemoto, 2010). Thus the preservation of soil carbon stocks is of importance to farmers in order to counter the release of GHGs as well as to enhance productivity of farms. Estimating current SOC stocks provides information on the immediate resource base and provides a baseline for determination of the best soil management practices to undertake.

2.6 Mitigation of Greenhouse Gas Emissions from Smallholder Coffee Producers

There are two approaches to mitigation of GHG emissions in coffee; reducing the contribution of coffee production to greenhouse gas emissions, this is primarily a function of the carbon footprint of coffee production and secondly sequestration of carbon in the shade trees or forest areas of the coffee farms, the conservation of existing trees could potentially be recognised under REDD+, while planting of new trees on land previously without trees have established protocols as mitigation against other emissions (Rahn *et al.*, 2014; Haggar &Schepp, 2012).

According to Rikxoort *et al.,* (2014), background soil emissions, fertiliser production and application contribute to about 35 % on average to the carbon footprint. The efficient use of fertilisers is therefore an important component of climate-friendly coffee production systems. Fertilisers should therefore be applied in accordance with recommendations from the local extension services, based on regular soil and foliar analyses. Management of tree litter and prunings by proper incorporation into the soil would also reduce the overall farm level footprint (Rahn *et al.,* 2014) In cases where full wet processing of coffee is carried out the emissions from processing may contribute over 50% of the overall footprint of coffee (Rikxoort *et al.,* 2014). Reducing the amount of water used for coffee fermentation and washing may reduce the methane emissions as well as considering better wastewater treatment methods to prevent anaerobic decomposition of the organic compounds.

Inclusion of shade trees within the coffee farms would improve carbon sequestration. The accumulation of carbon in biomass can offset the N_2O emissions from the soils (Vaast *et al*., 2005). Agroforestry systems can as well increase organic matter of the top soil layer through accumulation of litter. Boundary tree planting would also sequester carbon in coffee farms without compromising productivity of the coffee.

2.6.1 Emission Reduction from Wastewater Treatment using Adsorbents

Wastewater from coffee processing forms a major source of GHG emissions from the wet processing system commonly employed by Kenyan wet mills. The resultant wastewater from this processing system is acidic and contains high amounts of suspended and dissolved organic solids which have the potential to damage the environment (Selvamurugan, 2010). The high organic load give coffee wastewater a very high global warming potential as a result of the methane released during digestion of this load. In order to reduce the emissions at this level the organic load of the wastewater must be reduced. In the treatment of coffee wastewater various systems can be used; physical, biological and chemical. The treatment method chosen is dependent on the available resources and quantity of wastewater produced. For small holder coffee cooperatives a major hindrance to proper wastewater treatment systems is the lack of technical skills and financial ability to sustain these systems. Most of the cooperatives currently dispose their wastewater to open ponds which become mosquito breeding grounds and offer little reduction in the pollution load of the effluent. Therefore, to meet the environmental standards and to protect environment, it has become necessary to find suitable environmental friendly and economically viable treatment technologies (Devi, 2010).

Various low-cost adsorbents like chitin, chitosan, corn stalks, peat, rice husk, and wood have been used for removal of organic matter from industrial effluents (Devi, 2010). Discarded material based low-cost adsorbents of different origins like industrial waste material, bagasse fly ash, and jute processing waste can also be used for removal of organic matter from wastewater (Pala & Tokat, 2002; Wang & Wu 2006; Bhatnagar, 2007; Srivastava *et al.,* 2005). Adsorption-based technique (Devi *et al*., 2002; Devi & Dahiya, 2006) developed with low-cost carbonaceous materials showed good potential, more so for chemical oxygen demand (COD) removal from domestic wastewater. The use of activated charcoal in the treatment of wastewater has been investigated in various studies. Among these natural materials is pumice which is a volcanic stone with a low weight and porous structure (up to 85%) and can be found in many regions of the world. Due to its micro-porous structure, pumice has a high specific surface structure which is advantageous since it allows avoiding the preliminary step of calcination, a high energy cost and can float on water due to its low density. Recently many researchers have used pumice for removal of cadmium (Panuccio *et al.,* 2009), disinfection by product (Bakaroglu *et al.,* 2010), chromium (Muriuki *et al.,* 2014) and sulphur dioxide (Ozturk *et al.,* 2008). The adsorption approach can offer an easy and economical solution to these environmental challenges.

2.7 Conclusion

Small holder coffee production in Kenya forms an important portion of the coffee supply chain. Evidence of effects of climate change on coffee is revealed and knowledge gaps of the contribution of primary coffee production to GHG emissions identified. Coffee production contributes to greenhouse gas emissions throughout its supply chain through fertiliser production and use at farm level, production of pesticides used on the farm, management of crop residue on the farm and at processing level from energy use, pulp disposal and from wastewater used for wet processing. There is need to understand these small holder systems with regards to the hotspots for GHG emissions so as to propose the most suitable mitigation strategies.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

This study was conducted in Kiambu County (inset in Figure 3.1) where a certified cooperative society was selected and its member farmers used as respondents. The cooperative was selected due to its proximity to the research institution (JKUAT) and willingness to provide the required data. This cooperative has three wet mills associated with it. For confidentiality purposes, the names of the cooperative, wet mills and respondents cannot be disclosed and the mills will be referred to as A (36.84^{o}E, 1.16^{o}S), B (36.82^{o}E, 1.15^{o}S) and C (36.81^{o}E, 1.14^{o}S (Figure 4.1). The area lies at an altitude of between 1580m -1800m above sea level. The climate of the study area is tropical with an average annual temperature of 18.7^{o}C and annual average rainfall of between 813-1400mm (FAO Aquastat, 2014; Jaetzold *et al.,* 2006) The soil is characterized as medium textured, well drained with organic matter of between 1.72 and 5.16% and pH ranging between 4.9 and 6.2. The area falls under the upper midland zone 2 also known as the main coffee zone (Jaetzold *et al.*, 2006). This zone is characterised by a medium to long cropping season, intermediate rains and a medium to short cropping season allowing for sufficient production of coffee as well as legumes and fruit trees.

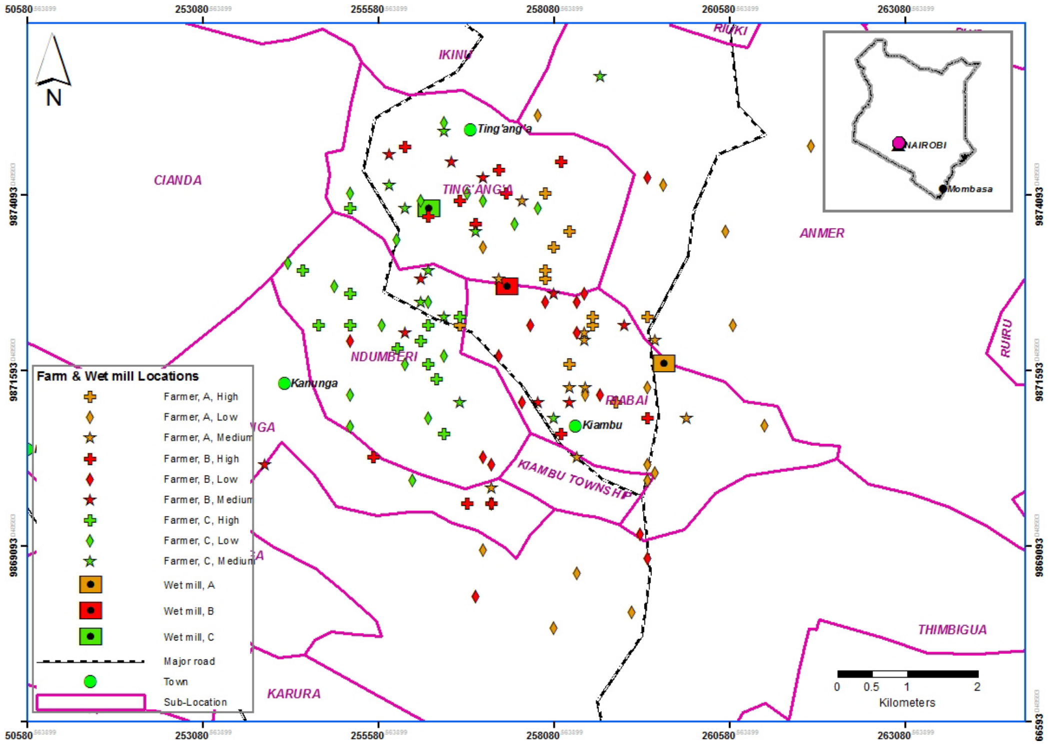

Figure 0.1: Map showing distribution of selected farmers and the coffee production areas

3.2 Evaluation of Greenhouse Gas Emissions from Smallholder Coffee Producers in Kiambu County

3.2.1 Farmer Sampling

The selected cooperative has 2600 members with 2127 of them active. The average number of trees and farm size per member is approximately 200 and 0.15ha, respectively, with an average production of 3kg cherry per tree. The population for this study was defined as all active smallholder coffee farmers who totalled 2127. As a sampling frame, the complete list of all active coffee growers with their production levels was obtained from the society’s main office. The production levels were based on yield per tree: high-level producers had yields of 5kg and above of cherry per tree while medium level lied between 3 and 4.9kg cherry and low producers less than 3kg cherry per tree. These classes were borrowed from what the cooperative uses to classify its farmers. A two-way stratified random sampling approach (Winkler, 2001; Winkler, 2009) was used in determining a sample from the population based on the wet mills that farmers took their produce, and farmer production level.

A two way table of strata cells (Table 3.1) was formed classifying the farmers by production level and by wet mill (Winkler, 2001). The table contained three rows (R) corresponding to the three wet mills and three columns (C) corresponding to the three production levels. A total of nine strata were formed from which a minimum sample size 2RC was required (Winkler, 2001).

Table 0.1: Table of Strata Cells showing Fractions of Farmers in the different Strata

Wet mill		Farmer Production Level High j=1	 Medium j=2	 Low j=3	Marginal Fractions
A	i=1	0.08	0.07	0.18	0.33
B	i=2	0.07	0.06	0.19	0.32
C	i=3	0.09	0.07	0.19	0.35
Marginal fractions		0.24	0.20	0.56	1.0

Considering the time frame of the research, the sample size was limited 36 farmers from the catchment for each wet mill, giving a total of 108 farmers. The marginal fractions of the different farmer groups was considered in the selection of individual farmers to enable proper representation of the population within the sample. The sample sizes and population of the different strata are shown in table 3.2.

Table 0.2: Sample sizes of the different Strata.

Wet Mill	High producers		Medium producers		Low producers	
	N	**N**	**N**	**n**	**N**	**N**
A	171	11	149	10	383	15
B	149	11	128	10	404	15
C	191	11	148	10	404	15

N = population of strata, n = sample size

3.2.2 Carbon Foot Print Boundary and Functional Unit

The study focused on emissions from coffee growing in the smallholder farms and initial processing at the wet mills as shown in Figure 3.2. Therefore only the emissions occurring within the operations of the cooperative society were taken into account.

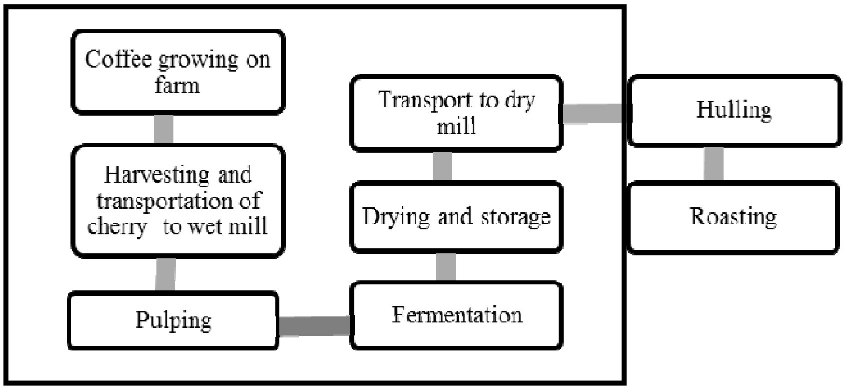

Figure 0.2: Coffee Processing Stages and Boundary of Footprint

The functional units used for this study were one kilogram coffee cherry, one acre of land and finally one kilogram of parchment. The first two units were used for footprints from farm level and the third for footprints from processing. The footprints were thus presented as kg CO_2e/kg coffee cherry, kg CO_2e/acre of land and kg CO_2e/ kg coffee parchment.

3.2.3 Selection of GHG Quantifying Tool

In order to select a suitable tool for greenhouse gas emission quantification, the following criteria were considered. Firstly, the tool had to be easy to use and could be applied within the time frame of the research project. It also needed to have the capability to take into account context specific variables such as soil and climate, and quantify not only GHG emissions arising from coffee production but also carbon stored in the coffee farms and the annual carbon sequestered. Further it had to be able to quantify emissions from primary processing especially from wastewater with reference to coffee and finally it was required to present results in both kg CO_2e/ha and kg CO_2e/kg to enable the assessment of both the performance of farming systems in terms of land-use efficiency and efficiency per unit product. A comparison of GHG quantification tools and models such as the CALM calculator, EX-ACT carbon tool, CFF calculator, DNDC model and the Cool Farm Tool (CFT) was carried out based on the above criteria. The CFT was used as the most suitable of the compared models as it met all the outlined criteria. Moreover the CFT has already been modified to various tropical crops (Hillier *et al.,* 2011), making it suitable for use with coffee.

3.2.4 Data Acquisition for the Cool Farm Tool

An interviewer administered questionnaire was used to collect data for the CFT (Appendix A). The questionnaire was based on a standard format designed by the Sustainable Food Lab to collect data for the CFT (Rikxoort *et al.,* 2013a). The questionnaire was pretested by administering to ten farmers to determine the clarity of the questions and the responses obtained from the farmers. After the pretesting of the questionnaire it was modified in order to make data collection more efficient and improve the quality of the data collected. The final questionnaire format used the sections; general data, crop management, sequestration and field energy use/primary processing. These different sections allowed for a structured and logical order in collecting the field data.

