EFFECT OF *Cordia africana* LAM SHADE ON PHYSIOLOGY, YIELD AND QUALITY OF ARABICA COFFEE

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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

This work is dedicated to my wife Roselyne and son Barrack Aim.

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GENERAL ABSTRACT

Coffee (*Coffea arabica* L.) is native to the shaded forests of Southern Ethiopia where it evolved as an understory crop. It was originally thought to be shade obligatory, but it has been shown to perform well in full sun. The question of whether shade is beneficial or not, has been debated and studied over the years mainly in Central and South America and to some extent in Southeast Asia. In Kenya, however, information on the effects of natural shade on coffee is scarce. Therefore a study was conducted at the Kenya Agricultural and Livestock Research Organization-Coffee Research Institute's (KALRO-CRI) demonstration farm in Namwela and two neighbouring small-holder farms from 2010 to 2012, with the following objectives: 1. to determine the effect of *Cordia africana* shade on physiological parameters of coffee plants namely transpiration, stomatal conductance and photosynthetic rate; 2. to determine the effect of *Cordia africana* shade on soil nutrient levels and nutrient uptake in coffee plants; 3. to assess the impact of *Cordia africana* shade and agronomic management on yield and quality of coffee; 4. to determine the effect of *Cordia africana* shade and agronomic management on the biochemical components of coffee beans. *Coffea arabica* L. variety, K7 and cordia (*Cordia africana* Lam.) shade tree were used in the study. In objective 1, photosynthetically active radiation (PAR), leaf temperature, transpiration, stomatal conductance and photosynthetic rate were assessed in coffee plants that were at regular distances from the shade tree trunk namely, 0 – 1.5 m, 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6.0 m (full sun). In the first objective, the experiment was laid out as a randomized complete block design with seven replicates. Measurements of the physiological parameters were taken in the early morning, at midday and late afternoon on intact plants in the field during two consecutive coffee growing seasons in the dry and rainy periods. In objective 2, Soil and plant nutrient analyses were carried out using standard procedures.

In objective 3, the effect of *Cordia africana* shade on coffee growth, yield and raw bean quality under different agronomic management levels was studied in the three farms; Coffee Research Institute's demonstration farm under high management, and two small holder farms under medium and low management respectively. The shade level was represented by distances from the shade tree trunk, 0 – 1.5 m, 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6.0 m (full sun). The experimental design was a split plot, with management level as main plot treatment and shading levels represented as the sub-plot. To determine biochemical components and beverage quality (objective 4) fully ripe cherries were harvested wet processed and the wet parchment dried to final moisture content of 10.5 to 11%. Caffeine, trigonelline and total chlorogenic acids (CGA), oil and sucrose were determined using standard methodologies. Fragrance/aroma, flavour, aftertaste, acidity, body, balance and overall beverage quality were evaluated by a panel of seven judges.

Photosynthetically active radiation (PAR) was highest in full sun in both the dry and rainy periods. It was also higher at midday in the dry period, however, no apparent trend was observed during the rainy period. Leaf temperature was highest at midday during the dry and rainy periods. The effect of shade on leaf temperature was only significant in the dry period. Generally, the rate of transpiration was significantly higher in shaded coffee in the morning, during both dry and rainy periods. Shade significantly increased stomatal conductance during the rainy period. Photosynthetic rates were generally higher, in the morning hours, in shaded coffee during the dry period. Shaded coffee recorded longer primary branch length extension, but had lower number of nodes than coffee in full sun. Shading significantly increased the content of the major soil nutrients namely N, P, K and Mg. There was, however, a reduction of soil Ca content under shade. Leaf nutrient accumulation was positively correlated with most major plant nutrients, except Ca. Coffee yields were significantly higher under high

agronomic management than under medium and low agronomic management. Shaded coffee had significantly higher bean yields than un-shaded coffee under medium and low management levels. The % grade 'A' beans among shading levels in high and low management levels were not different. Coffee at higher shading levels, 0 – 1.5 m and 1.5 – 3.0 m away from the shade tree trunk (equivalent to 80 and 70% shade) had significantly higher % grade 'A' coffee beans than un-shaded trees. Caffeine, oil, and trigonelline contents were higher in shaded coffee than in unshaded coffee. Sucrose was higher in coffee under medium and low management level. Shading significantly reduced sucrose content. Most of the biochemical components were positively correlated with shade and management levels. This showed the possibility of manipulating the two parameters to enhance the quality of coffee. The beverage quality attributes, except for acidity and balance, on the other hand were mostly unaffected by shade levels and management , nevertheless, trends showed that most of the parameters had higher scores in shade than in full sun. Shade was positively correlated with all sensory variables. The findings of this study indicate that shade can be used to increase coffee yields with no adverse effect on raw bean and beverage quality, particularly under smallholder low input conditions. The use of shade trees could also be beneficial in terms of diversifying farmers' incomes through provision of timber and other products. Overall, use of shade trees even under conditions of high agronomic management would enhance biodiversity and promote environmental sustainability.

CHAPTER ONE: INTRODUCTION

1.1 Background

Coffee is ranked as the third, after tea and horticulture, most important agricultural export commodity in Kenya. Besides contributing to foreign exchange earnings, it is also a source of livelihood for over half a million households. About 75% of all coffee in Kenya is grown by small scale farmers under rain-fed conditions. The natural environment in the coffee growing areas in the country provides opportunities for production of some of the top quality coffees in the world. However, the coffee enterprise is currently faced with numerous socio-economic and bio-physical constraints which have seen yields drop from an all-time high of 130,000 tons in 1989 to current production levels of about 50,000 tons (CRF, 2014). These constraints include high production costs due to high costs of agrochemical inputs and labour, an aged farmer population, and adverse climatic conditions such as high temperatures and unreliable rainfall. The constraints are further exacerbated by declining world coffee prices. Coffee farms' economic viability and sustainability may be improved by integrating, into them, annual food crops and perennials such as shade or fruit trees. The intercrops or shade trees could improve the farms' incomes through generation of food/tree products, improved coffee quality and enhanced biodiversity thus leading to environmental conservation (Njoroge and Kimemia, 1993; Vaast et al., 2006; Bote and Struik, 2011). On the other hand, shade trees could potentially cause considerable reduction in coffee yield and quality as a result of competition for light, nutrients and water especially during the dry periods (Beer et al., 1998).

The origin of coffee is in the shaded forests of southern Ethiopia where it is believed to have evolved as an under-storey crop. According to DaMatta (2004), early plantations were shaded using over-storey trees in order to mimic coffee's natural habitat since it was considered shade-obligatory. Even so, it has been shown in many situations that coffee can grow well without shade, sometimes producing higher yields than shaded coffee (Beer et al., 1998). Therefore, the question of whether shade is beneficial to coffee is controversial and has been contested for over 100 years.

Nonetheless, it has been documented through studies conducted in Central America and other areas of the world that coffee benefits from shade (Beer et al., 1998; Vaast et al., 2007; Somporn et al., 2012). The inclusion of shade or shelter trees is advantageous especially under conditions, such as high temperatures, high solar irradiance and low rainfall, that are considered sub-optimal for coffee production (Vaast et al., 2005; DaMatta and Ramalho, 2006). The trees moderate the effects of adverse climatic conditions, thereby providing a more suitable microclimate for coffee production. In addition, the litter from the trees acts as mulch which preserves soil moisture and reduces soil erosion by lessening the raindrop impact on the soil. Owing to their multifaceted biophysical structure, shaded coffee has great potential for conservation of biodiversity (Perfecto et al., 2003; Sommariba et al., 2004).

1.2 Problem statement and justification

The coffee industry in Kenya faces many socio-economic and biophysical challenges. Coffee yields in Kenya dropped from an all-time high of 130,000 tons in 1989 to current production levels of about 50,000 tons (CRF, 2010a). Some of the causes of the decline include high costs of production, uncertain weather patterns, low yields and poor cup quality. Drought and unfavourable temperatures constitute some of the major constraints to coffee production (DaMatta and Ramalho, 2006). These constraints are anticipated to become progressively more severe due to changing global climate and the spread of coffee cultivation to marginal areas where inadequate rainfall and high temperatures are the most important limitations to production.

In Kenya, coffee has been mainly grown as a sole crop in full sun, under optimal conditions of cool temperatures, high humidity and adequate rainfall which made shade seem unnecessary. Currently, coffee cultivation is expanding into relatively marginal areas with lower rainfall and higher temperatures. This trend is attributed to limited land in traditional coffee zones partly due to change in land use. The high potential coffee zones are also experiencing decreased rainfall amounts associated with climate variability. Moreover, a full sun system generally requires intensive management involving heavy application of inorganic fertilizers; yet most coffee in Kenya is produced by smallholder farmers who cannot afford to apply the required inputs. Even where the inputs are available, as in large estates, their indiscriminate use often leads to reduced plantation longevity and negative long-term environmental impacts, including water pollution and greenhouse gas emission (Castro-Tanzi et al., 2012). The beneficial effects of shade trees may therefore be crucial in many coffee producing areas in Kenya, especially those considered marginal for intensive production systems. *Cordia africana* Lam is heavily branched with a spreading umbrella shaped or rounded crown that provides excellent shade for tree crops. It is also the predominant shade tree used in the area of the study.