Data collection at each individual farm started with a semi-structured interview with the farmer to compile data on farm management, fertilizer use, pesticide use, shading, coffee and shade tree densities, yields, processing methodologies and energy use. Alongside this, visual inspection of the coffee farms was done to verify information gathered in the interview. In addition, the geographical locations of the visited farms were obtained using a hand held GPS system (eTrex Vista, Garmin, Germany). Shade tree species and density were obtained from information from the farmer about the number of trees per species on the farm. Shade tree diameters at breast height (1.35m from ground level) were measured for the entire population per farm due to their low numbers. For coffee 30 trees as suggested by Picard (2012) were measured per farm and these were selected randomly by moving in a zigzag direction within the farm. The diameters of the selected coffee trees were measured at 15cm from the ground level.

The status of the litter layer whether decomposed or not was assessed. Sampling frames of $1m^2$ were located within different sections of the farms and undecomposed plant material and crop residues was collected from the understory sampling frames for analysis of dry weight (Hairiah *et al.,* 2001). The extent of pruning and weeding practices was also registered in the field. Soil sampling frames were located randomly within the farms. Soil samples were collected from 0-15cm and 15-30cm depth using a shovel. Samples taken in replicate sampling grids were combined directly in the field (Hairiah *et al.,* 2001). The composite sample was mixed thoroughly to obtain a representative sample of the whole farm. From each farm two samples were collected one for each depth. The collected samples were analysed for organic carbon and pH.

At the three wet mills data was obtained on the total amount of cherry received, amount and type of energy used, the amount of water used for cherry pulping and washing, the total amount of parchment produced, the dry mills where parchment was delivered, mode of transportation of the parchment and the distance to the dry mills. Data spanning three years was obtained for computation of average values as required by the Product Category Rules (PCR) for coffee (Sustainable Agriculture

Initiative Platform SAI, 2013). Wastewater samples were collected for analysis of chemical oxygen demand and pH.

3.2.5 GHG Quantification

Data obtained from each farm was fed to the Cool farm Tool (version 2.0-beta 3) for quantification of GHG emissions. The software has been engineered in MS Excel. The tool has several input sections broken down in tabs. Once this data was fed into the CFT worksheets, the results for emissions were displayed at the bottom of each of input section and the net result displayed at the top of all pages. The net result from all the activities performed was also summarised on a separate sheet. The tool's result worksheet presented a general summary of emissions from all the activities and a more detailed breakdown of each activity. Table 3.4 shows the input variables for the different sections and the output from the CFT. For each farm, the CFT provided total emission information per farm, unit area and kilogram of finished product. The value of GHG emissions was presented in kgCO_2e/acre and kg CO_2e/kg of coffee.

Table 0.3: Data transformation by the CFT

Emission factor	Input variables	CFT Output
Fertiliser induced N_2O	Fertiliser type/ application rate per ha/ management practices	Kg CO_2e/ha, Kg CO_2e/kg product
Fertiliser production	Fertiliser type/ application rate, production technology	Kg CO_2e/ha, Kg CO_2e/kg product
Pesticide production	Number of applications	Kg CO_2e/ha, Kg CO_2e/kg product
Diesel use	Litres used	Kg CO_2e/ha, Kg CO_2e/kg product
Electricity use	Kwh	Kg CO_2e/ha, Kg CO_2e/kg product
Crop residue management	Kg/ management practice	Kg CO_2e/ha, Kg CO_2e/kg product
Wastewater production	Litres/ management practice	Kg CO_2e/ha, Kg CO_2e/kg product
Off farm transport	Km/weight/mode	Kg CO_2e/ha, Kg CO_2e/kg product

3.2.6 Data Analysis

Three main groups of data were generated by the first stage in the transformation with the CFT; carbon footprint measured per hectare basis, carbon footprint measured per unit product basis and a breakdown of the various emission sources. Within these three groups, comparison was done across the three production levels and the three wet mills. Graphs were plotted and data was analysed using a 2-way ANOVA where the factors were Wet Mill and Production Level, while the response variable at farm level were emissions per kilo or hectare of production. Interactions between the two factors were also investigated. These analyses were carried out using MS Excel 2007^{TM} and R i386 3.0.2.Ink statistical computer software

3.3 Evaluation of above Ground and Soil Carbon Stocks in the Smallholder Coffee Farms

3.3.1 Above Ground Carbon Stock Determination

Coffee and shade tree biomass was estimated through the use of allometric equations relating tree diameter to biomass. The biomass value was then used to calculate the carbon in trees. Shade tree diameter at breast height (1.3m from ground level) and coffee tree diameter 15 cm from the ground were measured (Hillier *et al.,* 2011; Segura *et al.,* 2006). The number of coffee trees and shade trees per farm were provided by the farmers during the interviews and the shade trees as well counted during diameter measurements on the farm, a final more representative value was then defined. The number of coffee trees provided by the farmer was also compared with records obtained from the wet mill and a final value was then defined. For measurement of shade trees entire populations were considered for diameter measurements due to their low numbers. In the determination of tree diameters, circumferences of the trees were measured using a tape measure (Figure 3.3) from which the diameters were then computed.

Figure 0.3: Measurement of Tree Diameters

For each selected shade tree, the circumference at 1.3m (breast height) above the soil surface was measured, except where trunk irregularities at this height occurred then the measurement was done at a height just above where the irregularity occurred (Hairiah *et al.*, 2001). Tree information such as botanical species or local name was noted to help in getting improved estimates of wood density. For coffee 30 trees as suggested by Picard (2012) were measured per farm and these were selected randomly by moving in a zigzag direction within the farm. The diameters of the selected coffee trees were measured at 15cm from the ground level. For trees with more than one stem, the diameter for each stem was computed individually after which the whole tree diameter was computed using equation 3.2 (Hairiah *et al.,* 2001). To obtain a final diameter figure for each tree species in a coffee farm the mean of all measurements per species was used.

$$D_{tree} = \sqrt{\left(D_{stem\,1}^{2} + D_{stem\,2}^{2} + D_{stem\,3}^{2} + .---\right)} \tag{3.2}$$

Allometric models proposed by Segura *et al.,* (2006) were used for the determination of biomass in coffee bushes (Table 3.4). For the estimation of biomass in shade trees grown on the smallholder coffee farms, equations proposed by Brown (1997) were used and various site specific equations from various sources were also used to give refined estimates of biomass.

Table 0.4: Allometric Models for Calculation of Tree Biomass

Tree species	Allometric equations	Source
Coffee (Coffea Arabica)	$AGB = a + b \times d_{15}$	Segura *et al.*, (2006)
Banana (Musa spp.)	$AGB = 0.03 D^{2.13}$	Hairiah *et al.*, (2001)
Grevillea robusta	$AGB = 21.297 - 6.953(DBH) + 0.740(DBH)^2$	Brown (1997)
	$\ln AGB = 0.01 + 1.81 \ln(DBH)$	Tumwebaze *et al.*, (2013)
Other tree species	$AGB = 0.091 \times (DBH)^{2.472}$	Kuyah *et al.,* (2012)

(AGB - above ground biomass, DBH - diameter at breast height (1.35m) and D is girth of banana trees, a=-0.357 and b=0.371 d_{15}-coffee tree diameter at 15cm from the ground)

The results obtained were extrapolated to determine aboveground biomass on hectare basis (Mg ha^{-1}). Belowground biomass for each tree species was calculated according to Cairns *et al.* (1997; Table 2), as successfully applied to tropical regions in Africa (Gautam &Pietsch, 2012). The above- and belowground plant C for each tree species was computed as a fraction of the above- and belowground plant biomass, respectively. For bananas, coffee, and other tree species the biomass was multiplied by 37.9% (Abdullah *et al.,* 2012), 45% (Van Noordwijk *et al.*, 2002) and 50% (Becker *et al.,* 2012), respectively. Total C pools under each were calculated by summation of aboveground, belowground and soil C in the soil layers (top and subsoil).

In the determination of amount of litter per farm, sampling frames of $1m^2$ were located within different sections of the farm. Coarse litter (undecomposed plant material and crop residues) was collected from the understory sampling frames

(Hairiah *et al.*, 2001). The litter was shaken and sieved to remove any soil and then weighed. A sub sample was taken at this stage for oven drying at 80°C for two hours. After oven drying the sub sample was then weighed and the dried weight per square meter determined as equation 3.3 (Hairiah *et al.,* 2001). The carbon stored in the litter layer was computed by multiplying the total dry weight by the carbon content and total area of the farm (Labata *et al.,* 2012)

$$W_D = \frac{W_F \times S_D}{S_F \times A} \tag{3.3}$$

In equation 3.3, W_D is the total dry weight (kg/m^2), W_F is the total fresh weight (kg), S_D is the Sub sample dry weight (kg), S_F is the Sub sample fresh weight (kg) and A is the Sample area (m^2).

3.3.2 Soil Carbon Stock Determination

Soil sampling

Sampling frames were located randomly within the farms. Soil samples were collected from 0-15cm and 15-30cm depth using a shovel. Samples from the same depth taken in replicate sampling grids were combined directly in the field (Hairiah *et al.*, 2001). The composite sample was mixed thoroughly to obtain a representative sample of the whole farm. From each farm two samples were collected one for each depth. For bulk density determinations a soil core sampler was used to obtain samples from the farms. The metallic core cylinder was removed and the top and bottom levelled off using a knife and the cylinder capped. The cylinders were then labelled. Core samples were obtained at 15cm and 30cm soil depth.

Organic carbon determination

The loss on ignition method was used for organic carbon determination. This method was selected due to the numerous samples to be tested and its safety of use (Schumacher, 2002). Out of the 216 collected soil samples, 30 were randomly selected for refinement of organic carbon determination. Soil samples were ground using a pestle and mortar and sieved through a 2mm sieve. In addition, 5-10g of the sieved soil were weighed and placed in metallic tins. The metallic tins were labelled with the farmer name and the depth from which the sample was obtained that is either 0-15 or 15-30. The weighed samples were then placed in an oven at a temperature of 105°C for 24 hours after which the dried soil was weighed and the weights before and after drying recorded. The dried soil samples were then placed in a pre-heated muffle furnace which was set at a temperature of 360°C for two hours after which they were placed in desiccators to cool. Upon cooling the samples were weighed and the weights recorded. Equation 3.3 was used to determine % organic matter (Schulte and Hopkins, 1996).

$$OM\% = \frac{W_1 - W_2}{W_1} \tag{3.3}$$

Where $W_1$is the weight before ignition and W_2 is the weight after ignition

The above procedure was repeated for muffle furnace temperatures of 400°C and 550°C. The 30 samples whose organic matter content had been determined using LOI were also subjected to Walkey-Black analysis and organic carbon was calculated as in equation 3.4 (Schumacher, 2002). In this equation, M is Molarity and W is the weight of dry soil.

$$OC\% = \frac{(mL_{blank} - mL_{sample})(MFe^{2+})(0.3)}{W} \tag{3.4}$$

The general linear form of the regression equation (3.5) was calculated to estimate soil carbon after ignition at different temperatures 360, 400 and 500°C from carbon obtained by the Walkey-black method for samples from the two depths (Salehi *et al.,* 2010).

$$SOC_{WB} = b_o + b_1 LOI \tag{3.5}$$

Coefficient of determination R^2 and Root Mean Square Error RMSE were calculated for the above equation. RMSE was calculated from

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left[P(xi) - M(xi)\right]^2}{n}} \tag{3.6}$$

Where

P(xi) = estimation of soil carbon by Loss on ignition at farm xi

M(xi) =measured soil carbon by Walkey-Black method at farm xi

The most ideal temperature for LOI was then selected and used for determination of organic carbon for all the remaining soil samples.

Bulk density determination

The metallic caps were removed from the core cylinders with wet soil which were then weighed and the weight recorded (M_1). The weighed core cylinders were then placed in the constant temperature oven set at 105°C for 36 hours. After drying, the core cylinders were removed and weighed once again and the weight recorded (M_2). The soil was then removed from the cylinders and the empty cylinders weighed (M_3). The volume of the core cylinder was then determined. Bulk density (ρ) was determined as in equation 3.7 (Salehi *et al.,* 2010).

$$\rho = \frac{M_2 - M_3}{Vol\, of\ cylinder} \tag{3.7}$$

Where M_2 is the weight of dry soil and M_3 is the weight of empty cylinder

The bulk density and the organic carbon values were then used to compute the total carbon available in the farms as in equation 3.8 (Labata *et al.,* 2012) where S.C is soil carbon, ρ is bulk density and V is volume.

$$S\,C = \rho \times V \times \%\, SOC$$

(3.8)

3.3.3 Data Analysis

Analysis of variance and multiple mean comparisons were carried out in order to compare carbon densities from the different compartments among the studied coffee systems.

3.4 Evaluation of the Use of Pumice and Charcoal in the Reduction of Greenhouse Gas Emissions from Wastewater from Coffee Processing

3.4.1 Experimental Set Up

Twelve 2kg containers were used as water treatment cells. The experimental set up consisted of three treatments with three replications each (Figure 3.4). The treatments were pumice, charcoal and a mixture of pumice and charcoal. The control had red soil as a substrate. The pumice and charcoal used for the study were first prepared by rinsing with distilled water until the effluent turbidity was lower than 0.1NTU, and then dried in the oven at 100^{o}C for 24 hours. The dried pumice and charcoal were then crushed and passed through a 0.6 mm sieve. Three containers were halfway filled with pumice, another three halfway filled with charcoal and a third set of three halfway filled with a mixture pumice and charcoal in the ratio of 1:1 by volume. The final three containers were used for the control thus were halfway filled with red soil (Figure 3.5).

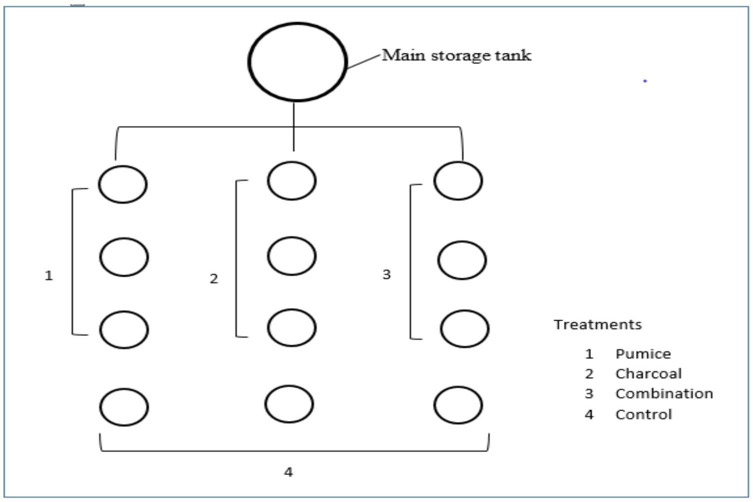

Figure 0.4: Experimental set up showing the placement of the 2kg containers

Figure 0.5: 2kg containers with the crushed adsorbents

3.4.2 Data collection procedure

The wastewater generated during processing of Arabica coffee was collected from the final outlet of the three coffee processing wet mills. The collection was done during the peak of the coffee processing season which is normally in November. For characterisation of the wastewater, three samples were collected from each wet mill and transferred to the SOBEE laboratory within an hour. The raw wastewater samples obtained from the wet mill were then analysed for total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD) and electrical conductivity (EC). These were estimated using the standard methods for examination of water and wastewater (APHA, 1992). Temperature and pH were measured using standard pH electrode meter (Hanna HI 98129 pH ECD/TDS, Hanna Instruments Inc. Woonsocket USA)

For the water treatment experiment fifty litres of wastewater was collected from wet mill A. A sample of this influent was collected and analysed for TSS, TDS, pH, BOD and electrical conductivity. Each container in the experimental set up was then filled with two litres of raw wastewater. Samples of effluent from the set up were collected from the bottom of the containers at intervals of one hour for analysis of TSS, TDS pH and electrical conductivity. This was done for eight hours. Effluent BOD was measured after 8, 24, 32, 48, 56 and 72 hours.

3.4.3 Data analysis

Graphs relating change in the different parameters with time for the different treatments were plotted in order to compare their performance in wastewater treatment. Analysis of variance was also performed to determine whether or not there existed significant differences in the performance of the different adsorbents. These analyses were carried out using MS Excel 2007^{TM} and R i386 3.0.2.Ink statistical computer software.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Greenhouse Gas Emissions from Small Holder Coffee Farmers and Wet Mills

4.1.1 Characteristics of the Smallholder Coffee Farms

The smallholder coffee farms were largely less than one hectare with the area under coffee ranging from 0.1 to 1.6 Ha (Table 4.1). The farms varied in management practices such as pruning, fertiliser use and shade. The smallholder coffee farmers practised some few elements of conservation agriculture such as residue incorporation and inclusion of cover crops within the coffee plots. For food crops, the farmers planted maize, beans, bananas and potatoes while some farmers practised mixed farming in which dairy cows contributed to both milk and organic manure. Some farms had napier grass grown within the edges of the coffee plots.

The age of coffee trees in these farms ranged from 22 years to 55 years (mean: 51±1.2 years). On average coffee plant densities were about 2000 trees per hectare and the average yield levels per hectare were 7333kg, 1850kg and 1158kg for high, medium and low producers respectively (Table 4.1). The soils in the area had a pH ranging from 4.3 to 6.7 and organic carbon content ranging from 2.6 to 5.31. The values of organic carbon from the selected farms reflected high levels of applied organic matter. Most of the soils in the area had a sandy loam texture.

Table 0.1: Characteristics of the smallholder coffee farms

	High producers (n =33)	Medium producers (n=30)	Low producers (n=45)
Farm size (ha)	1.27 SD=0.59 (0.4-2.4)	0.88 SD=0.37 (0.2-1.6)	0.90 SD=0.49 (0.2-3.6)
Area under coffee (ha)	0.6 SD=0.36 (0.2-1.6)	0.27 SD=0.12 (0.1-0.4)	0.26 SD=0.18 (0.1-1.0)
Coffee tree density (trees/ha)	1941 SD=800 (494-4118)	1817 SD=926 (593-3479)	2005 SD=1170 (395-6177)
Shade tree density (trees /ha)	157 SD= 21 (43-512)	95 SD=13 (21-213)	159 SD=15 (62-423)
Coffee yield (kg/ha)	7333 SD= 286 (1685-10754)	1850 SD= 178 (1212-2936)	1158 SD=203 (598-2660)

4.1.2 Carbon Footprints from Smallholder Coffee Farms

The carbon foot prints at farm level ranged from -0.37 to 0.35 kg CO_2e per kg coffee cherry for high producers, -0.1 to 0.76 kg CO_2e for medium producers and 0.09 to 1.29 kg CO_2e for low producers. Comparison of average emission values from the different farmer groups showed there was an increase in emissions for farmers from all the mills as the level of production decreased (Figure 4.1). A negative carbon footprint indicated that a farm was sequestering more carbon than it was emitting. A 2-way ANOVA (Appendix Table B6) for emissions per kilogram cherry at each production level across the wet mills showed that there were no significant differences in emissions per kg cherry from farmers from the three levels of production across the three wet mills ($P=0.51$). These results imply that there was homogeneity of farmers at each production level across the three wet mills. Further, the results indicate that there was a highly significant difference in emissions across the three production levels ($P<0.001$) at individual wet mills (Appendix table B9). This implies that production level had a significant negative effect on the product carbon footprint of coffee. The product carbon footprints decreased with increase in production. There was however no interaction between farmer production level and wet mill (P=0.87).

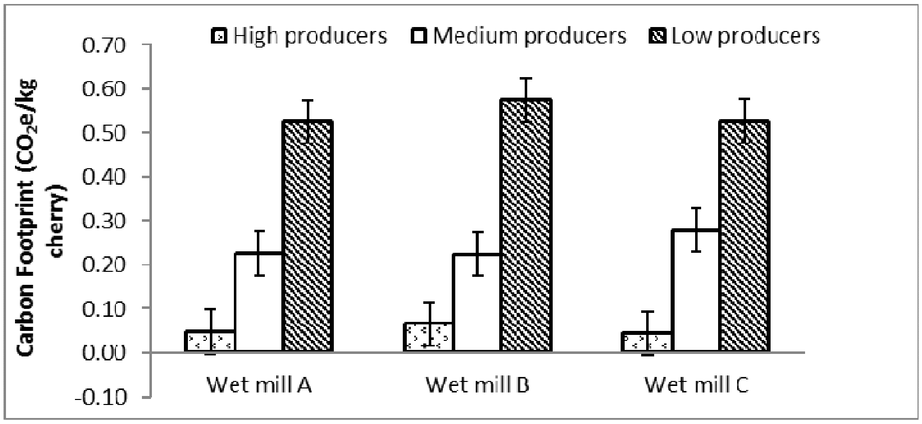

Figure 0.1: Mean Carbon Footprints Per Kg Cherry Across the Three Production Levels and Wet Mills

The variation of emissions with production level can be explained by the fact that in agricultural supply chains carbon footprint is measured per unit of product (Rikxoort, 2010). According to Rikxoort *et al.*, (2013a), in the calculation of Product Carbon Footprint (PCF) all emissions arising from a production system are allocated to the amount of coffee produced which therefore has an impact on the final footprint thus the higher the yields the lower the carbon footprint. These results are in agreement with Attarzadeh and Noponen (2010) who concluded that product carbon footprints decrease with increase in production.

The GHG emissions per hectare at farm level for individual farms ranged from -1043 to 1038 kg CO_2e/ha for high producers, 114 to 1300 kg CO_2e/ha for medium producers and 410 to 1833 kg CO_2e/ ha for low producers. There was an increase in carbon footprint per hectare with decreasing production levels from farmers across all the wet mills (Figure 4.2). High production level farmers had the lowest footprints per hectare of land with those from wet mill A storing more carbon than they are emitting hence a negative footprint.

Figure 0.2: Mean Carbon Footprints Per Hectare of Land Across the Three Production Levels and Wet Mills

A 2-way ANOVA for carbon footprint per hectare across the three production levels showed that there were highly significant differences in emissions per hectare across the three production levels ($P<0.001$). Production level of the small holder farmers therefore had a significant effect on emissions per area of land as well. Moreover the results indicated significant differences in emissions per acre across the three wet mills ($P = 0.019$) but no interactions between production and wet mill ($P = 0.9$). High production farms are characterized by higher fertiliser use, heavier pruning regimes, better management practices and higher coffee and shade tree densities, as a result the amount of carbon sequestered in these ecosystems is much higher. This counters the apparently higher emissions from fertiliser use resulting in the lower per acre footprints recorded.

A breakdown of the various emission sources at farm level showed that the major source of emissions from the small holder coffee farms is the application of fertilisers (Figure 4.3 and 4.4). Fertiliser production and nitrous oxide emissions accounted for 94% of the total on-farm emissions, as contrasted with crop residues which account for 4% of the total farm emissions. Pesticide use and transport of cherry from the farm each contributed 1% of the overall emissions. The results also showed that the emissions per kilogram cherry from the different sources increase with a decreasing production levels (Figure 4.3). This could be due to the fact that the computation of PCF based on total cherry produced thus the footprints are inversely proportional to the amount of coffee cherry produced. However carbon stock changes per unit product increased with decreased productivity indicating a greater level of carbon storage per unit product for the low producers.

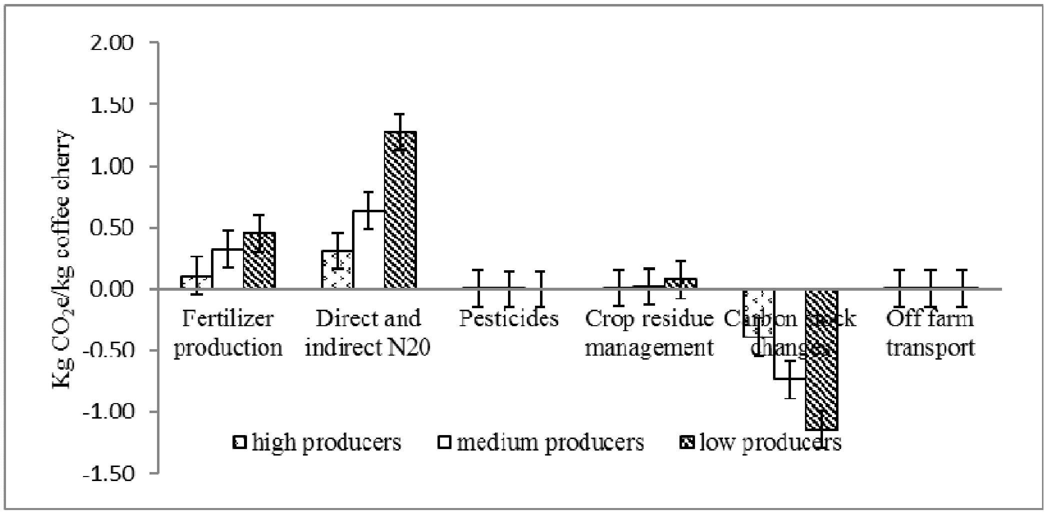

Figure 0.3: Emissions Per Kilogram Cherry from Various Sources at Farm Level

Emissions per acre of land from individual sources showed that emissions from fertiliser use increased with increase in production while the carbon sequestered was highest for high producers followed by low producers and lowest for medium producers (Figure 4.4). High production level farmers had the highest fertiliser emissions indicating a high reliance on inorganic fertilisers. Carbon stock changes were higher for these farms as well which may be attributed to the high pruning regimes, better farm management practices and a higher density of shade trees. Low producers had higher carbon stock change values as a result of intercropping coffee with crops such as beans, pumpkins thus more residue incorporated into the soil. This implies that intercropping has the potential for improving carbon storage in the coffee farms. Intensifying production while maintaining the carbon storage potential of these farms would greatly improve the climate friendliness of the low producers.

The carbon footprint from soils and fertilizer use did not differ significantly among systems, reflecting the high variability of these emissions in all systems and the fact that in the high production farms the higher use of mineral fertilizer was often compensated by higher yields

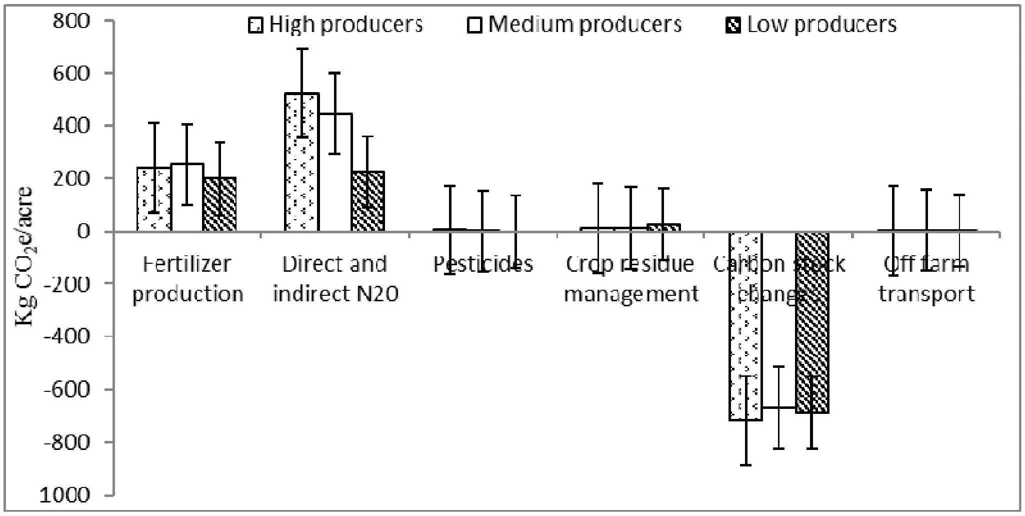

Figure 0.4: Emissions Per Acre From Various Sources at Farm Level

From the results of Figures 4.3 and 4.4, it is evident that the use of footprints per area of land is most suitable for comparison of the various farmer types in this study as the footprints per kg produce are biased towards productivity. The footprints per area of land bring to the foreground the effect of variations in farming activities on farm level emissions. This is contrary to the findings of Haverkort and Hillier (2011) who argue that for comparison of products from different sources, the use of footprints per kg of product is much suitable.