The use of shade or shelter trees has been proposed as a possible strategy to alleviate the effects of these adverse climatic conditions. Shade trees reportedly have several benefits especially under these sub-optimal conditions for coffee production. In such situations, shade trees moderate the effects of adverse climatic conditions (high temperatures, high solar irradiance and low rainfall), thereby providing a more suitable microclimate for coffee production. Furthermore, the litter from the trees acts as mulch which preserves soil moisture and reduces soil erosion by lessening the raindrop impact on the soil.

Shade trees help to recover soil nutrients from deep in the soil to the coffee rooting top soil through litter fall, fix atmospheric nitrogen if leguminous, control soil erosion and weeds and encourage rainfall. In addition, the shade trees enhance water shed services; promote biodiversity and CO_2 sequestration (Beer et al., 1998). It is for the foregoing reasons that there has been greater attention given to the use of shade in coffee worldwide.

In terms of coffee quality, several studies have demonstrated that shading increases bean size and improves biochemical composition and cup quality (Geromel et al., 2008; Vaast et al., 2006; Muschler, 2004). Vaast et al. (2006) observed that shade delayed ripening of coffee berry skin by up to four weeks thereby increasing bean size, composition and cup quality.

Extensive studies have been carried out, on the effect of shade on coffee productivity. However, a lot of it has been carried out under conditions that are markedly different from the situation in Kenya. For instance, the production zones in Costa Rica and other countries in Central America are located in the altitude ranges of 500 to 1700 and 30 to 1600 m (Siles, 2007), respectively, whereas in Kenya the areas are located in an altitude range of 1200 to 2100 m above sea level (Kimemia and Kaminchia, 1994). In Kenya, most coffee growing areas experience bimodal rainfall patterns with rainfall amounts ranging from 1000 to 2000 mm, whereas in Costa Rica, for instance, coffee growing zones receive more than 3000 mm (Siles, 2007).

In Kenya, few studies have been conducted on the effects of shade on coffee physiology, bean biochemical content and cup quality. The potential of shade trees to diversify farmers' incomes and conserve biodiversity, has rekindled the interest in their use in coffee farming.

The current study will focus on these areas of research under low-input and high input production systems. The results of the study would, therefore, be useful towards making recommendations on the use of natural shade.

1.3 Objectives

The main objective of this study was to assess the effect of shade on coffee physiology, yield, and quality of coffee. The specific objectives of this study were: -

1. To determine the effect of *Cordia africana* shade on leaf temperature, transpiration, stomatal conductance and photosynthetic rate of Arabica coffee.
2. To determine the effect of *Cordia africana* shade on soil nutrient content and plant nutrient accumulation in Arabica coffee.
3. To assess the impact of *Cordia africana* shade on yield and quality of Arabica coffee under three different agronomic management conditions.
4. To determine the effect of *Cordia africana* shade on the biochemical components and beverage quality of Arabica coffee beans under three different agronomic management conditions.

1.4 Hypothesis

The central hypothesis of this study is that *Cordia africana* shade effects on the microenvironment of coffee trees will lead to positive changes in coffee physiology, growth, bean yield, bean biochemical content and beverage quality.

CHAPTER TWO: LITERATURE REVIEW

2.1 Ecology of coffee

Coffee in its natural habitat, tropical high rain forest in south-western Ethiopia, grows as an under-storey shrub (Paulos and Tesfaye, 2000; Cambrony, 1992). The altitude in this region is in the range of 1600 – 2800 m with an average annual temperature of 20°C; rainfall is well spread varying from 1600 mm to more than 2000 mm, with a dry season lasting 3 to 4 months coinciding with the coolest period (DaMatta and Ramalho, 2006). Coffee, as an under-storey plant, is permanently in shade and therefore is not subjected to high temperatures and vapour pressure deficit (Maestri and Barros, 1977).

Temperature is one of the climatic factors which have a major impact on the physiology of coffee. The optimal mean temperature for Arabica coffee ranges from 18 to 22°C; however, it can withstand temperatures of 15°C during the night and 25 to 30°C during the day. Temperatures above the optimum 22°C lead to accelerated development and ripening of berries which results in poor quality coffee beans. Exposure to temperatures of over 30°C for extended periods could lead to stunted growth and defects such as yellowing of leaves. High temperatures during flowering, especially if combined with drought may cause abortion of flowers. Conversely, low temperatures below 18°C result in depressed growth due to frost damage (DaMatta, 2004).

Coffee is categorized as a shade adapted plant species since it displays characteristic features of such species which include ability to photosynthesize in low light, high leaf area to woody structure ratio and the absence of fruit thinning mechanism to regulate fruit load (Franck et al., 2005). However, coffee leaves likewise show wide flexibility in their adaptation to irradiance as shown by the wide range of radiation conditions in which coffee can be grown.

Coffee is, therefore, considered a shade adapted rather than a typical shade plant (Da Matta, 2004).

The adaption of coffee to shade favours its cultivation in agroforestry systems and this practice has regained popularity especially in Central America (Vaast et al., 2005). Whether shade trees are beneficial to coffee or not, is a question that has been debated over the years. Nevertheless, it has been established that coffee may benefit from shade especially under sub-optimal conditions (Vaast et al., 2007; van Kanten and Vaast, 2006). In Kenya, the early plantations were established under shade. However, during the late 1960's there was a move towards intensification of coffee production and trees were removed and coffee grown in full sun. Intercropping coffee with food or tree was not officially allowed as it was thought that the intercrops would lower the quality for which Kenya is renowned (Kimemia, 1998).

2.2 Effect of shade on pests, diseases and weeds on coffee yield and quality

Coffee is vulnerable to several insect pests and diseases leading to losses in productivity and quality. Shading may change the environment for insect pests and diseases by modifying their microclimate through the moderation of wide fluctuations in air and soil temperatures and by increasing moisture. The litter fall also increases soil organic matter and mulch. The shade trees further enhance the variety of habitat for other organisms including pests, diseases and their natural competitors (Hietz, 2005; Muschler, 2004; Miguel and Toledo, 1999). The economically important pests in Kenya include coffee berry borer (*Hypothenemus hampei*), leaf miner (*Leucoptera meyricki*) and thrips (*Diathrothrips coffeae*) (Crowe, 2004). The important diseases are coffee berry disease caused by *Colletotrichum kahawae*, coffee leaf rust caused by *Hemileia vastatrix* and Bacterial Blight of Coffee caused by *Pseudomonas syringae* (Muller et al., 2004). Studies have been carried out to determine the influence of shade on these pests, diseases and weeds. Mouen et al, (2007) observed that coffee trees found under shade of fruit trees were considerably less susceptible to coffee berry disease than those in full sun. On the other hand, incidences of attack of coffee by coffee leaf rust (*Hemileia vastatrix*) are higher under shade (Staver et al., 2001). Shade similarly promotes the incidence of coffee berry borer (*Hypothenemus hampei*) (Staver et al., 2001). Kimemia (2004) noted that natural shade, particularly of *Mimosa scrabella*, reduced weed incidences and species. He attributed this to the leaf fall which formed mulch and hence interfered with growth of weeds. Under the *Mimosa scrabella*, the possibility of presence of allelopathic compounds may have contributed to the low level of weeds.

2.3 Effect of natural shade on soil and coffee leaf temperature

Temperature is the climatic factor that has the highest influence on the physiology of arabica coffee. The optimal temperature range for this species is 18°C – 22°C (Descroix and Snoeck, 2004). Air, leaf and soil temperatures can be substantially higher in unshaded plantations than in shaded plantations sometimes by more than 10°C (Muschler, 2004). Generally, shade act as buffers to the coffee microclimate, since they tower over coffee. For example, under shade in Mexico the maximal temperature during the hot season was reduced by an average of 5.4°C while the minimal temperature was increased by up to 1.5°C (Barradas and Fanjul, 1986). Leaf temperature affects stomatal opening, transpiration and photosynthesis. High leaf temperatures may lead to excessive heat stress, moisture loss and damage to plant cells. Shade may limit or ameliorate the effects of hot dry conditions and limit moisture loss by moderating leaf temperatures. Shaded plantation systems can decrease extreme variations in leaf temperature and humidity within it (Kirkpatrick 1935; Barradas and Fanjul 1986). Increase in shade cover could lead to a reduction in temperatures at the time of the day when plants are subjected to severe heat stress (Lin, 2007). Vaast et al., (2006) observed differences of leaf temperature of 4°C for inner leaves and 2°C for outer leaves were reported between coffee trees grown in full sun and coffee trees grown in the shade.

Shade makes the major difference in climatically marginal coffee production conditions, and higher levels of shade are needed with increasing temperature stress (Beer et al., 1998). Growing coffee under natural tree shade may be an important climate adaptation coping strategy for small-holder farmers, given that climate change is associated with rainfall decline and increased fluctuations of temperature extremes. Systems with more shade have better moisture availability due to the lower rate of evapotranspiration from the coffee and soil layer (Lin, 2007). In an agroforestry system, the shade canopy may enhance water conservation by decreasing runoff, nutrient and fertilizer drainage, and soil erosion (Wallace, 1996). The lowering of air temperatures by shade when combined with the higher soil moisture would produce lower moisture stress on the shaded plants. The trees protect the coffee from direct sunlight and mulch the soil with their litter fall which also protects the soil from extreme temperature and conserve soil moisture by decreasing rate of evaporation (Alemu, 2015). Soil temperature not only impacts the absorption of water and nutrients by plants, but also microbial activity that enhances organic matter content (Pregitzer and King, 2005).