4.1.3 Effect of Fertiliser Application on the Carbon Footprint

The major emission hot spot at farm level was from coffee nutrition which accounted for 94% of the total emissions (Figure 4.3 and 4.4). Coffee nutrition for the smallholder farming systems involves the use of both inorganic fertilisers and organic manure. The main type of manure used by the coffee farmers was cattle farm yard manure with a carbon content of 13.6% and a pH of 8. The highest levels of farmers using organic manure only was in the low production level. Average fertiliser application rates were 56kg N/acre, 24kgN/acre and 11kgN/acre for high, medium and low producers respectively.

There was an increase in fertiliser use with production level for farmers across all the wet mills (Figure 4.5). Analysis of variance for fertiliser use across the production levels showed that there were highly significant differences in fertiliser use amongst the three levels of production ($P<0.001$). High producers were using significantly higher amounts of fertiliser than the medium and low producers.

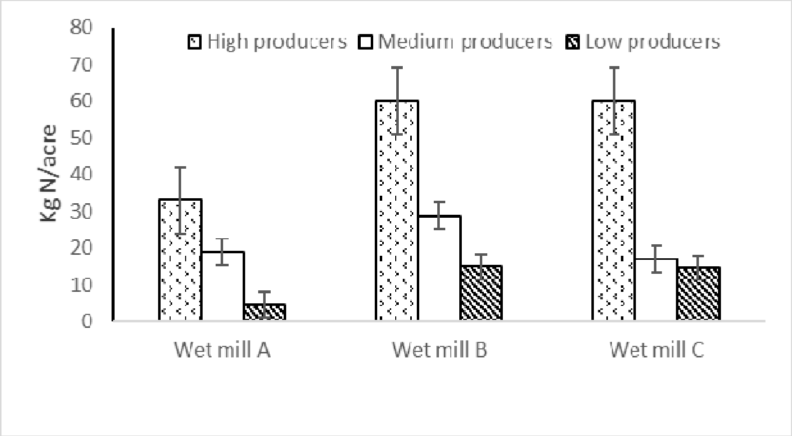

Figure 0.5: Fertiliser Application Rates across the Smallholder Farms

The relationship between soil N_2O emissions and the total product carbon footprint is presented in Figure 4.6. The figure shows an increase in the carbon footprint as the amount of soil N_2O emissions increase thus indicating a strong correlation between emissions from fertiliser application and the total carbon footprint. These findings are in line with Noponen *et al.,* (2012) who found that there was a strong correlation between soil N_2O emissions and overall footprint both in organic and conventional farming systems. The overall farm carbon footprint was therefore highly dependent on emissions from fertiliser application therefore the higher the amount of fertilisers used the greater the farm carbon footprint especially if the use of these fertilisers does not result in a significant increase in yields. More efficient use of external inputs would thus help in reducing the overall carbon footprint.

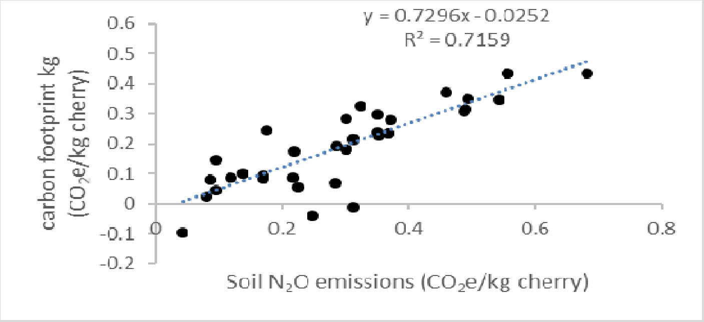

Figure 0.6: Relationship between Soil N_2O Emissions and the Overall Carbon Footprint

Considering individual farms, there was an inverse relationship between the footprints from fertiliser use and yield. Foot prints from fertiliser application decreased with increasing yield levels as expressed by a power curve (Figure 4.7). Despite their higher levels of use of fertilisers, high producers had a lower fertiliser carbon footprint. The apparent high emissions from fertiliser application were countered by the high yields in these farms. Low producers had the highest fertiliser emissions per kilogram of product because the resulting soil emissions accrued to a small amount of product thus even modest applications of mineral or organic fertiliser could drive the footprint up if they did not result in proportional yield increases.

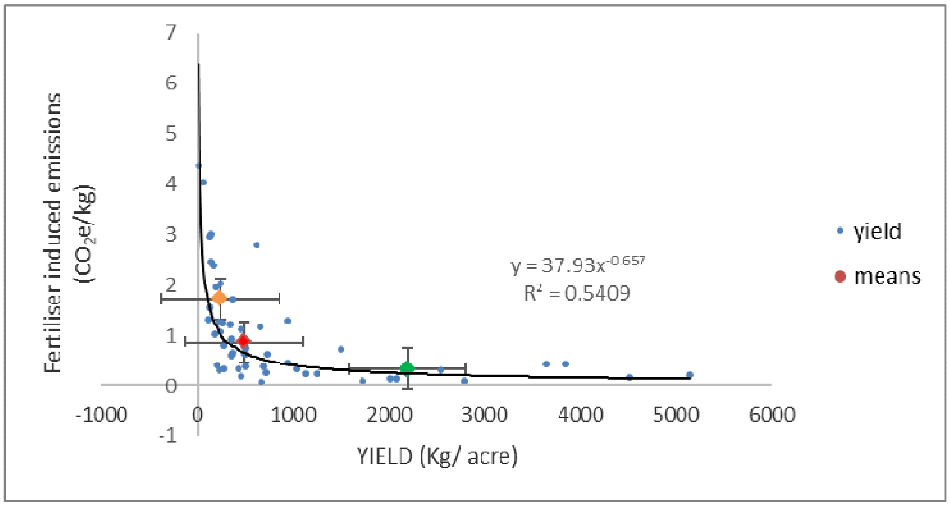

Figure 0.7: Relationship between Fertiliser Induced Emissions and Coffee Yield from Individual Farms

4.1.4 Emissions from Coffee Processing

The collected coffee processing wastewater from the three wet mills showed high BOD values (6000-10000mg/l) and low pH values. The average amount of water used for pulping washing and fermentation was 5.39l/kg and 4.99l/kg per kg coffee cherry for wet mill B and C, respectively. Data on water use from wet mill A was not available at the time of the study as the meter was broken. Recirculation of water in the wet mills greatly reduced the total amount of water used for processing. Von Eden and Calvert (2002) report a value of 20l/kg without a recirculation system which is higher than the values reported from the studied wet mills. Processing level emissions are presented in Table 4.2. The results reveal that at processing level the major source of emissions is the generation of wastewater from pulping, fermentation and washing of coffee cherry. This accounts for 97% of the total processing emissions, which is consistent with observations by Rahn *et al.,* (2014), who reported pulping and fermentation as the greatest sources of emissions from primary processing of coffee. Energy use at primary processing was mainly from the depulping machines and recirculation pumps as drying of coffee at these wet mills is mainly by open sun hence low energy use emissions.

Table 0.2: Emissions (kgCO2e/kg Coffee parchment) from various sources at Processing Level

Wet mill	Processing emission sources			
	Energy use	Wastewater	Transport	Total
A	0.150	-	0.036	0.51
B	0.014	2.57	0.036	2.62
C	0.019	2.341	0.036	2.40

The study revealed an average footprint of 4kg CO_2e kg coffee parchment for the selected small holder coffee supply chain. This footprint is lower than Rahn *et al.,* (2014) who used the CFT and reported a footprint of 5.81 kg CO_2e/kg coffee for Nicaragua coffee farms. This difference may be attributed to variations in coffee management especially on coffee nutrition. Emissions from coffee processing contributed to more than half of the carbon footprint (Table 4.3). Thus for small holder coffee production in Kenya, the bulk of production emissions is at primary processing level. On the average of all systems, 33 % of the carbon footprint of the coffee was due to fertilizer production and application including background soil emissions, 4% was due to emissions from prunings and crop residues decomposing on the ground, 1% was from pesticide application and 63 % was due to emissions from fermentation and waste water. These values are similar in trend to those reported by Rikxoort *et al.,* (2014).

Table 0.3: Total Emissions from the entire Small holder Production Chain

Wet mill	Emissions at farm level		Emissions at processing level
	kg CO_2e/kg coffee cherry	Kg CO_2e/kg coffee parchment	kg CO_2e/kg coffee parchment
A	0.33	1.65	-
B	0.28	1.40	2.62
C	0.30	1.50	2.40

A comparison of the carbon footprint at farm level obtained from this study with earlier studies shows some differences which may be attributed to the different methodologies used. The studies in Costa Rica and Nicaragua used PAS 2050 and direct IPCC equations to calculate the footprints while this study applied the Cool Farm Tool to calculate the footprints. Attarzadeh and Noponen (2010) concluded that input levels of the farms and production level had an impact on the product carbon footprint and resulted in variation of carbon footprints.

4.2 Biomass and Soil Carbon Stocks in the Smallholder Farms

4.2.1 Plant Biomass and Carbon Stocks

Majority of the farmers managed a shaded coffee production system and used the prunings of their coffee and shade trees as firewood. Depending on farm size and management, between 2 and 4 species of shade trees were present with uses including timber, fruits and firewood. Smaller farms tended to have higher total numbers of species than larger farms. There was a general trend of species homogenization towards grevillea and banana systems. 44% of the farms grew coffee and a mixture of *Grevillea robusta*, macadamia, mango, and avocado and banana trees while 33 % of the farms grew coffee with only grevillea trees as shade. The coffee-banana intercrop system was practised by 15% of the farmers and only 8% of the farmers had full sun coffee.

The results reveal that most of the aboveground biomass is stored in trees (97-98%) with shade trees having higher values (58-67%) than coffee trees despite their smaller numbers (Table 4.4). This is consistent with findings from other studies where more than 90% of the biomass is commonly found in trees (Labata *et al.,* 2012). High production farms reported higher values of coffee biomass compared to the medium and low producers. However low producers stored most of their carbon in shade trees with high producers having the least shade tree carbon (Table 4.5). This indicates that most high production farms tend towards fully in-sun coffee thus less competition with the coffee plants hence healthier coffee plants leading to the high biomass values. Low producers and medium producers on the other hand have more shade trees to supplement the low income from coffee. The major shade trees in these farms were fruit trees and trees used for timber.

Table 0.4: Above Ground Biomass from Various Sources in the Small Holder Coffee Farms

Production level	Above ground biomass density (Mg/ha)			
	Coffee	Shade tree	Litter	Total
High	5.2 (30%)	11.35 (67%)	0.53 (3%)	17.08
Medium	4.9 (40%)	7.18 (58%)	0.31 (2%)	12.39
Low	4.4 (35%)	7.86 (62%)	0.34 (3%)	12.6

Table 0.5: Above Ground Carbon Stocks from Various Sources in the Small Holder Coffee Farms

Production level	Carbon content (Mg/ha)			
	Coffee	Shade tree	Litter	Total
High	2.34(29%)	5.60(68%)	0.25(3%)	8.19
Medium	2.23(17%)	10.69(82%)	0.15(1%)	13.07
Low	1.99(14%)	11.67(84%)	0.16(2%)	13.82

4.2.2 Soil Carbon Stocks

The values of soil carbon ranged from 2.75-5.31% for a depth of 0-10cm and 2.2-4.56% for a depth of 10-30cm (Table 4.6). There was an increase in soil carbon values as the ignition temperatures increased. This increase may be as a result of the breakdown of inorganic carbonates within the soil (Schumacher, 2002).

Table 0.6: Descriptive Statistics for Soil Carbon Determined from the Two Methods

	Soil depth 0-10cm (n=25)			Soil depth 10-30cm (n=25)		
	Min.	Max	Mean ± SE	Min	Max	Mean ± SE
SOC_{WB}	2.75	5.31	4.0 ± 0.17	2.2	4.56	3.3 ± 0.16
$SOC_{LOI(360)}$	6.3	12.46	9.32 ± 0.38	7.02	10.01	8.54 ± 0.18
$SOC_{LOI(400)}$	9.32	18.12	12.46 ± 0.55	10.76	14.11	12.32 ± 0.18
$SOC_{LOI(500)}$	13.65	20.02	16.49 ± 0.47	14.47	17.87	16.33 ± 0.22

A significant linear relationship was observed between Loss on Ignition at all temperatures and Walkey-Black with a stronger correlation between $SOC_{LOI\ (360)}$ and SOC_{WB} (Table 4.7) Coefficients of determination were higher for 0-10cm depth compared to 10-30cm depth. Coefficient of determination decreased and RMSE increased with increasing ignition temperatures. Salehi *et al.,* (2011) report similar results when carrying out Loss on ignition at different temperatures for two hours. The results show that an ignition temperature of 360°C was most suitable for determination of soil carbon from the selected farms because of the high R^2 values and low RMSE values. The loss on ignition analysis at 360°C was therefore carried out on all the soil samples from the selected 108 farms.