2.4 Effect of natural shade on photosynthesis, stomatal conductance and transpiration

Several studies have shown that photosynthetic processes in coffee trees can be reduced markedly by high temperatures and irradiance. In Kenya, Kumar and Tieszen (1980) observed that photosynthetic rates were substantially decreased at air temperatures of more than 26 °C. Other studies have also shown that coffee plants exposed to air temperatures above 25°C may suffer high temperature stress, which is the rise in temperature above a critical threshold for a period of time, enough to cause irreparable damage to plant growth and development (Luo et al., 1999). Nunes et al., (1993) reported a 10% reduction of photosynthetic rate for every 1°C rise in temperature. High temperatures can decrease the net carbon gain by increasing photorespiration (Ramalho et al., 2013). High level of radiation is associated with photo-inhibition, which reduces coffee leaves' capacity for photosynthesis (Nunes et al., 1993; Ramalho et al., 1997). Plant growth and development consist of many biochemical reactions, all of which are sensitive to temperature (Oliveira et al., 2010). As a result, un-shaded coffee trees that are exposed to such temperatures suffer significant yield losses. On the other hand, excessive shading reduces the quality of the transmitted radiation which similarly affects photosynthesis and growth (Franck and Vaast, 2009; Baliza et al. 2012). However, few studies have been carried out on the effect of shade on photosynthesis in coffee under field conditions in Kenya.

Coffee is remarkably sensitive to variations in leaf temperature, especially above 25°C (Bote and Struik, 2011). For coffee trees grown in open sun, increased temperature above this level resulted in subsequent reduction of stomatal conductance (Kasai, 2008; Bote and Struik, 2011). Coffee leaves that were in permanent shade were reported to have had higher stomatal conductance rates than those that were exposed in full sun (Weidner et al. 2000). Other studies (Mohotti and Lawlor, 2002; Vaast et al. 2007) have reported higher stomatal conductance rates in the morning and lower rates later in the day under shade. This has been attributed to high temperatures and vapour pressure deficit that induce stomatal closure. Baliza et al. (2012) reported that stomatal conductance was highest in coffee trees under 35 to 50% shade level.

Coffee in unshaded plantations is normally more water stressed than shaded plants. In Central America, studies have shown that, where there was severe drought, the stress alleviating effect of shade trees was more beneficial than the competition for water was detrimental (Muschler, 2004). Van Kanten and Vaast (2006) found that trees in full sun tended to transpire more than those under shade trees, implying they faced a higher level of environmental stress. However, they also observed that the daily water usage was higher for coffee plants grown under shade, due to their greater vegetative growth, than those in full sun. Furthermore, the water use by associated shade trees under these conditions had no effect on soil water availability for coffee, although this may have been due to the high rainfall (over 3100 mm). There is, however, the possibility of competition for moisture particularly under during the dry periods (Beer et al., 1998).

2.5 Effect of shade trees on soil fertility

There is a general understanding that the presence of trees positively influences soil nutrient content (Jose, 2009). Trees can provide the soil with nutrients from their litter, primarily species that can fix nitrogen from the air (Souza et al., 2012; Romero-Alvarado et al., 2002). Shaded coffee agro-ecosystems reportedly have higher total C stock and higher total litter biomass than full sun or open systems (Dossa et al., 2008; Evizal et al., 2012). Total carbon (C), due to its bearing on other physical, chemical and biological indicators, is considered as the key indicator of soil quality and agronomic sustainability (Snoeck and Vaast, 2004; Reeves, 1997). Pinard et al., (2014) reported that non-leguminous trees increased Ca, Mg and K concentrations in the soil. Conversely, De Souza et al., (2012) found no substantial variance in soil properties under shade and in open sun conditions. Physically, trees offer a network of fine and coarse roots which binds the soil thereby preventing erosion.

The ability of many trees to utilize nutrient pools deeper in the soils, than crops would normally be able to access, leads to increased nutrient capture efficiency (Schaller et al., 2003). Besides, the competition between shade trees and coffee roots for nutrients is considerably reduced since they utilize nutrients from different layers in the soil profile (Schaller et al., 2003). These nutrients are assimilated into the biomass of the trees and are returned to the soil surface over time through litter fall, decomposition and mineralization processes thus making them available to the crops (Nair, et al., 1999). In order to reduce the possibility of competition between shade trees and coffee, particularly under low soil fertility, shade trees should be pruned regularly. This would lead to an increase organic matter and nutrient return to the soil (Dossa et al., 2008). In Kenya, there are limited studies on the impact of shade trees on soil fertility under coffee cropping systems.

2.6 Effect of natural shade on growth and yield of coffee

Shade trees create a microclimate that promotes coffee growth and production especially under less than optimum situations. Shade, therefore, is important in sustaining coffee productivity; it conserves soil, water and biodiversity (Vaast et al, 2007). Shade trees do buffer wide temperature fluctuations. In Mexico, Beer et al. (1998) observed that during the hot period temperatures were 5°C lower and 2°C higher than the minimum ambient temperature. In Costa Rica, shade trees reduced the global radiation by 40% to 50% of the highest coffee leaf temperature and increased the leaf temperature by 0.5°C during the night (Siles, 2007). Baggio et al. (1997) observed that coffee inter-planted under grevillea shade was not affected by the severe frost that damaged most coffee plants in Brazil in 1994.

Studies conducted in Central America have shown that shade in the range of 30 –50% is beneficial at low to medium elevations (Beer et al, 1997). At higher elevations (>1000 m), shade can reduce yields by 20-30%. Soto-Pinto et al., (2000) also observed that shade of between 23 and 38% had positive effect on yield. Soto-Pinto et al. (2000) further, reported that increasing the shade cover up to 48% had no effect on yield, but observed a yield reduction in shade levels of 50% and above. Shade reportedly reduces biennial or alternate bearing (Vaast et al., 2006). This has been attributed to the influence of shade on total tree carbon absorption, promotion of vegetative rather than flower buds, fewer nodes formed per branch and fewer flower buds (Cannell, 1975). The major adverse effect shade has on coffee yield appears to be lower flower induction hence a lower number of productive nodes on a branch (Franck, 2005). Shade also promotes growth of larger individual leaf size, plant longevity and reduction in leaf specific mass and hence lower carbon demand for a similar leaf area index (LAI) compared to sun grown plants (Franck, 2005). In addition, shade-grown coffee plants experience less overbearing dieback due to enhanced vegetative growth and carbon reserves in branches and roots (Wintgens, 2004). In Kenya, studies to determine the impact of shade under different coffee management levels are quite limited.

2.7 Biochemical components and beverage quality attributes

Green coffee consists of many diverse chemical compounds which react and interact during coffee processing to produce an end product that is even more variable and complex in structure (Kathurima, 2013). These include biochemical compounds that give distinctive odour or taste to edible plants as well as adaptive properties to plants such as resistance to diseases and pests (Dessalegn, 2005). Coffee bean size, density, beverage and bean biochemical quality characteristics are inherent factors, yet, the environment and genetic diversity are essential in determining their expression (Leroy et al., 2006). The key biochemical compounds in coffee include caffeine, oils trigonelline, sucrose and chlorogenic acids.

Caffeine (1, 3, 7-trimethylxanthine) is one of the key alkaloids that is found in leaves, seeds or fruits of several plants (Belay, 2010). Common caffeine sources include coffee, cocoa beans, coconuts and tea leaves (Mumin et al., 2006). It is perhaps the most commonly consumed pharmacologically active substance in the world (Mussatto et al., 2011). The stimulating effect of coffee has been attributed to caffeine hence making it an important constituent of coffee (Franca et al., 2005). Even though there is no data to support relationship between caffeine and coffee quality (Kathurima, 2013), coffee cultivars with low caffeine content (0.2%) generally have inferior quality (Clifford, 1985). The caffeine content is genetically defined in a measurable, polygenic manner and is also affected by external elements (Pearl et al., 2004).

Oil, a component of lipids, is an important component of coffee although most of it is lost with the grounds during the preparation of the brew (Folstar, 1985). Coffee oil comprises diterpenes of the kaurene family in proportions of up to 20% of the total lipids (Speer and Kölling-Speer, 2006). Green Arabica coffee supposedly contains 75% triglycerides with a high percentage of unsaponifiables including about 19% total free and esterified sterols and the rest is made up of other substances such as tocopherols (Clarke and Vitzthum, 2001). Coffees with higher oil contents give better roasts (Northmore, 1965). The oil, therefore, is crucial in the overall presentation of coffee flavour although the oil is poorly extracted into the coffee brew.

Trigonelline is a nicotinic acid related alkaloid that is essential to the coffee bean (Sridevi and Giridhar, 2013). It is important in the development of the main flavour compounds during roasting (Kathurima, 2013). Trigonelline decomposes readily as temperature approaches 160 ºC, and 60% of the initial trigonelline is broken down, leading to the formation of carbon dioxide, water and the development of a large group of aromatic compounds called pyridines. The pyridines are involved in the production of various aromas such as found in coffee.

Chlorogenic acids (CGA) are phenolic compounds commonly found in green coffee beans (Belay, 2010). The total CGA content of green coffee beans varies according to species, degree of maturation and to a lesser extent agricultural practices, climate and soil (Clifford, 1985; Farah et al., 2005). The CGA play an important role in formation of pigments, taste and flavor of coffee beans which determine quality and acceptance of the beverages. They contribute to the final acidity of the beverages and formation of lactones and other phenol derivatives responsible for flavor and aroma (Variyar et al., 2003).

Coffee beverage or liquor quality is a vital characteristic of coffee and is used to determine its price (Muschler, 2001; Agwanda et al., 2003). The beverage quality is centred on the description of many factors including flavour and aroma (Kathurima et al., 2009) which are linked to the biochemical composition of roasted beans whose presence could be favourable, for instance, trigonelline and sugars, or unfavourable in the case of caffeine and chlorogenic acids (Clifford, 1985). Coffee beverage quality is affected by many factors including environmental and agronomic management practices.

Coffee flavour is the main measure for quality assessment and a key motivation for consumer preferences (Cantergiani et al., 1999; Clarke, 1987). It is the overall view and depiction of the coffee's distinctive features including fragrance/aroma, acidity, and body. The smell of ground coffee when still dry is the fragrance, while the smell of the coffee when infused with hot water is the aroma. Aftertaste is the taste remaining in the mouth after swallowing a sip of coffee. (Lingle, 2001). Body defines the "mouth feel" of the coffee as it settles on your tongue, its tangible impression or weight and consistency as perceived in the mouth (Lingle, 2001).

Acidity has been accepted as an essential attribute of the sensory quality in coffee. The International Standard ISO-5492 (2008) defines acidity as a simple taste produced by dilute aqueous solutions of most acid substances. Some of the acids contributing to this sensation are formed during the development of the coffee bean while some are generated during roasting (Ginz and Enhelhardt, 2000).

2.8 Effect of natural shade on coffee beverage quality

Many authors have reported the positive influence of shade on coffee quality (Geromel et al. 2008; Vaast et al., 2006; Muschler, 2004). Vaast et al. (2006) reported that shade delayed ripening by one month leading to an increase in size and improvement in the biochemical composition of the coffee bean. Muschler (2004) found that shade significantly reduced the ratio of fallen berries, while un-shaded coffee trees often dropped more than 20% of the berries to the ground. This has been attributed to the physical protection of ripe berries from the effect of raindrops provided by the tree canopy, and also increased ability of shaded plants to retain ripe berries on the plant. It has also been noted that shade reduces the portion of rejects which include diseased, shrunken or dried berries. In Costa Rica, Muschler (1998) found that coffee bean rejects were more than ten times greater in the unshaded than the shaded samples. Pinard et al. (2014), on the other hand, found that shade did not delay coffee berry maturation nor did it reduce alternate bearing pattern. They also found that shade did not increase or improve the final quality grading of green coffee beans. Shade trees could also compete for light, water and nutrients with coffee trees and possibly modify conditions for incidences of pests and diseases (Staver et al., 2001; DaMatta, 2004; Mouen Bedimo et al. 2012). Due to the intricate and varied relations, the influence of shade on coffee production often depends on sites, varieties of coffee and species of shade tree (Beer et al., 1998; Vaast et al., 2007; Hagar et al., 2011; Läderach et al., 2011). However, information on the effect of shade on quality of Kenyan local coffee varieties is inadequate.

CHAPTER THREE: EFFECT OF *Cordia africana* SHADE ON STOMATAL CONDUCTANCE, TRANSPIRATION AND PHOTOSYNTHETIC RATE OF ARABICA COFFEE

3.1 Abstract

Stomatal conductance, transpiration and photosynthetic rate in coffee are dependent on ecological conditions such as irradiance, temperature and nutrient supply which ultimately have a major impact on its productivity. In studies elsewhere, the use of shade trees has been found to alleviate the effects of high temperatures, high solar irradiance and low rainfall, thereby providing a suitable microclimate for coffee production. In Kenya, however, the information on shade effects on coffee physiology is scanty. This study was, therefore, carried out to evaluate the effect of *Cordia africana* shade on stomatal conductance, transpiration and photosynthetic rate. The experiment was laid out as a randomized complete block with seven replicates. The coffee plants were subjected to varying shade levels which were based on the distance from the shade tree trunk; 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m and > 6 m (coffee trees under full sun). Photosynthetically active radiation (PAR), stomatal conductance, transpiration and photosynthesis were measured simultaneously, on intact plants in the field, using a differential CO_2/H_2O infrared gas analyser. The measurements, taken in the early morning, midday and late afternoon, were made in two consecutive coffee growing seasons during the dry and rainy periods. During the dry period, shaded coffee had higher leaf temperature than unshaded coffee at 900 hrs but the converse was the case at 1200 and 1500 hrs. Shade had no effect on leaf temperature during the rainy period. Generally, the rate of transpiration was significantly higher in shaded than unshaded coffee in the morning, during both dry and rainy periods. Shade significantly increased stomatal conductance during the rainy period. Photosynthetic rates were generally higher, in the morning hours, in shaded

coffee during the dry period. The results confirm that shade does have some beneficial effects on coffee physiology that may positively impact production.

3.2 Introduction

Coffee is thought to have originated in the tropical high rain forests in Ethiopia, as an under–storey shrub (Chaves et al., 2008; Cavatte et al., 2012). Its evolution as an under storey plant meant that coffee was permanently in shade and hence was not exposed to high temperatures and vapour pressure deficit (Maestri and Barros, 1977). Consequently, coffee had been presumed to be a shade obligatory species. In many situations, however, coffee grows well and even produces higher yields in the sun than in shade (DaMatta, 2004; DaMatta et al., 2010; Pompelli et al., 2010). Coffee leaves could, therefore, be assumed to exhibit wide flexibility in their adaptation to irradiance as shown by the variety of radiation conditions in which coffee can be grown (Matos et al., 2009). Coffee is, therefore, considered a shade adapted rather than a typical shade plant (DaMatta, 2004). It shows distinctive features of such species which include ability to photosynthesize in low light, high leaf area to woody structure ratio and the lack of fruit thinning ability to regulate fruit load (Franck et al., 2005). The altitude in coffee's natural habitat ranges from 1600 to 2800 m with an average annual temperature of 20°C; rainfall is well distributed varying from 1600 mm to more than 2000 mm, with a dry season lasting 3 – 4 months corresponding with the coolest period (DaMatta and Ramalho, 2006).

The adaption of coffee to shade favours its cultivation in agroforestry systems and this practice has been regaining popularity especially in Central America (Beer et al., 1998). The question of whether shade trees are beneficial has been debated over the years with the fundamental issue being the competition for nutrients and water. Nonetheless, it has been documented through studies conducted in Central America and other parts of the world that coffee benefits from shade (Beer et al., 1998; van Kanten and Vaast, 2006; Vaast et al., 2007; Somporn et al., 2012). The inclusion of shade or shelter trees is advantageous especially under conditions, such as high temperatures, high solar irradiance and low rainfall, that are considered sub-optimal for coffee production. The trees moderate the effects of adverse climatic conditions, thereby providing a more suitable microclimate for coffee production.

Coffee physiological factors such stomatal conductance, transpiration and photosynthesis, are dependent on environmental conditions such as irradiance, temperature and nutrient supply among other factors, so that they fluctuate daily and seasonally. Air temperature is among the most critical climatic factors in the physiology of coffee. It has a major impact on leaf temperature which determines the vapour pressure deficit (VPD) within the leaf and consequently the stomatal conductance, transpiration and photosynthetic rates (Monteith et al., 1991). The effect of temperature on coffee photosynthesis has been reported in earlier studies, with net CO_2 assimilation decreasing at temperature above 24°C (Nunes et al., 1968; Nutman, 1937). Shade has a direct influence on the amount of light that reaches the coffee plants which in turn regulate their growth and development functions in reaction to changes in light intensity (Walters, 2005; Lusk et al., 2008). Variances in the availability of solar radiation can cause changes in the function and structure of coffee plant leaves, (Baliza et al., 2012). Results of the study conducted on the effect of shading on the photosynthetic rates of coffee plants have been inconsistent. Some studies have shown that coffee plants under high radiation had higher assimilation of CO_2 than those with shaded leaves exposed to lower radiation (Araújo et al., 2008; Chaves et al., 2008). Other authors have, however, reported that coffee plants under shading recorded higher photosynthetic rates (Nutman, 1937; Kumar and Tieszen, 1980; Freitas et al., 2003). Kumar and Tieszen (1980) further noted that the rate of photosynthesis for coffee plants under shade is nearly twice that of plants under full sun.