Table 0.7: Regression Parameters between Soil Carbon Calculated by Walkey-Black Procedure and Loss on Ignition Analysis

Temperature °C	Soil Depth 0-10cm				Soil Depth 10-30cm			
	Intercept	Slope	R^2	RMSE	Intercept	Slope	R^2	RMSE
360	0.093	0.419	0.948	0.0524	-3.109	0.752	0.778	0.0524
400	0.636	0.271	0.796	0.0866	-4.029	0.586	0.555	0.0920
500	-0.818	0.292	0.695	0.1259	-5.237	0.524	0.549	0.1303

The total soil carbon stocks were highest for low producers and lowest for medium producers (Table 4.8). The higher values of soil carbon in low producing farms may be as a result of more residue incorporation although the differences in the values were not significant. Overall, almost 60% of the total carbon stock was found in soil. The higher values of soil carbon stock compared to above ground carbon is because it has the longest residence time of carbon among organic carbon pools (Lugo & Brown 1993). These results are in agreement with Lasco *et al.,* (2001).

Table 0.8 Soil Carbon Stocks for the Small Holder Farmers

Production level	Carbon content (Mg/ha)	
	0-10cm	10-30cm
High	16.36	14.23
Medium	15.89	13.98
Low	16.54	14.68

The climate benefits of high standing carbon stocks in a land use system are not captured in the carbon footprint which measures carbon flows between the production system and its environment. Rikxoort *et al.,* (2014) proposes a the most desirable combination of climate change mitigation being those systems that have minimal carbon footprints and are able to preserve high levels of standing carbon.

4.2.3 Annual Carbon Sequestration

Annual carbon sequestration values across the farms ranged from 273 – 1442 kg CO_2e for high producers, 235-918kg CO_2e for medium producers and 368-1152kg CO_2e for low producers. The mean annual carbon sequestration values are shown in Figure 4.8. Wet mill A farmers were sequestering the most carbon annually while wet mill B farmers had the lowest annual sequestration values. Carbon sequestration in the farms was mainly as a result of management changes in practices such as cover cropping, manure application and residue incorporation. Sequestration in tree biomass was not factored as a Periodic Annual diameter increment of 0 cm was assumed for coffee and shade trees since this was not available for East African systems. Rikxoort *et al.* (2014) also propose the exclusion of biomass carbon sequestration because the biomass in the vegetation may fluctuate cyclically as trees and other plants grow, are harvested, pruned back to avoid over-shading of the coffee, or die.

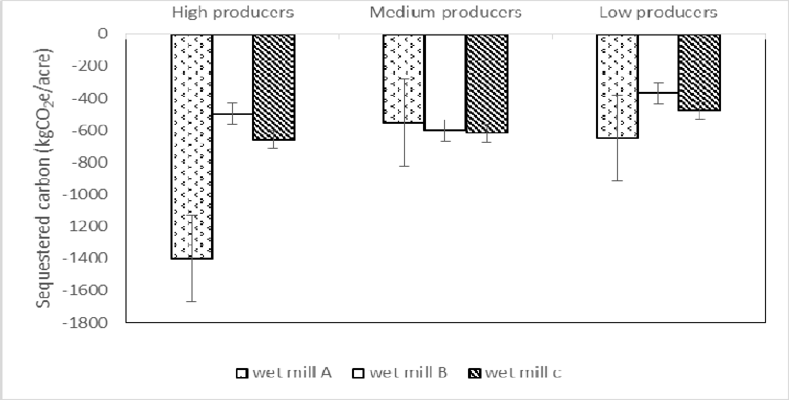

Figure 0.8: Annual Carbon Sequestered Across the Production Levels

4.3 Use of Pumice and Charcoal in Reduction of Greenhouse Gas Emissions from Wastewater from Coffee Processing

4.3.1 Characterisation of Waste Water from Coffee Processing

The characteristics of the wastewater from the three wet mills are presented in Table 4.9. The wastewater had a pH range of 3.9 to 4.5 which was found to be highly acidic compared to the WHO permissible standards (Table 4.9). This acidic pH is due to the presence of organic acids in berry skin and pulp. The range obtained is in accordance with the findings of Hue *et al.,* (2006). The EC of the coffee wastewater ranged from 0.96 to 1.2 dS/m which could be due to the presence of nutrients. This range is in accordance with the findings of Matos *et al.,* (2001). The total dissolved solids and total suspended solids ranged from 623mg/l to 1432mg/l and 528mg/l to 1157mg/l respectively. The appreciable amounts of suspended and dissolved solids present in the wastewater may be due to the presence of pectin, protein and sugars which are biodegradable in nature. The BOD and COD values ranged from 1926mg/l to

2789mg/l and 2956mg/l to 3965mg/l respectively. The high BOD values recorded indicate a high amount of organic substances in the wastewater.

Table 0.9: Measured Parameters of the Wastewater from Coffee Processing

Parameter	Characteristics of coffee processing water			WHO permissible limits
	Wet mill A	Wet mill B	Wet mill C	
pH	4.3	3.9	4.5	6.8-8.5
TSS (mg/l)	1157	634	528	200
TDS (mg/l)	623	745	1432	450
Turbidity NTU	567	445	655	5-10
EC (dS/m)	0.96	1.2	1.0	0.001
BOD (mg/l)	1926	2563	2789	100
COD (mg/l)	2956	3965	3023	300

4.3.2 Effect of Adsorbents on Total Suspended Solids

The adsorbents reached equilibrium after one hour after which there was no change in the value of TSS of the wastewater (Figure 4.9). The percentage TSS reduction was found to be 93.9, 92.6, 96.9 and 90.8% for pumice, charcoal, combination and the control respectively. The higher removal of TSS using the pumice-charcoal composite may be due to the good adsorption capacity of the mixture, more pore structure of this mixture and the numbers of available adsorption sites on the surface of the adsorbents. Similar trends have been reported by Matos *et al* (2001) and Devi (2010).

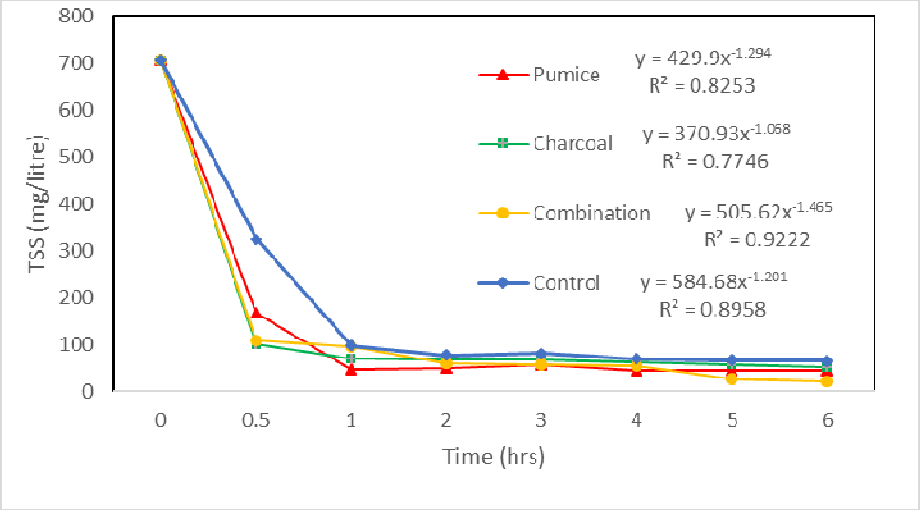

Figure 0.9: Effects of Adsorbents on TSS of Wastewater from Coffee Processing

4.3.3 Effect of Adsorbents on Total Dissolved Solids (TDS)

Removal of TDS was achieved in all the adsorbents (Figure 4.10). The percentage TDS reduction was found to be 37.8, 62.2, 28.9 and 21.6% for pumice, charcoal, combination and the control respectively. Charcoal showed the highest reduction of TDS with time which may be due to the fact that charcoal has a slightly higher specific surface area and porosity which enhances the sedimentation and filtration processes. The results are in agreement with those obtained by Mortula and Shabani (2012) who investigated the removal of TDS and BOD from industrial wastewater using commercial adsorbents.

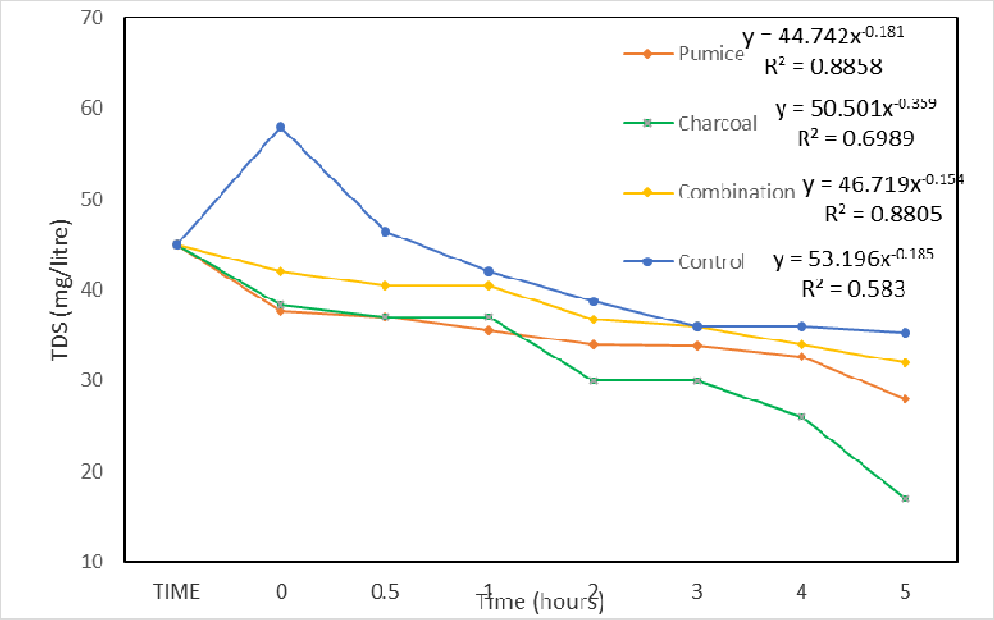

Figure 0.10: Effect of Adsorbent on Total Dissolved Solids of Wastewater from Coffee Processing

4.3.4 Effect of Adsorbents on Ph

Pumice**,** charcoal and a combination of the adsorbents showed a gradual increase in pH in the first 30 minutes after which the pH levelled off (Figure 4.11). The final pH values recorded were 6.1, 7.1 and 7.9 for pumice, charcoal and combined adsorbents respectively. The control showed only a slight increase in pH with a final value of 4.01. Pumice took the shortest time to neutralise the pH but there was no significant difference in performance of the two adsorbents in pH reduction.

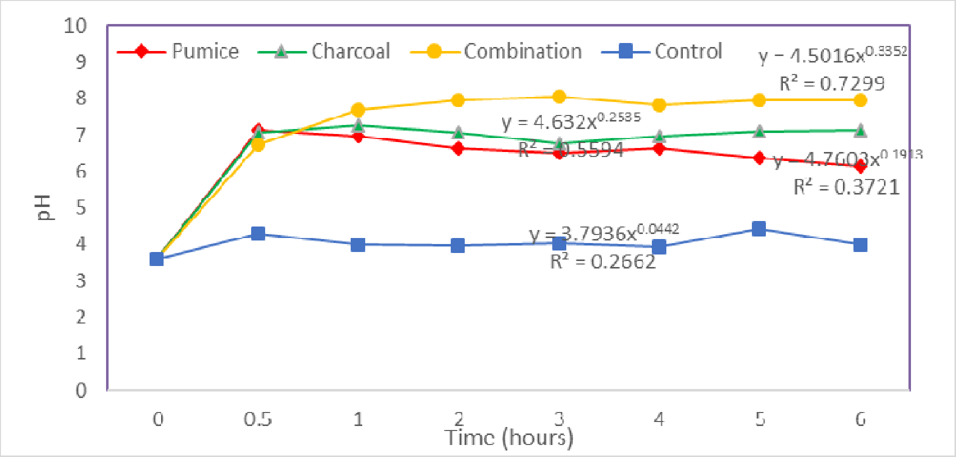

Figure 0.11: Effect of Adsorbents on Ph of Wastewater from Coffee Processing

4.3.5 Effect of Adsorbents on Turbidity

The adsorbents reduced turbidity gradually for two hours after which equilibrium was reached (Figure 4.12). The highest levels of turbidity reduction was observed in the control set up. The percentage reduction in turbidity was 98.1, 96, 91.8 and 91.1% for control, combined adsorbents, charcoal and pumice respectively. The graph shows better performance of the combined adsorbents compared to the individual adsorbents. There were no significant differences in the set ups for turbidity reduction. Similar results have been reported by Shoba *et al.,* (2015) using tamarind kernel as a low cost adsorbent to reduce the turbidity of wastewater.

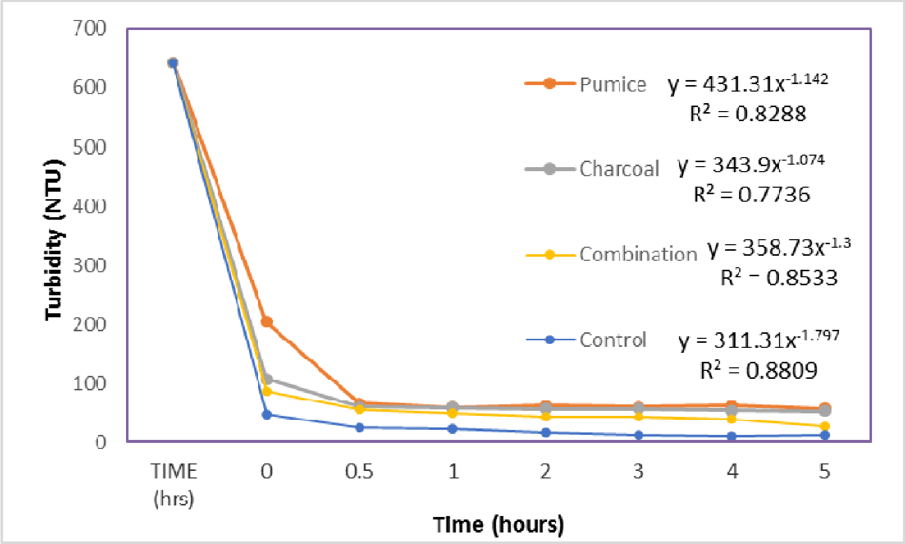

Figure 0.12: Effect of Adsorbents on Turbidity of Wastewater from Coffee Processing

4.3.6 Effect of Adsorbents on Bio-Chemical Oxygen Demand

The adsorbents showed a gradual decrease in BOD over time (Figure 4.13). The percent of removal increased with an increase in contact time and reached maximum at 56 hours by attaining equilibrium conditions and afterwards, sluggishness was observed which can be attributed to the saturation of binding sites. The final percentage reduction in BOD obtained was 71.3, 62.4, 59.1, and 45.4% for pumice, charcoal, combination and control respectively over a period of 72 hours. However there were no significant differences in the performance of the two adsorbents in reduction of BOD (P=0.56). Similar trends are reported by Devi (2010) when using avocado peel carbon to reduce the BOD and COD of coffee processing wastewater.