The categorization of shade effects on the physiology of coffee plants is important in deciding the optimal intensities of radiation as well as supporting studies on growth of shaded plants aimed at determining the best coffee plant arrangement that optimizes the absorption of the available solar radiation under shaded conditions (Baliza et al., 2012). Information on the microclimatic changes in the shaded systems, both from the productive and ecological points of view, through the crop cycle and in various times of the year is imperative to determine agronomical and viable practices (Morais et al., 2006). Hernandez et al., (1989) suggested that large VPD is the factor limiting total crop photosynthesis and hence shading which reduces leaf temperature and hence VPD is an effective means of increasing productivity over longer period of time. The use of shade trees can thus reduce the ecological and economic vulnerability of resource poor small holder farmers (DaMatta et al., 2007; Camargo, 2010).

In Kenya, the early plantations were established under tree shade. However, during the late 1960's there was a move towards intensification of coffee production and trees were removed and coffee grown in full sun (Kimemia and Njoroge, 1988). However, with the renewed interest in shade coffee, there is need for information on the influence of natural shade on coffee physiology in Kenya. This study, therefore, was carried out to evaluate the effect of *Cordia africana* shade on leaf temperature, stomatal conductance, transpiration and photosynthetic rate of Arabica coffee.

3.3 Materials and Methods

3.3.1 Site

This study was conducted at the Kenya Agricultural and Livestock Research Organization – Coffee Research Institute (KALRO–CRI) demonstration plot in Namwela from year 2010 to 2012. Namwela is located in Bungoma County at 0° 45’43N 34° 33’42E, 1641 metres above sea level and an average rainfall of 1329 mm. The rainfall pattern is unimodal, starting in March/April and ends in December. The site experiences a dry spell between December and April. The temperatures range from a minimum of 13 °C to a maximum of 27 °C. The soils are mainly humic acrisols which are moderately fertile, sandy and mildly acid. These soils require frequent liming to correct excess acidity and routine alkaline correction with urea or ammonium sulphate (AS) fertilizer for good rooting and better nutrient uptake. The effect of shade on coffee physiology was assessed under the high management level, where the established coffee trees were managed using all the recommended practices (CRF, 2013).

3.3.2 Experimental treatments, design and agronomic management

The treatments consisted of different shade levels under high agronomic management. The shade level was based on distances from shade tree trunk, 0 – 1.5 m, 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6.0 m (full sun). The shade level (amount of light intercepted by the shade trees) was estimated by measuring photosynthetic photon flux density (PPFD) using a Line Quantum Sensor (LI- 191, LICOR Biosciences) at regular and increasing distances from the tree trunk as described by Vaast et al., (2007). The experiment was laid out as a randomized complete block design (RCBD) with seven replicates. Measurements were taken under the shade tree canopy (1 m above coffee bushes) and in full sun, about 10 m outside the canopy. Twenty instantaneous measurements of PPFD were taken at each point (mid-way between the various distances from shade tree trunk) and the averages were expressed as a percentage of the average readings recorded in full sun. This was done at midday, following the same order to ensure that the diurnal variation in intensity of shading was minimized. The recording was done on four consecutive days per month, during the dry period in November 2010.

The traditional coffee variety K7 spaced at 2.74 m x 2.74 m was used in the study. The coffee variety, K7, is a selection from “French Mission” coffee and is the most commonly grown variety in the study area. The cultivar has resistance to some races of coffee leaf rust as well as partial resistance to coffee berry disease. The coffee trees were under high agronomic management, using all the recommended practices, including fertilizer and pesticide applications and canopy management (CRF, 2013). The main crop at the study site flowers in March to April and therefore NPK compound fertilizers, 20:10:10, were applied earlier in October (6 months before flowering) at the rate of 250 g/coffee tree. Foliar applications of Boron and Zinc were also applied, at the rate of 3 kg/ha, 3 months before flowering. After the main flowering in March/April, the first round of calcium ammonium nitrate (CAN) fertilizer at the rate of 100 g/tree was applied. Two more rounds of CAN applications were made at 4 weeks interval giving a total of 300 g/tree per annum, (3 equal split applications). Pruning of the coffee trees was undertaken in January of both year 2010 and 2011. This involved the removal of unwanted branches to promote growth of the desired branches. Major insect pests such as antestia bugs and thrips were controlled using Dursban 480 EC (active ingredient: chlorpyrifos) at the rate of 1000 ml/ha. Weeds were managed by application of glyphosate (36%) herbicide which was applied during the rainy period when the weeds were young.

The coffee trees were under the natural shade of *Cordia africana* Lam, which is a small to medium sized evergreen tree that grows up to 30 m. It is heavily branched with a spreading umbrella shaped or rounded crown that provides excellent shade for tree crops (Orwa et al., 2009). The species occurs at medium to low altitudes in warm and moist areas, often along riverbanks. It also grows in drier conditions but thrives in good rainfall areas. It is the predominant shade tree used in Bungoma County.

3.3.3 Physiological measurements

All physiological measurements were made on intact plants in the field. Data was recorded on photosynthetically active radiation reaching the coffee tree, leaf temperature, transpiration, stomatal conductance and photosynthetic rate. Photosynthetically active radiation (PAR), leaf temperature, transpiration rate, stomatal conductance and photosynthetic rate of the leaves were measured simultaneously using a differential CO_2/H_2O Infra-red gas analyser (LC ADC Bio Scientific Ltd., Hoddesdon, UK) connected to a broadleaf chamber. Measurements were taken on four fully developed exposed leaves (3^{rd} to 6^{th} pair of leaves from the branch tip) sampled on plagiotropic branches at middle level in the canopy. Four (4) leaves from two (2) trees per treatment were monitored. The measurements were taken three times per day: early morning (7 to 9 am), mid-day (11 am to 1 pm) and late afternoon (3 to 5 pm). This was carried out during the dry period in February/March and the rainy period in July/August of 2011 and 2012.

3.3.4 Data analysis

All the data collected were subjected to analysis of variance using CoStat version 6.400 (1998-2008, Co Hort Software). Mean separation was performed using the least significant difference test at $p \leq 0.05$.

3.4 Results

3.4.1 Shade level

Light interception at the top of the coffee canopy increased with increase in distance from the *Cordia africana* shade tree trunk. It varied from 325 µmolm^{-2}s^{-1} (0 – 1.5 m from the shade tree trunk) to 1629 µmolm^{-2}s^{-1} (full sun). Distances 0 – 1.5 m, 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6.0 m (full sun) from the shade tree trunk had 80, 70, 50, 30 and 0% shade, respectively (Table 3.1).

Table 3.1: Effect of *Cordia africana* shade on mean percentage light (µmolm^{-2}s^{-1}) reaching the coffee canopy

Distance (m) from the tree trunk	Light interception	
	µmolm^{-2}s^{-1}	% Shade
0 – 1.5	325	80.06
1.5 – 3.0	481	70.47
3.0 – 4.5	811	50.17
4.5 – 6.0	1146	29.66
> 6 m (Full Sun)	1629	0.00
LSD $_{0.05}$	158	-
CV (%)	16.3	-

Key: - means not separated by LSD

3.4.2 Effect of *Cordia africana* shade on photosynthetically active radiation reaching coffee plants

Shade level had a significant effect ($p \leq 0.05$) on PAR reaching the coffee leaves during the dry (Table 3.2) and rainy period (Table 3.3). During the dry period, in February/March 2011 and 2012, the PAR reaching the coffee trees increased with the distance from the shade tree trunk. The PAR recorded in full sun was significantly ($p \leq 0.05$) higher than that recorded in the shade at all times during the day. Coffee at a distance of 0 – 1.5 m from shade tree trunk (equivalent to 80% shade level) had significantly lower PAR reaching it than coffee at distances of 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6 m (coffee in full sun). There was, however, no significant difference in PAR reaching coffee plants among the distances (from the shade tree trunk) of 1.5 – 3.0 m, 3.0 – 4.5 m and 4.5 – 6.0 m at 900 hrs and 1500 hrs. At 1200 hrs there was no difference in PAR reaching coffee at 4.5 – 6.0 m from the shade tree trunk and under full sun (Table 3.2).

The highest PAR, 838 µmol $m^{-2}s^{-1}$, was recorded at 1200hrs in full sun while the lowest, 81 µmol $m^{-2}s^{-1}$, was recorded at 1.5 – 3.0 m from shade tree in February/March 2012 (Table 3.2). The PAR generally increased during the morning and peaked at noon and dropped in late afternoon. During the rainy period, the PAR followed a similar pattern to that during the dry period (Table 3.3). In the rainy period (July/August 2011), the highest PAR, 641 µmol $m^{-2}s^{-1}$, was recorded in full sun at 900 hrs and the lowest, 95 µmol $m^{-2}s^{-1}$, was recorded at a distance of 0 – 1.5 m (equivalent to 80% shade) from the shade tree trunk. In season 2, the highest PAR, 695 µmol $m^{-2}s^{-1}$, was recorded in full sun at 1500 hrs and the lowest, 155 µmol $m^{-2}s^{-1}$, was recorded at 0 – 1.5 m (equivalent to 80% shade) from the shade tree trunk at 900 hrs. There were significant differences in PAR between the coffee in full sun (0% shade) and coffee under shade at 900 and 1500 hrs in the dry period. On the other hand, there was no difference in PAR between coffee in full sun and coffee at 4.5 – 6.0 m (equivalent to 30% shade) from the shade tree trunk, at 1200 hrs in the rainy period (Table 3.3).

Table 3.2: Effects of *Cordia africana* shade on photosynthetically active radiation (µmol $m^{-2}s^{-1}$) reaching coffee plants during dry period – February/March 2011/2012

February/March 2011	Photosynthetically active radiation (µmol m-2s-1)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	137	282	133
1.5 – 3.0	335	439	170
3.0 – 4.5	356	494	185
4.5 – 6.0	325	795	202
> 6 (Full Sun)	557	838	764
P value (SL)	0.0000***	0.0000***	0.0053**
$LSD_{0.05}$ (SL)	100	129	77
CV (%)	26.6	20.5	23.9
February/March 2012	Photosynthetically active radiation (µmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	244	222	87
1.5 – 3.0	305	241	81
3.0 – 4.5	326	419	112
4.5 – 6.0	378	531	127
> 6 (Full Sun)	420	893	247
P value (SL)	0.0375*	0.0000***	0.0000***
$LSD_{0.05}$ (SL)	114	127	33
CV (%)	31	25	23

Key: SL – Shade level; * significant at 5% level, **significant at 1% level, ***significant at 0.1% level

Table 3.3: Effects of *Cordia africana* shade on photosynthetically active radiation (μmol $m^{-2}s^{-1}$) during rainy period – July/August 2011/2012

July/August 2011	Photosynthetically active radiation (μmol m-2s-1)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	212	110	95
1.5 – 3.0	269	182	162
3.0 – 4.5	357	218	211
4.5 – 6.0	380	420	208
> 6 (Full sun)	641	480	533
P value (SL)	0.0000***	0.0000***	0.0000***
$LSD_{0.05}$ (SL)	108	100	70
CV (%)	26	32	26
July/August 2012	Photosynthetically active radiation (μmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	155	217	233
1.5 – 3.0	287	326	281
3.0 – 4.5	310	360	317
4.5 – 6.0	314	403	399
> 6 (Full sun)	483	413	695
P value (SL)	0.0001***	0.0001***	0.0000***
$LSD_{0.05}$ (SL)	97	76	97
CV (%)	28	20	23

Key: SL – Shade level; ***significant at 0.1% level

3.4.3 Effect of *Cordia africana* shade on coffee leaf temperature

The effect of shade on the leaf temperature was significant (p=0.05) in the dry period of February/March 2011 and 2012 (Table 3.4). The shaded coffee plants recorded higher leaf temperatures at 900hrs than coffee in full sun. However, coffee in full sun recorded higher leaf temperatures at 1200hrs and 1500hrs than shaded coffee. The lowest (28.4°C) and highest (38.0 °C) leaf temperatures, in February/March 2011, were both recorded in full sun at 900hrs and 1200 hrs respectively. No significant differences were noted among shade levels at 900 and 1200 hrs.

During the rainy period, shade level had significant ($p<0.001$) effect on leaf temperature (Table 3.5). The leaf temperatures were higher at 1200 and 1500hrs in full sun than in the shade. In July/August 2011, leaf temperatures were generally higher than those recorded in July/August 2012.

Table 3.4: Effect of *Cordia africana* shade on leaf temperature (°C) during dry period – February/March 2011/2012

February/March 2011	Leaf temperature (°C)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	30.0	35.6	32.6
1.5 – 3.0	30.3	35.2	32.2
3.0 – 4.5	30.4	35.0	32.0
4.5 – 6.0	29.9	36.5	31.7
> 6 (Full sun)	28.4	38.0	36.7
P value (SL)	0.0000***	0.0000***	0.0000***
$LSD_{0.05}$ (SL)	0.7	1.1	1.81
CV (%)	2.20	2.70	4.98
February/March 2012	Leaf temperature (°C)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	26.0	29.6	29.6
1.5 – 3.0	25.8	30.1	30.4
3.0 – 4.5	27.1	30.0	30.3
4.5 – 6.0	27.6	30.4	30.2
> 6 (Full sun)	26.1	30.2	32.6
P value (SL)	0.0585	0.7433	0.0003***
$LSD_{0.05}$ (SL)	NS	NS	1.19
CV (%)	4.86	3.30	3.52

Key: SL – Shade level; NS – not significant, ***significant at 0.1% level

Table 3.5: Effect of *Cordia africana* shade on leaf temperature (°C) during rainy period – July/August 2011/2012

July/August 2011	Leaf temperature (°C)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	27.6	30.1	30.1
1.5 – 3.0	27.6	30.0	29.9
3.0 – 4.5	27.8	29.9	29.9
4.5 – 6.0	27.7	30.6	29.6
> 6 (Full sun)	24.9	28.3	31.8
P value (SL)	0.0000***	0.0000***	0.0063**
$LSD_{0.05}$ (SL)	0.7	0.7	1.2
CV (%)	2.4	2.1	3.6
July/August 2012	Leaf temperature (°C)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	27.9	26.8	25.7
1.5 – 3.0	28.1	26.5	25.6
3.0 – 4.5	28.2	26.6	25.6
4.5 – 6.0	28.0	26.9	25.5
> 6 (Full sun)	26.0	28.7	27.4
P value (SL)	0.0000***	0.0000***	0.0000***
$LSD_{0.05}$ (SL)	0.7	0.8	0.4
CV (%)	2.3	2. 6	1.5

Key: SL – Shade level; * significant at 5% level, ***significant at 0.1% level

3.4.4 Effect of *Cordia africana* shade on transpiration rate

Shade significantly (p=0.05) affected the coffee leaf transpiration rate only at 1200 and 1500 hrs during the dry period in February/March 2011 and 2012 (Table 3.6). At 1200 hrs, shaded coffee, except at 4.5 – 6.0 m from the shade tree trunk, had significantly higher transpiration rate than coffee grown under full sun. Transpiration rate ranged from 0.43 (full sun) to 0.74 µmol $m^{-2}s^{-1}$ (0 – 1.5 m from the shade tree trunk). At 1500 hrs, the trend was similar except that the difference between coffee at 3.0 – 4.5 m from the shade tree trunk and coffee under full sun was not significant (Table 3. 6). Transpiration rate ranged from 0.44 (full sun) to 0.70 µmol $m^{-2}s^{-1}$ (0 – 1.5 m from the shade tree trunk). In February/March 2012, shaded coffee (0 – 1.5 m, 3.0 – 4.5 m and 4.5 – 6.0 m from the shade tree trunk) had higher transpiration rate than coffee under full sun. Transpiration rate ranged from 0.48 (full sun) to 0.72 µmol $m^{-2}s^{-1}$ (4.5 – 6.0 m from shade tree trunk). At 1500 hrs, the transpiration rate in full sun was significantly higher than that at 0 – 1.5 m from the shade tree trunk. Shade levels at 1.5 – 3.0 m, 3.0 – 4.5 m and 4.5 – 6.0 m from the shade tree trunk had no effect on transpiration rate relative to full sun.

During the rainy period, shade had significant effect on transpiration rate only at 1200 hrs in July/August 2011 and at all the times in July/August 2012 (Table 3.7). In July/August 2011, the transpiration rates of coffee at 1200 hrs in full sun were significantly lower than shaded coffee, regardless of shade level. However, there were no significant differences in transpiration rate among the shaded coffee. Transpiration rate of coffee plants ranged from 0.34 to 0.65 µmol $m^{-2}s^{-1}$. In July/August 2012, coffee in full sun recorded significantly lower transpiration rates than shaded coffee at all shade levels at 900 and 1200 hrs. However, at 1500 hrs, the transpiration rate for coffee in full sun was not significantly different from coffee at 0 – 1.5 m and 1.5 – 3.0 m from the shade tree trunk. The transpiration rates ranged from 0.44 (full sun) to 0.74 µmol $m^{-2}s^{-1}$ at 900 hrs, 0.33 to 0.64 µmol $m^{-2}s^{-1}$ at 1200 hrs, and 0.40 to 0.57 µmol $m^{-2}s^{-1}$ at 1500 hrs.