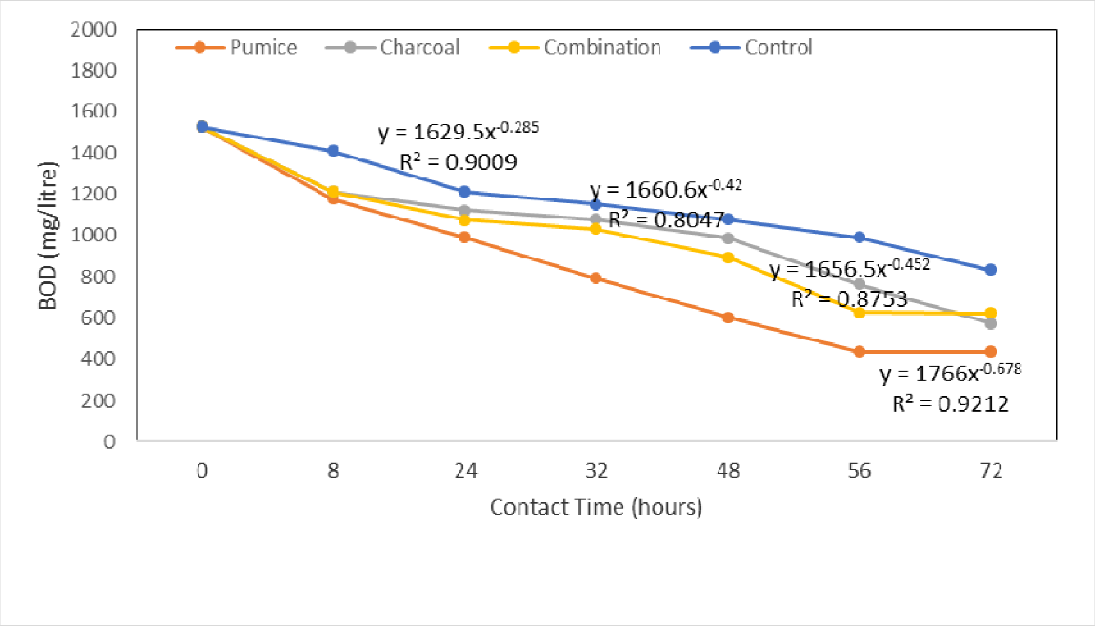

Figure 0.13: Effect of Adsorbents on BOD of Wastewater from Coffee Processing

The low cost adsorbents investigated in the study were able to reduce the pollution load of the wastewater from coffee processing as evidenced by the percentage reduction of the various parameters. The principle factor in determining the methane generation potential of wastewater is the amount of degradable organic material in the wastewater (Davi *et al.,* 2010). The parameter used to measure the organic component of the wastewater is the BOD. Reducing the BOD of wastewater therefore serves as a climate change mitigation measure by reducing the potential of generating methane from this water.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. The main aim of this study was to determine the carbon footprint of smallholder primary coffee production and propose suitable mitigation options. The results presented here in reveal that coffee yield levels have a significant effect on the carbon footprint measured on a product basis. Low yielding farmers had a higher carbon footprint per kilogram of cherry as all the occurring emissions are allocated to less produce. There was a significant difference in emissions per kilogram cherry across the production levels ($P< 0.001$) thus production level has a significant effect on the overall carbon foot print of a farm The main sources of GHG emissions for the prevalent coffee production systems were identified as - in order of decreasing importance— (1) coffee depulping and fermentation, (2) fertiliser and manure application (3) decomposition of tree litter and prunings in the field, and (4) pesticide application.
2. Above ground carbon stocks increased with decrease in production level. Above ground biomass for the smallholder farms was 17.1Mg/ha, 12.4Mg/ha and 12.6Mg/ha for high, medium and low producers respectively while the above ground carbon stocks for the small holder farms were 8.2Mg/ha, 13.1Mg/ha and 13.9Mg/ha for high, medium and low producers respectively. For all the smallholder farmers, more than 60% of the aboveground carbon stock was stored in the shade trees within the farms. The highest carbon pools was in the soil which had 16.4Mg/ha, 15.9Mg/ha and 16.5Mg/ha for high, medium and low producers respectively. Low producers reported the highest values of both biomass and soil carbon. Annual sequestration values were highest for high producers and lowest for medium producers.
3. Low cost adsorbents can successfully be used in the reduction of greenhouse gas emissions from wastewater from coffee processing. The study found that both pumice and charcoal were effective adsorbents in the treatment of wastewater

from coffee processing. Removal of BOD was found to increase with contact time. Maximum BOD removal of 71.3%, 62.4% and 59.1% was obtained for pumice, charcoal, and the combination of the two, respectively. Since the BOD is an indicator of the potential of wastewater to emit methane, the reduction in BOD obtained by the use of the adsorbents indicates a reduction in the global warming potential of the wastewater. Low cost adsorbents can therefore be used to mitigate against climate change in smallholder primary processing factories.

5.2 Recommendations

1. The study revealed that yield levels had a significant effect on the carbon footprints therefore improving the yields of smallholder coffee farmers would bring down their carbon footprints. Increase in yields can be achieved by proper management of the coffee plant through sufficient fertilisation and pruning. Emission reduction at farm level can be achieved by focusing on the emission hot spots which are fertiliser application and residue management. Emissions from fertiliser use can be countered by management practices such as planting of cover crops, residue incorporation and reduced tillage.

   In this study farmers from one coffee production region were considered, a clearer picture of the carbon footprint of the smallholder farmer would be obtained by inclusion and comparison of farmers from different coffee producing regions. Further comparison of emissions from small holder producers with emissions from estates should also be done to get a clear picture of the footprint of Kenyan coffee. As well inclusion of emissions from Estates would facilitate comparison of monoculture and polyculture systems in the country.

2. Small holder farmers were storing carbon in their coffee crop and shade trees. The diversification of coffee production systems with trees can contribute to climate mitigation by increasing carbon storage on the farm. Nitrogen fixing trees may reduce reliance on organic fertilisers thus bringing down the footprints to some extent. Fruit trees can also indirectly contribute to lowering the carbon footprint if their products are commercialized and product allocation is used in

assigning the total greenhouse gas emissions from a production system to its various products relative to their economic value.

Destructive sampling of coffee trees and shade trees could not be carried out in this study thus development of site specific allometric equations was not possible. Site specific allometric equations would make it possible to obtain more accurate biomass figures of the smallholder coffee farms.

3. The study only investigated the effect of adsorbent contact time on wastewater. To get a clearer picture of the effectiveness of the adsorbents aspects such as the effect of adsorbent dose and pH need to be investigated to determine the best configuration for treatment of coffee processing wastewater. Coffee wet mills can include these adsorbents in their wastewater treatment systems to lower the BOD of the water thus reducing their carbon footprint further.

REFERENCES

Albrecht, A. & Kandji. T. S. (2003). Carbon sequestration in tropical Agroforestry Systems. *Agriculture, Ecosystems and Environment, 99*, 15-27.

Amani, P. & Scheifer, G. (2011). Data availability for Carbon Calculators in measuring GHG emissions produced by the food sector. *International Journal on Food System Dynamics, 2*(4), 397-407

Anim-Kwapong, G. & Osei-Bonsu, K. (2009). Potential of natural and improved fallow using indigenous trees to facilitate cacao replanting in Ghana. *Agro forest Systems, 76*, 533-542

Attarzadeh, N. & Noponen, M. (2010). Coffee production and processing Costa Rica and Nicaragua. *Carbon footprint summary report*.

Austin, K. (2012). Coffee exports as ecological, social, and physical unequal exchange: A cross-national investigation of the java trade. *International Journal of Comparative Sociology, 53*(3), 155–180.

Bakaroglu, S.S.K., Yigit, N.O., Karanfilb, T. & Kitis, M. (2010). The adsorptive removal of disinfection by-product precursors in a high-SUVA water using iron oxide-coated pumice and volcanic slag particles. *Journal of Hazardous Materials*, *183* (1–3), 389–394.

Bellarby, J., Foereid, B., Hastings A. & Smith, P. (2008). Cool farming: Climate impacts of agriculture and mitigation potential. *Greenpeace International, Amsterdam.*

Bhatnagar, A. (2007). Removal of bromophenols from water using industrial wastes as low cost adsorbents. *Journal of Hazardous Materials*, *139*(1), 93–102.

Bouwman A.F., Boumans L.J. & Batjes N.H. (2002). Modeling global annual N_2O and NO emissions from fertilized fields. *Global Biogeochem. Cycles, 16* (4), 1080.

Brown, S. (1997). Estimating biomass and biomass change in tropical forests: A primer FAO, Forest Resources Assessment Publication. FAO, Rome, Italy.

Cairns, M.A., Brown, S., Helmer, E.H. & Baumgardner, G.A., (1997). Root biomass allocation in the world's upland forests. *Oecologia, 111*, 1–11.

Calvert, K.C. (1998). The Microbiology of Coffee Processing, part 1. PNGCRI Coffee Research Newsletter

Camargo, M. B. P. (2009). The impact of climate variability in coffee crop. *22nd International Conference on Coffee Science ASIC 2008*, Campinas SP Brazil

Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck D. & Zhao, Q. (1997).Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutrient Cycling in Agroecosystems, 49*, 221–228.

Colomb, V., Bernoux, M., Bockel, L., Chotte, J., Martin, S., Martin Phipps, C., Mousset, J., Tinlot, M. & Touchemoulin, O. (2012). Review of GHG calculators in agriculture and forestry sectors: A Guideline for Appropriate Choice and Use of Landscape Based Tools Version 2.0.

Coltro, L., Mourad, A.L., Oliviera, P., Baddini, J. P. & Kletecke P.M. (2006). Environmental Profile of Brazillian Green Coffee. *International Journal of Life Cycle Assessment, 11*(1), 16-21.

Davis, A.P., Gole, T.W., Baena, S. & Moat, J. (2012). The Impact of Climate Change on Indigenous Arabica Coffee (*Coffea arabica*): Predicting Future Trends and Identifying Priorities. *PLoS ONE 7*(11), e47981

Devi, R. (2010). Innovative Technology of COD and BOD Reduction from Coffee Processing Wastewater Using Avocado Seed Carbon (ASC). *Water Air Soil Pollution, 207*, 299–306

Devi, R., & Dahiya, R. P. (2006). Chemical oxygen demand (COD) reduction in domestic wastewater by fly ash and brick kiln ash. *Journal of Water, Air and Soil Poll, 174*(1–4), 33–46.

Devi, R., Dahiya, R. P., & Gadgil, K. (2002). Investigation of coconut coir carbon and sawdust based adsorbents for combined removal of COD and BOD from domestic wastewater, *Water and Environmental Management Series, International Water Association, 2002*, 1209–1218.

EPA (Environmental Protection agency), (2007). Inventory of U.S. Greenhouse gas emissions and sinks: 2001-2005.

Gathaara, M.P.H & Gitau, K.M. (1998). The effects of planted shade trees on some physiological parameters in Arabica coffee. Report. Coffee Research Foundation (CRF)

Granli, T. & Bockman, O.C. (1994) 'Nitrous oxide from agriculture'. Norwegian *Journal of Agricultural Science*, (12), 128

Haggar, J. & Schepp, K. (2011). Coffee and climate change: Impacts on four pilot countries.

Hairiah K., Sitompul M. & Van Noordwijk M. (2001). Methods for sampling carbon stock above and below ground. *International centre for Research in Agroforestry.* Bogor Indonesia

Haverkort, A. J. & Hillier, J. G. (2011). Cool Farm Tool-Potato: Model Description and Performance of Four Production Systems. *Potato Research, 54*,355–369.

Hillier J., Walter D., Malin T., Garcia-Suarez L. & Smith P. (2011). A farm-focused calculator for emissions from crop and livestock production. *Environmental Modeling & Software, 26 (9)*, 1070-1078.

Hoebink, P., Ruben, R., Elbers, W., & Bart van Rijsbergen. (2014). The Impact of Coffee Certification on Smallholder Farmers in Kenya, Uganda and Ethiopia. *Solidaridad report.*

Hultgreen, G. & Leduc P., (2003). The effect of nitrogen fertiliser placement, formulation, timing, and rate on greenhouse gas emissions and agronomic performance. Saskatchewan Department of Agriculture and Food. Final Report Project No. 5300G, ADF#19990028. Regina, Saskatchewan, Canada.

ICO (International Coffee Organization) (2014). World coffee trade. Retrieved from http://www.ico.org/trade_e.asp?section=About_Coffee

IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Program, Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds). Published: IGES, Tokyo Japan.

IPCC, (2007). Climate Change: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds)]. Chapter 8 Agriculture, (pp 498-540). Cambridge University Press.

ITC (International Trade Centre), (2010). Climate change and the coffee industry. Technical paper. 28 p Geneva, Switzerland. Retrieved from http://www.intracen.org/uploadedFiles/intracenorg/Content/Exporters/Sectors/Fair_trade_and_environmental_exports/Climate_change/Climate-Coffee-Ch-13-MS-ID-3-2-2010ff_1.pdf

ITC (International Trade Centre), (2012). Product carbon foot printing standards in the agro-food sector. Technical Paper. 46 p. Geneva, Switzerland. Retrieved from http://www.intracen.org/Product-Carbon-Footprinting-Standards-in-the-Agri-Food-Sector) on Feb 20, 2014

Jaetzold, R., Schmidt, H., Hornetz, B., & Shisanya, C. (2006). Farm Management Handbook of Kenya, Natural conditions and Farm Management Information, volume II, part B subpart B2: Central Kenya 2nd Edition, Ministry of Agriculture Kenya

Jaramillo, J., Muchugu, E., Vega, F.E., Davis, A. & Borgemeister, C. (2011). Some Like It Hot: The Influence and Implications of Climate Change on Coffee

Berry Borer (*Hypothenemus hampei)* and Coffee Production in East Africa. *PLoS ONE,* 6(9), e24528.

Jarvis, A., Ramírez-Villegas, J., Tapasco, J., Navarro, C., Peterson, A. C., Zapata-Caldas, C. & Myles J. (2013). Are Climate Change Adaptation and Mitigation Options Eco-Efficient? In Eco-efficiency: from vision to reality

Jassogne L., Laderach, P., & Piet van Asten (2013). The impact of climate change on coffee in Uganda: Lessons from a case study in the Ruwenzori Mountains. *Oxfam Research Report*

Kegode P. (2005) Economic governance of the coffee sector – Focus on Central province. *Final Report*

Ketterings, Q.M., Coe, R., van Noordwijk, M., Ambagau, Y., & Palm, C. (2001). Reducing uncertainty in the use of Allometric biomass equations for predicting above ground tree biomass in mixed secondary forests. *Forest Ecology and Management, 146*, 199-209

Killian, B., Rivera. L., Riviera, L. & Navichoc, D. (2013). Carbon footprint across the coffee value chain: The case of Costa Rican coffee. *Journal of Agricultural Science and Technology*, 151-170

Kimemia, J.K. (2013). Coffee Production in Kenya. Coffee Research Foundation. Presentation to the Japan External Trade Organization.

KIPPRA (2013). The Kenya Economic Report 2013 Creating an Enabling Environment for Stimulating Investment for Competitive and Sustainable Counties. The Kenya Institute for Public Policy, Research and Analysis (KIPPRA). Nairobi, Kenya

Kiseve S. M. (2012). Evaluation of legume cover crops intercropped with coffee. (Masters' Thesis University of Nairobi)

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R. & Neufeldt, H. (2012). Allometric Equations for Estimating Biomass in Agricultural

Landscapes: Aboveground Biomass. *Agriculture and Ecosystem Environment*, *158*, 216-224.

Labata M., Aranico E. C., Tabaranza A. C., Patricio P.H. & Amparado F. R. (2012). Carbon stock assessment of three selected agroforestry systems in Bukidnon Philippines. Advances in Environmental Sciences. *International Journal of the Bioflux Society, 4*, 54-62.

Laderach, P., Lundy, M., Jarvis, A., Ramirez, J., Portilla, P.E., Schepp K. & Eitzinger, A. (2011). Predicted impact of climate change on coffee supply chains. In *The Economic, Social and Political Elements of Climate Change, Climate Change Management,* DOI 10.1007/978-3-642-14776-0_42, Springer-Verlag Berlin Heidelberg

Lal R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science, 304*(5677), 1623‑1627.

Lasco, R. D., Sales, R. F., Estrella, R., Saplaco, S. R., Castillo, A. S. A., Cruz, R. V. O. & Pulhin, F. B. (2001). Carbon stock assessment of two agroforestry systems in a tropical forest reserve in the Philippines. *The Philippine Agricultural Scientist*, *84*(4), 401-407.

Lugo, A. E. & Brown S. (1993). Management of tropical soils as sinks or sources of atmospheric carbon. *Plant and Soil, 149*, 27-41.

Masiga M. (2013). Analysis of adaptation and mitigation options: Territorial approach to climate change in the Mbale region of Uganda project.

Matos, D. T. A., Lo Monaco, P. A., Pinto, A. B., Fia, R., & Fukunaga, D. C. (2001). Pollutant potential of wastewater of the coffee fruits processing. Federal University of Viçosa, Department of Agricultural Engineering, Viçosa-MG, Brazil.

Mburu, J.K., Thuo, J.T. & R.C. Marder. (1994). The characterization of coffee waste water from coffee processing factories in Kenya. *Kenya Coffee*, *59* (690), 1757-1761.

Mithamo, W. M. (2013). Effect of intercropping coffee with fruit trees on coffee eco-physiological and soil factors at Coffee Research Foundation in Ruiru Kiambu County (Masters' Thesis, Kenyatta University, Kenya)

Monroy L., Mulinge W. & Witwer M. (2013). Analysis of incentives and disincentives for coffee in Kenya. *Technical notes series*, MAFAP, FAO, Rome

Mureithi, P. L. (2008). Coffee in Kenya: Some challenges for decent work, U.N International Labour Office Sectoral Activities Programme, Geneva.

Mutua, J. (2000). Postharvest handling and processing of coffee in African countries. FAO. Rome Italy

Nemoto, R. (2010). Long term soil carbon changes in different Agricultural management systems under past and future climate. (Masters' thesis). University of Bern

Noponen, M.R.A., Jones G.E., Haggar, J.P., Soto, G., Attarzadeh, N. & Healey J. R. (2012). Greenhouse gas emissions from coffee grown with differing input levels under conventional and organic management. *Agriculture, ecosystems and Environment*, *151*, 6-15

Odhiambo, M., Kristanson, P. & Kashangaki P. (1996). Comparative cost of production analysis in East Africa: Implications for competitiveness and comparative advantage. *Productive Sector Growth and Environment Division,* USAID.

Ogle, M., Breidt, J. & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperature and tropical regions. *Biogeochemistry 72*, 87-121.

Oreskes, N. (2004). Beyond the ivory tower: The Scientific Consensus on Climate Change. *Science*, *306* (5702), 1686

Ozturk B, Yildirim Y. (2008) Investigation of sorption capacity of pumice for SO_2 capture. *Proc Saf Environ Protect*, *86* (1), 31–36.

Pala, A., & Tokat, E. (2002). Color removal from cotton textile industry wastewater in an activated sludge system with various additives. *Indian Journal of Environmental Protection, 36*, 2920–2925.

Pandey, D. & Agrawal, M. (2014). Carbon footprint estimation in the agricultural sector. In *Assessment of carbon footprint in different industrial sectors, 1*, 25-47.

Panuccio, M. R., Sorgona, A., Rizzo, M. & Cacco G. (2007). Cadmium adsorption on vermiculite, zeolite and pumice: Batch experimental studies. *Journal of Environmental Management, 90*(1), 364–374.

Pye-Smith C. (2011). Farming's climate-smart future. Technical Centre for Agricultural and Rural Cooperation (CTA). Wageningen, the Netherlands. http://ccafs.cgiar.org/sites/default/files/assets/docs/farmings_climatesmart_future.pdf Accessed on 3rd June 2014

Rahn, E., Laderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D. & H. van Rikxoort (2014). Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies?, *Mitigation and Adaptation Strategies for Global Change, 19*, 1119‑1137

Rao, P., Edvardsson, L., Jessup, R., Nkedi-Kizza P. & Hornsby, A. (2010). Special variability of pesticide sorption and degradation parameters. *American chemical society ACS Symposium series, 315*(6), 100-115.

Richards, M. (2013). Reducing agriculture emissions while maintaining yields-can it be done? *Research Program on Climate change*, agriculture and food security.

Ridley, F.V., (2011). The past and future climatic suitability of arabica coffee (Coffea-arabica L.) in East Africa., *Durham theses*, Durham University.

Rikxoort, H., Schroth, G., Laderach P. & Rodriguez, B. (2014). Carbon footprints and carbon stocks reveal climate-friendly coffee production. Agronomy for sustainable development**,** DOI 10.1007/s13593-014-0223-8

Rikxoort, (2010). Carbon foot printing as part of the add-on climate module, 4C Association

Rikxoort, H., Jassogne, L., Laderach, P. & Piet van Asten. (2013b). Integrating climate change adaptation and mitigation in East African coffee systems, In *Agro ecological intensification of Agricultural systems in the African Highlands*. (Pp 175-183), Routledge publishing, New York

Rikxoort, H., Laderach, P. & Hal, J. (2013a). The potential of Latin American coffee production systems to mitigate climate change. In W. Leal Filho (ed.), *Climate Change and Disaster Risk management* (pp655-678), Springer Berlin

Salami, A., Kamara B. A. & Brixiova Z. (2010). Smallholder agriculture in East Africa: Trends, constraints and opportunities. Working paper, African Development Bank Series.

Salehi, M. H., Hashemi Beni, O., Beigi, H., Esfandiarpour, I. and Motaghian, H. R. (2011). Refining soil organic matter determination by loss-on-ignition. *Pedosphere, 21*(4), 473–482.

Salomone, R. (2003). Life cycle assessment applied to coffee production: investigating environmental impacts to aid decision making for improvements at company level, *1*(2), 295–300.

Sangana PPP. (2011). Climate change adaptation and mitigation in the Kenyan coffee sector. Guide Book - Sangana PPP - 4C Climate Module

Schulte, E.E. & Hopkins B. G. (1996). Estimation of soil carbon by weight loss on ignition. In: Magdoff et al. (eds). *Soil organic matter: analysis and interpretation.* (Pp.21-31) SSSA Spec. Publ. No. 46. SSSA Madison, WI.

Schumacher, B.A. (2002). Methods for the determination of total organic carbon (TOC) in soils and sediments. Ecological Risk Assessment Support Center, Office of Research and Development. US Environmental Protection Agency. Las Vegas, NV. 25p

Segura M., Kanningen M, & Suárez, D. (2006). Allometric models for estimating aboveground biomass of shade trees and coffee bushes grown together. *Agroforest Syst, 68*, 143-150.

Selvamurugan, M., Doraisamy P., Maheswari, M. & Nandakumar, N. B. (2010) Evaluation of Batch Aeration as a Post treatment for Reducing the Pollution load of Biomethanated Coffee Processing Wastewater. *Global Journal of Environmental Research*, *4*(1), 31-33.

Shoba, B., Sagthiganesh, R. & Raju, S. (2015). Treatment of Dairy Wastewater using Tamaring Kernel as an Adsorbent. *International Journal of Innovative Research in Engineering and Management*, *3*(1), 221-223

Smith P., Powlson S., Glendining J. &Smith U. (1997). Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biol. 3*, 6779.

Srivastava, V. C., Mall, I. D., & Mishra, I. D. (2005). Treatment of pulp and paper mill wastewaters with poly aluminium chloride and bagasse fly ash. *Colloids and Surfaces. A, Physicochemical and Engineering Aspects, 260*(1–3), 17–28.

Sustainable Agriculture Initiative Platform (SAI) (2013). Carbon Footprint product category rules for green coffee. Version 1.01

Tchibo GmbH, (2008). Case study Tchibo private Kaffee: rarity machare by Tchibo GMBH. Retrieved from http://www.pcfprojekt.de/files/1232962944/pcf_tchibo_coffee.pdf

Tumwebaze, S. B., Bevilacqua E., Briggs. R. & Volk, T. (2013). Allometric biomass equations for tree species used in agroforestry systems in Uganda. *Agroforestry systems, 87*:781-795.

United Nation Framework Convention on Climate Change UNFCCC (2002). Kyoto Protocol: Status of Ratification. United Nations Framework Convention on Climate Change.

Vaast P., Beer J., Harvey C., & Harmand, J. (2005) Environmental services of coffee agroforestry systems in Central America: a promising potential to improve the livelihoods of coffee farmers' communities. In: CATIE (ed) *Integrated management of environmental services in human-dominated tropical landscapes.* (pp 35-39) Tropical Agriculture Research and Higher Education Center, Turrialba,

Van Noordwijk, M., Rahayul, S., Hairiah, K., Wulan, Y. C., Farida, A. & Verbist, B. (2002). Carbon Stock Assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. *Science in China Series*, *45* (Suppl.), 75-86.

Von Enden J.C & Calvert K.C. (2002), Limit Environmental Damage by Basic Knowledge of Coffee Waste Waters. GTZ-PPP Project "Improvement of coffee quality and sustainability of coffee production in Vietnam".

Von Enden, J.C. (2002) Best practices at wet processing pay financial benefits to farmers and processors. GTZ-PPP Project "Improvement of coffee quality and sustainability of coffee production in Vietnam

Wang, S., & Wu, H. (2006). Environmental-benign utilization of fly ash as low-cost adsorbents. *Journal of Hazardous Materials*, *136*(3), 482–501.

Wiedmann T. and Minx J. (2008). A Definition of 'Carbon Footprint', In: *C.C Pertsova, Ecological Economic Research Trends* Chapter 1, (pp 1-11), Nova Science Publishers.

Winkler, E. W. (2001). Multi-way Survey Stratification and Sampling, Statistical Research Division, US Bureau of Census, Washington DC.

Winkler, E. W., (2009). Sample Allocation and Stratification, Statistical Research Division, US Bureau of Census, Washington DC.

Winston E., Laak J., Marsh T., Lempke H. & Chapman K. (2005). Arabica Coffee Manual for Lao-PDR, FAO document repository. ISBN 974-7946-78-5

Wood, S. & Cowie, A. (2004). A review of greenhouse gas emission factors for fertilizer production. For IEA Bioenergy Task 38. Cooperative Research Centre for Greenhouse Accounting. Research and Development Division, State Forests of New South Wales.