Table 3.6: Effect of *Cordia africana* shade on transpiration rate (mmol $m^{-2}s^{-1}$) during dry period – February/March 2011/2012

February/March 2011	Transpiration rate (mmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.84	0.74	0.70
1.5 – 3.0	0.76	0.63	0.65
3.0 – 4.5	0.70	0.60	0.53
4.5 – 6.0	0.71	0.56	0.46
> 6 (Full sun)	0.67	0.43	0.44
P value (SL)	0.19	0.01*	0.05*
$LSD_{0.05}$ (SL)	NS	0.16	0.20
CV (%)	21.8	24.5	32.2
February/March 2012	Transpiration rate (mmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.60	0.56	0.46
1.5 – 3.0	0.75	0.67	0.49
3.0 – 4.5	0.75	0.66	0.58
4.5 – 6.0	0.70	0.72	0.64
> 6 (Full sun)	0.64	0.48	0.59
P value (SL)	0.33	0.01*	0.03*
$LSD_{0.05}$ (SL)	NS	0.15	0.12
CV (%)	23.9	21.5	20.3

Key: SL – Shade level; NS – not significant, * significant at 5% level, ***significant at 0.1% level

Table 3.7: Effect of *Cordia africana* shade on transpiration rate (mmol $m^{-2}s^{-1}$) during rainy period – July/August 2011/2012

July/August 2011	Transpiration rate (mmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.67	0.65	0.45
1.5 – 3.0	0.66	0.64	0.45
3.0 – 4.5	0.58	0.69	0.56
4.5 – 6.0	0.58	0.77	0.58
> 6 (Full sun)	0.69	0.34	0.37
P value (SL)	0.44	0.000***	0.20
$LSD_{0.05}$ (SL)	NS	0.17	NS
CV (%)	23.09	25.61	36.59
July/August 2012	**Transpiration rate (mmol $m^{-2}s^{-1}$)**		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.71	0.55	0.45
1.5 – 3.0	0.74	0.55	0.50
3.0 – 4.5	0.68	0.53	0.57
4.5 – 6.0	0.69	0.64	0.55
> 6 (Full sun)	0.44	0.33	0.40
P value (SL)	0.01**	0.00**	0.02*
$LSD_{0.05}$ (SL)	0.16	0.14	0.11
CV (%)	21.8	24. 1	20.13

Key: SL – Shade level; * significant at 5% level, ***significant at 0.1% level

3.4.5 Effect of *Cordia africana* shade on stomatal conductance

The stomatal conductance was significantly affected by natural shade at 1200 and 1500 hrs during the dry spell in season 1. Stomatal conductance was significantly lower in full sun than in coffee under natural shade. In February/March 2012, however, the effect of shade on stomatal conductance was not significant (Table 3.8). During the rainy period, the effect of shade on stomatal conductance was significant (p=0.05) only at 900 hrs in season 1 (Table 3.8). The stomatal conductance was significantly lower in full sun than in coffee at 0 – 1.5 m, 1.5 – 3.0 and 3.0 – 4.5 m from shade tree trunk. However, there was no significant difference in stomatal conductance between coffee in full sun and coffee at 4.5 – 6.0 m from shade tree (Table 3.9). Stomatal conductance rates were 0.005 to 0.045 µmol $m^{-2}s^{-1}$ in the dry period (Table 3.7) and 0.017 to 0.063 µmol $m^{-2}s^{-1}$ in the rainy period (Table 3.9).

Table 3.8: Effect of *Cordia africana* shade on stomatal conductance (mol $m^{-2}s^{-1}$) during the dry period – February/March 2011/2012

February/March 2011	Stomatal conductance (mol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.023	0.013	0.013
1.5 – 3.0	0.022	0.012	0.012
3.0 – 4.5	0.019	0.013	0.015
4.5 – 6.0	0.019	0.015	0.016
> 6 (Full sun)	0.025	0.005	0.008
P value (SL)	0.1332	0.0000***	0.0185*
$LSD_{0.05}$ (SL)	NS	0.003	0.006
CV (%)	24.03	22.24	37.58
February/March 2012	Stomatal conductance (mol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.043	0.030	0.024
1.5 – 3.0	0.041	0.030	0.027
3.0 – 4.5	0.045	0.028	0.031
4.5 – 6.0	0.041	0.033	0.036
> 6 (Full sun)	0.030	0.026	0.023
P value (SL)	0.1054	0.6743	0.1425
$LSD_{0.05}$ (SL)	NS	NS	NS
CV (%)	25.80	31.78	28.86

Key: SL – Shade level; * significant at 5% level, ***significant at 0.1% level

Table 3.9: Effect of *Cordia africana* shade on stomatal conductance (mol $m^{-2}s^{-1}$) during the rainy period – July/August 2011/2012

July/August 2011	Stomatal conductance (mol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.063	0.026	0.023
1.5 – 3.0	0.041	0.026	0.019
3.0 – 4.5	0.037	0.026	0.020
4.5 – 6.0	0.031	0.029	0.021
> 6 (Full sun)	0.026	0.023	0.017
P value (SL)	0.000***	0.55	0.59
$LSD_{0.05}$ (SL)	0.010	NS	NS
CV (%)	22.4	27.9	33.5
July/August 2012	Stomatal conductance (mol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	0.048	0.033	0.030
1.5 – 3.0	0.044	0.032	0.025
3.0 – 4.5	0.043	0.032	0.028
4.5 – 6.0	0.040	0.030	0.022
> 6 (Full sun)	0.038	0.025	0.023
P value (SL)	0.3029	0.3181	0.0573
$LSD_{0.05}$ (SL)	NS	NS	NS
CV (%)	21.3	24.8	21.8

Key: SL – Shade level; NS – Not significant, *** - significant at 0.1% level

3.4.6 Effect of *Cordia africana* shade on photosynthetic rates

Photosynthetic rates were not significantly affected by shade during both the dry period and the rainy period (Table 3.10 and 3.11). The photosynthetic rates ranged from 1.10 to 4.33 µmol $m^{-2}s^{-1}$ in the dry period and 1.39 to 3.12 µmol $m^{-2}s^{-1}$ in the rainy period.

Table 3.10: Effect of *Cordia africana* shade on photosynthetic rate (µmol $m^{-2}s^{-1}$) during the dry period – February/March 2011/2012

February/March 2011	Photosynthetic rate (µmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	1.84	1.67	1.43
1.5 – 3.0	1.66	1.62	1.40
3.0 – 4.5	1.64	1.50	1.38
4.5 – 6.0	1.61	1.52	1.33
> 6 (Full sun)	1.42	1.32	1.10
P value (SL)	0.27	0.49	0.19
$LSD_{0.05}$ (SL)	NS	NS	NS
CV (%)	20.7	24.7	20.6
February/March 2012	Photosynthetic rate (µmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	4.33	3.85	2.27
1.5 – 3.0	3.39	3.17	1.69
3.0 – 4.5	3.46	2.81	2.21
4.5 – 6.0	3.02	3.19	1.85
> 6 (Full sun)	3.10	3.03	2.14
P value (SL)	0.1574	0.0985	0.3588
$LSD_{0.05}$ (SL)	NS	NS	NS
CV (%)	29.53	21.53	30.37

Key: SL – Shade level; NS – Not significant

Table 3.11: Effect of *Cordia africana* shade on photosynthetic rate (µmol $m^{-2}s^{-1}$) during the rainy period – July/August 2011/2012

July/August 2011	Photosynthetic rate (µmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	2.84	2.05	1.52
1.5 – 3.0	2.31	1.97	1.43
3.0 – 4.5	2.21	2.09	1.50
4.5 – 6.0	1.97	1.65	1.46
> 6 (Full sun)	1.95	1.68	1.39
P value (SL)	0.1930	0.7163	0.9684
$LSD_{0.05}$ (SL)	NS	NS	NS
CV (%)	32.70	40.10	25.95
July/August 2012	Photosynthetic rate (µmol $m^{-2}s^{-1}$)		
Distance (m) from tree trunk	Time (hrs)		
	900	1200	1500
0 – 1.5	3.12	2.29	1.90
1.5 – 3.0	2.73	2.42	1.64
3.0 – 4.5	2.50	2.24	1.60
4.5 – 6.0	2.47	2.05	1.88
> 6 (Full sun)	2.26	2.11	1.72
P value (SL)	0.1608	0.6205	0.7703
$LSD_{0.05}$ (SL)	NS	NS	NS
CV (%)	24.62	21.69	30.53

Key: SL – Shade level; NS – Not significant

3.5 Discussion

3.5.1 Effect of shade on photosynthetically active radiation reaching coffee tree

Coffee in full sun recorded higher photosynthetically active radiation (PAR) reaching it than shaded coffee. This agrees with the findings by Baliza et al., (2012) who also observed a decrease in photosynthetically active photon flux density (PPFD) with increase of the shading level due to the effect of tree leaves filtering out the red light and transmitting the green. The PAR reaching coffee trees also increased with increasing distance from shade tree (reducing shade levels). The daily differences were more pronounced especially at midday, during the dry period, where the PAR recorded under coffee in full sun was much higher than that recorded under shaded coffee. During the rainy period, the daily trend in PAR was similar to that recorded in the dry period, however, the ranges tended to be higher in the late afternoon. These results concur with those by Vaast et al., (2006) and Mayoli and Gitau (2012). Comparable findings reported by Karunaratne et al., (2003) established that unshaded tea plants received significantly higher PAR. This study showed that during the dry period, the PAR under shade was lower than under full sun. Morais et al., (2006) demonstrated that shade causes a significant reduction in incident global solar radiation and PAR during the day. Shade has a direct impact on photosynthesis since it determines the amount of light that reaches the plants which in turn regulate their growth processes in reaction to changes in light intensity (Walters, 2005; Lusk et al., 2008). In our study, the PAR was mostly higher, on average, during the dry period reaching a maximum value of 893 µmol $m^{-2}s^{-1}$ while in the rainy period the highest value obtained was 695 µmol $m^{-2}s^{-1}$. This contrasts with results by Baliza et al., (2012) who reported higher values in the rainy season than in the dry period. The conflicting findings may be due to the difference in methodology between the studies. For instance, Baliza et al., (2012) used plastic screens to provide different shading levels of 0 (full sun), 35, 50, 60 and 90%, whereas in the current study, *Cordia africana* shade tree was used. Factors such as shading type (natural or artificial), shading density and species used can affect the outcomes of studies of this nature (Carelli et al., 1999).