Wright, J., Smith, K., Masseder, J., Flynn, H. & Smith, J. (2009). Scottish agriculture and global change – nitrous oxide emissions from fertilizer use, Environmental group research summary 2004/09

APPENDICES

Appendix i: Questionnaire for the Cool Farm Tool

COOPERATIVE SOCIETY………………………………………………..…

• GENERAL DATA	
Name of wet mill	
Factory manager	
Coffee year	
Cherry received	
Parchment to mill	
Mean temperature	
• ENERGY USE	
Electricity from grid (kWh)	
Diesel use (litres)	
Oil (litres)	
Cost per year (kshs)	
• WATER USE	
Total water use	
Cost per year (kshs)	
Water use per kg of cherry	
Is the water recycled?	
• TRANSPORT TO MILL	
Name of mill	
Distance btw factory and mill	
Mode of transport	
No of trips	

FARM DATA

GENERAL INFORMATION

Farmer's name	
Age	
Family size	
Membership number	
Location	
GPS coordinates	
Farm size (acres)	
Area under coffee (acres)	
No. of coffee plants	
Age of trees	
Cherry production	
Area under other crops (acres)	
Other crops grown	

CROP MANAGEMENT

<table>
<tr><td colspan="5">Soil texture</td></tr>
<tr><td>Fine</td><td colspan="2">Medium</td><td colspan="2">Coarse</td></tr>
<tr><td colspan="5">Soil colour</td></tr>
<tr><td colspan="5">Soil Organic matter content</td></tr>
<tr><td>Exact:</td><td>≤1.72</td><td>≤5.16</td><td>≤10.32</td><td>>10.32</td></tr>
<tr><td colspan="5">Are your soils moist or dry during the growing period (Do you irrigate?)</td></tr>
<tr><td colspan="2">Moist (1)</td><td colspan="2">Medium (2)</td><td>Dry (3)</td></tr>
<tr><td colspan="5">Describe your soil drainage</td></tr>
<tr><td colspan="2">Good</td><td colspan="3">Poor</td></tr>
<tr><td colspan="5">Slope</td></tr>
<tr><td colspan="5">Soil pH?</td></tr>
<tr><td>≤5.5</td><td colspan="2">≤7.3</td><td>≤8.5</td><td>>8.5</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">Fertilizer use</td></tr>
<tr><td>Type</td><td>Total volume (kg)</td><td>Application rate (g/tree)</td><td>Time of application</td><td>Application method)</td></tr>
<tr><td>CAN</td><td></td><td></td><td></td><td></td></tr>
<tr><td>NPK</td><td></td><td></td><td></td><td></td></tr>
<tr><td>ASN</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Foliar feed</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lime</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Farm yard manure</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Compost manure</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Others</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Insecticides and herbicides</td></tr>
<tr><td>Type</td><td>Total volume (kg)</td><td>Application rate</td><td>Number of rounds</td><td>Application method</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Treatment of crop residue</td></tr>
<tr><td>Source of residue</td><td colspan="2">Quantity (kg/acre)</td><td colspan="2">How is this residue used?</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
</table>

SEQUESTRATION

Year coffee was planted	
Original vegetation	

Has there been tillage change?		
Change	How long ago was this change made?	Percentage of land with this change?
Has there been a change in the use of cover cropping?		
Change:	How long ago was this change made?	Percentage of land with this change?
Has there been a change in the use of composting?		
Change	How long ago was this change made?	Percentage of land with this change?
Has there been a change in the use of manure additions?		
Change	How long ago was this change made?	Percentage of land with this change?
Has there been a change in the use of residue incorporation?		
(Q5) Change	How long ago was this change made?	Percentage of land with this change?

Annual biomass for trees in cropping system				
Species	**Providing shade? (yes/no)**	**Number of trees**	**Year planted**	**Average DBH (cm)**
Coffee (Arabica)				
Grevillea				
Macademia				
Eucalyptus				
Avocado				
Others				

ENERGY USE

Transport to factory	
Distance from factory	
Mode of transport	
No of trips	
Field energy use	
Fuel wood (kg)	
Charcoal (kg)	
Diesel (litres)	
Kerosene (litres)	
Solar	
Electricity (kwh)	

Appendix ii: List of Tables

Table 0.1 Mean farm sizes and yield levels of the small holder coffee producers

Production level	Wet mill	Farm size (acres)			Yield (kg/tree)			Yield (kg/acre)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
High	A	0.50	1	0.94	4.99	7.76	5.56	697.51	4009	3203.42
	B	0.75	3	1.75	4.79	5.9	5.21	503.81	3462.53	2319.90
	C	0.50	3	1.63	4.93	10.85	5.89	846.02	5590.38	3382.14
Medium	A	0.50	1	0.71	3.08	4.45	3.52	558.24	1152.11	680.12
	B	0.25	1	0.5	2.97	3.67	3.09	508.31	1008.08	649.73
	C	0.25	1	0.75	3.01	3.43	3.20	625.00	1406.22	916.45
Low	A	0.25	1	0.68	0.22	1.38	0.93	172.02	1060.30	604.71
	B	0.25	1	0.58	0.18	1.78	0.92	286.75	1000.42	322.67
	C	0.25	1.2	0.63	0.78	1.76	1.67	266.63	1172.00	682.13

Table 0.2 Soil organic carbon for the sampled farms

Organic carbon content (%)					
Soil depth 0-15 cm			Soil depth 15-30cm		
High	Medium	Low	High	Medium	Low
5.97	2.56	4.23	3.93	2.30	3.56
3.49	3.30	3.10	2.82	2.38	2.30
4.00	4.67	3.56	3.97	4.00	3.67
3.78	5.01	5.01	3.27	4.78	4.30
4.38	3.31	3.12	3.68	2.98	3.30
4.26	3.28	4.48	4.60	3.62	4.38
5.31	4.12	3.19	4.75	4.15	3.87
3.60	3.97	4.35	3.71	3.10	4.05
5.75	2.93	5.3	5.12	2.87	4.12
2.71	3.46	5.82	2.56	3.22	2.62
3.42	3.19	3.93	3.30	3.89	3.15
2.26	4.05	2.82	2.27	2.15	3.1
5.31	2.6	5.97	5.01	2.45	4.87
4.60	3.65	4.27	4.30	2.38	3.52
2.75	2.70	4.38	2.38	2.62	3.89
3.71	4.12	3.6	3.19	3.15	3.15
4.12	3.56	4.75	4.05	2.38	3.45
4.56	3.30	5.71	4.30	3.19	2.38
3.30	4.67	3.12	3.22	3.05	2.98
3.67	3.81	3.56	4.13	4.30	3.43
5.01	4.97	3.30	3.38	3.82	3.02
6.30	3.49	3.67	5.19	3.03	2.81
3.49	4.00	5.01	3.12	4.82	3.64
6.00	2.78	4.30	4.56	2.97	3.82

	Organic carbon content (%)					
	Soil depth 0-15 cm			Soil depth 15-30cm		
	High	Medium	Low	High	Medium	Low
	4.78	2.38	3.38	3.82	2.27	4.17
	3.38	3.26	3.19	3.97	2.38	3.18
	4.26	5.31	4.05	3.56	4.19	3.89
	4.75	3.6	4.3	3.3	3.31	3.16
	3.63	2.75	3.82	3.67	2.31	3.26
	2.75	3.71	4.93	3.01	3.12	3.18
	5.65		3.38	4.30		3.53
	3.98		5.19	3.82		4.97
	5.23		3.12	4.93		3.06
			6.56			4.34
			3.67			2.82
			4.06			3.97
			3.87			3.56
			6.13			5.3
			3.22			3.67
			3.62			3.56
			3.98			4.11
			4.11			3.38
			3.19			3.1
			3.07			3.45
			5.65			4.23
Mean	**4.25**	**3.62**	**4.16**	**3.79**	**3.17**	**3.58**

Table 0.3 Farm level carbon footprints per kg cherry for the selected farms

	Product carbon footprints (kgCO$_2$e/kg cherry)								
	Wet mill A			Wet mill B			Wet mill C		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
	-0.04	0.51	0.10	0.35	-0.10	0.82	-0.33	0.28	0.59
	0.09	-0.03	1.06	0.24	0.26	0.47	0.15	0.32	0.75
	0.01	0.16	0.09	-0.10	0.18	0.59	-0.23	0.19	0.55
	0.06	0.25	0.93	0.07	0.76	1.05	0.20	0.22	0.30
	0.15	0.17	0.46	0.09	0.34	0.46	-0.01	0.25	0.64
	0.10	0.30	0.76	-0.37	0.30	0.40	0.20	0.42	0.70
	0.02	0.14	0.70	0.03	0.26	0.54	0.08	0.11	0.50
	-0.10	0.06	0.57	0.23	0.38	1.29	-0.01	0.40	0.81
	0.13	0.38	0.23	0.15	0.25	0.46	0.23	0.58	0.52
	-0.05	0.31	0.31	0.10	0.13	0.20	0.00	0.14	0.58
	0.18		0.91	-0.07		0.19	0.15		0.32
			0.38			1.05			0.47
			0.33			0.49			0.26
			0.63			0.90			0.65
			0.49			0.51			0.65
Mean	**0.05**	**0.23**	**0.53**	**0.06**	**0.28**	**0.62**	**0.04**	**0.29**	**0.55**
Std Dev	**0.09**	**0.15**	**0.29**	**0.19**	**0.21**	**0.24**	**0.17**	**0.14**	**0.16**

Table0.4 Footprints per acre of land for the selected farms

	Carbon footprints $kgCO_2e$/acre of land								
	Wet mill A			Wet mill B			Wet mill C		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
	-247.6	155.5	225.0	1384.6	-114.4	655.8	-421.7	176.2	115.8
	81.6	-146.4	144.6	-410.4	178.9	286.5	375.1	288.9	218.4
	53.4	159.6	465.5	-552.6	667.0	278.6	-214.7	70.1	217.0
	29.0	120.0	292.5	152.8	518.1	329.3	187.1	62.1	329.5
	74.6	46.8	137.1	561.0	526.1	379.5	-71.7	346.0	444.7
	106.3	96.4	29.1	-769.6	364.8	328.2	-610.9	431.5	372.6
	42.0	278.9	170.1	191.7	350.5	580.9	233.5	120.6	279.9
	-405.1	45.6	106.4	57.3	282.4	442.8	140.8	247.5	742.9
	212.8	178.4	277.8	420.8	315.5	269.2	-61.8	415.2	347.5
	-146.2	232.4	36.5	129.2	123.6	577.0	882.4	135.8	138.9
	130.1		51.1	733.0		208.9	162.2		186.5
			150.3			159.3			94.4
			82.3			184.1			29.2
			174.5			281.7			421.6
						485.7			24.6
Mean	**-6.3**	**116.7**	**167.3**	**172.5**	**321.3**	**363.2**	**54.6**	**229.4**	**264.2**
Std Dev.	**175.2**	**112.4**	**114.2**	**585.0**	**213.0**	**148.0**	**384.7**	**130.2**	**182.4**

Table 0.5 average number of coffee and shade trees per farm

Wet mill	Production level	Average no. of coffee trees per acre	Average no of shade trees per acre			
			Grevillea	Banana	Macademia	Avocado
	High	735	17	11	0	2
A	Medium	547	5	3	0	0
	Low	370	8	12	3	2
	High	843	23	7	17	2
B	Medium	504	18	7	1	0
	Low	633	12	10	5	4
	High	716	13	9	1	0
C	Medium	481	9	10	0	0
	Low	451	11	8	1	2

Table 0.6 ANOVA for variation of emissions per kg cherry from high producers across the three wet mills

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Wet mill	2	0.0022	0.001079	0.035	0.966	3.32
Residuals	30	0.6496	0.030935			
Totals	32	0.6518				

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 0.7 ANOVA for variation of emissions per kg cherry from medium producers across the three wet mills

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Wet mill	2	0.0117	0.00587	0.144	0.867	3.35
Residuals	27	0.6099	0.04066			
Totals	29	0.6216				

Table 0.8 ANOVA for variation of emissions per kg cherry from low producers across the three wet mills

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Wet mill	2	0.091	0.04542	0.24	0.787	3.22
Residuals	42	11.913	0.18910			
Totals	44	12.004				

Table 0.9 ANOVA for variation of emissions per kg cherry across the three production levels

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Production level	2	4.894	2.4470	19.35	7.01e-08***	3.09
Residuals	105	13.277	0.1265			
Totals	107	18.171				

Table 0.10 ANOVA for interaction between wet mill and production level

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Production	2	4.8941	2.44705	18.3909	1.615e-07 ***	3.09
Wet mill	2	0.0423	0.02116	0.1590	0.8532	3.09
Production *Wetmill	4	0.0624	0.01561	0.1173	0.9761	2.46
Residual	99	13.1727	0.13306			
Totals	107					

Table 0.11 ANOVA for variation of emissions per acre from high producers across the three wet mills

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Wet mill	2	181866	90933	0.476	0.626	3.32
Residuals	30	5730513	191017			
Totals	32					

Table 0.12 ANOVA for variation of emissions per acre from medium producers across the three wet mills

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Wet mill	2	209882	104941	3.779	0.0357 *	3.35
Residuals	27	749781	27770			
Totals	29					

Table 0.13 ANOVA for variation of emissions per acre from low producers across the three wet mills

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Wet mill	2	277875	138937	5.637	0.00687 **	3.22
Residuals	42	1010573	24648			
Totals	44					

Table 0.14 ANOVA for variation of emissions per acre across the three production levels

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Production level	2	737823	368911	4.702	0.0005564***	3.09
Residuals	105	8160490	78466			
Totals	107					

Table 0.15 ANOVA for variation of fertiliser use across the three production levels

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	F critical
Production level	2	97281	48640	12.04	1.91e-05 ***	3.09
Residuals	105	436353	4040			
Totals	107					

Table 0.16: Results from Tukey HSD test at 95% confidence level for fertiliser use across the production levels

Production level	Difference	Lower	Upper	$P_{adjusted}$
Low-High	-70.66964	-104.89613	-36.44315	0.0000098
Medium-High	-49.56767	-94.46604	-4.66930	0.0267131
Medium-Low	21.10197	-18.36281	60.56676	0.4147705