3.5.2 Effect of shade on leaf temperature

Leaf temperature was significantly affected by shade during the dry period but not during the rainy period. In the current study, leaf temperatures tended to be lowest in the morning, peaking at midday then decreasing thereafter. Very high leaf temperatures of up to 38°C were attained in full sun coffee at midday in the dry period. Leaf temperatures are generally higher than air temperatures since leaves are heated by absorbing solar radiation. Likewise, Chaves et al., (2008) recorded leaf temperatures of up to 35°C in sunlit leaves and Siles and Vaast (2002) recorded temperatures of above 25°C. Shaded coffee tended to have lower leaf temperatures than unshaded coffee during the dry period, with the difference ranging from an average of 1.2°C to 1.93°C. Jassogne et al. (2013) similarly observed that shade reduced temperatures in the coffee trees by up to 2°C. Baliza et al., (2012) found that leaf temperatures for both dry and rainy season were highest under full sun but declined with increase in shading level. Our results partly concur with the findings by Siles and Vaast (2002) who registered coffee leaf temperatures 2°C higher, in full sun during the dry season, than under *Eucalyptus deglupta* or *Terminalia ivorensis* shade. They further reported differences of up to 4°C in leaf temperatures during the wet season, whereas in this study no differences were observed among the different shade levels. Air temperature is one of the climatic factors, which has a major impact on the physiology of coffee. Exposure to temperatures of over 30°C for extended periods could lead to stunted growth and abnormalities such as yellowing of leaves. High temperatures during flowering, especially if combined with drought, may cause abortion of flowers. Conversely, low temperatures below 18°C result in depressed growth due to frost damage (DaMatta, 2004).

In the face of climate change and the resulting rainfall decline and increased fluctuations of temperature extremes, tree shade appears as an important climate adaptation coping strategy for small holder farmers. Shade could, thus, reduce the ecological and economic vulnerability of resource poor small holder farmers (DaMatta et al., 2007; Camargo, 2010).

3.5.3 Effect of shade on transpiration

Generally, shaded coffee had higher transpiration rate than coffee in full sun with the exception of the dry period in February/March 2012. The findings are comparable to those reported by van Kanten and Vaast (2006) who showed that, while coffee transpired more per unit leaf area in full sun, the diurnal water intake per hectare was higher under shade. They further observed that the annual pooled water transpiration by coffee and associated shade trees ranged from 20 to 250% more than sole coffee grown in full sun. Results of this study show that shade had a significant effect on transpiration rate during the dry and rainy seasons. The transpiration rate in both the dry and rainy period was higher in the morning and decreased in the course of the day. The transpiration rate was slightly higher during the dry period than during the rainy period. This was attributed to the higher vegetative growth of shade grown coffee plants than those in full sun. Baliza et al., (2012) also showed that shaded coffee had better growth. This agrees with the current study, where shaded plants had longer primary branches and larger leaves (Chapter 5 of this thesis). The transpiration rates were consistently higher in the morning hours and declined as the day progressed. The transpiration rates were, however, very low generally registering values below 1 mmol $m^{-2}s^{-1}$. The low transpiration could be attributed to the fairly high leaf temperatures that were registered during this study. As reported by Gates (1968), leaf temperature determines the vapour pressure deficit (VPD) within the leaf and is therefore the prime mover of transpiration. The results were supported by Hernandez et al., (1989) and Mayoli and Gitau (2012) who observed a strong and direct reaction of stomata to VPD. Van Kanten and Vaast (2006) found that coffee transpiration was restricted at higher VPD, recorded during the dry period, due to stomatal closure.

3.5.4 Effect of shade on stomatal conductance

During the dry and rainy period, the stomatal conductance was higher in the morning and decreased at midday and was generally lower, with few exceptions, in late afternoon. This agreed with the findings by Vaast et al., (2007) and Franck and Vaast (2009) who recorded higher stomatal conductance rates in the morning. Mohotti and Lawlor (2002) working with tea also reported that the stomatal conductance was greatest in the early morning between (8 h and 10.00 h), decreased towards midday and increased in the late afternoon. In the current study, the relationship between stomatal conductance and PAR was inconsistent. Other studies have shown that stomatal conductance decreased with increase in PAR and increasing global irradiance (van Kanten and Vaast, 2006; Chaves et al., 2008; Mayoli and Gitau, 2012). This reduction in stomatal conductance may be attributed to increasing air temperature around the coffee leaves as suggested by Larcher (2003), who demonstrated that stomatal conductance reacts to the plants' microclimatic conditions and plant water status. In our study, the stomatal conductance was generally higher under shaded coffee in both the dry and the rainy period. Similarly, Weidner et al., (2000) established that coffee leaves in permanent shade had higher stomatal conductance than sun-exposed ones. The current study shows that stomatal conductance was higher during the rainy period where it ranged from 0.017 to 0.063 µmol $m^{-2}s^{-1}$, while in the dry period it ranged from 0.005 to 0.045 µmol $m^{-2}s^{-1}$. In the current study, stomatal conductance was higher under shaded coffee with the highest rate being obtained at 80% shade level. Baliza et al., (2012) reported that stomatal conductance rates were highest in coffee under 35 and 50% shade, during the rainy period but found that the lowest stomatal conductance rates were obtained in coffee grown at 65 and 90% shade levels.

3.5.5 Effect of shade on photosynthetic rates

In this study, the photosynthetic rate was not significantly affected by shade. This finding is supported by Araujo et al., (2008) who found that there was no difference in photosynthetic rates between sun and shade leaves. In contrast, Pompelli et al., (2010) established that coffee underneath 50% shade had higher photosynthetic rates than plants under full sun in winter conditions. The rate of photosynthesis was higher in the dry season, in which the PAR was higher, than in the rainy period. The photosynthetic rates ranged from 1.10 to 4.33 mmol $m^{-2}s^{-1}$ during the dry period and 1.39 to 3.12 mmol $m^{-2}s^{-1}$ during the rainy period. In contrast, Baliza et al., (2012) found significant reduction in photosynthetic rates in the dry season. Increase in photosynthetic rate under high radiation has been reported in several studies (Friend, 1984; Fahl et al., 1994; Araujo et al., 2008; Chaves et al., 2008). In the current study, the values registered for photosynthetic rates were quite low ranging from 1.10 to 4.33 mmol $m^{-2}s^{-1}$. Chaves et al., (2008) found that, regardless of light treatment, coffee trees showed very low rates of photosynthesis (below 2.5 µmol $m^{-2}s^{-1}$). They attributed this to photo-inhibition during the cool, dry season and discrete, dynamic photo-inhibition during the warm, rainy season. Huner et al., (1998) also revealed that chronic photo-inhibition can significantly decrease plant productivity. Stomata characteristically close early in the morning in coffee trees. Stomatal conductance values as low as 10-20 mmol $m^{-2}s^{-1}$, due to high stomatal sensitivity to increase in vapour pressure deficit, have been recorded during the afternoon (Ronquim et al., 2006; Chaves et al., 2008). The low stomatal conductance constrains the CO_2 influx into the leaves thereby reducing the rate of photosynthesis during the afternoon (DaMatta and Ramalho, 2006).

3.6 Conclusion

This study showed that *Cordia africana* shade reduced PAR reaching the coffee tree, reduced leaf temperatures, and increased stomatal conductance and transpiration rates. *Cordia africana* shade had no effect on photosynthetic rates of the coffee trees.

CHAPTER FOUR: EFFECT OF *Cordia africana* SHADE ON SOIL NUTRIENT LEVELS AND PLANT NUTRIENT ACCUMULATION IN ARABICA COFFEE

4.1 Abstract

Soil fertility is essential in promoting the growth and productivity of coffee trees. Information on how shade trees influence soil nutrients levels and plant nutrient uptake in Kenya is, however, scarce. A field study was therefore carried out to determine the effect of *Cordia africana* shade on soil nutrient levels and plant nutrient accumulation. The trials were set up at the Kenya Agricultural and Livestock Research Organization's Coffee Research Institute (KALRO-CRI) demonstration farm and at two smallholder coffee farms in Namwela, Bungoma County. The three farms represented high, medium and low agronomic management level treatments, respectively. The management levels were categorized depending on field operations and externally applied inputs. The coffee plants were subjected to varying shade levels (%), which were based on the distance from the shade tree trunk; 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m and > 6 m (coffee trees under full sun) which were equivalent to 80, 70, 50, 30 and 0% shade respectively. Soil and plant nutrient analyses were conducted. Shaded soil had significantly higher soil pH, N, P, K, Ca and Mg contents than unshaded coffee. Soils under high agronomic management level had significantly lower pH than soils under medium and low management but had significantly higher total carbon, N, P, K, Ca and Mg. Accumulation of N and P in coffee berries and P in coffee branches significantly increased with increase in shade level. Shading coffee with *Cordia africana* trees enhances plant nutrient availability and uptake.

4.2 Introduction

Coffee places high demands on soil quality and nutrients are removed yearly by the harvested products (Snoeck and Vaast, 2004). Soil fertility is, therefore, the key factor that supports the growth and yield of coffee trees. Clearly, the nutrients taken up in the green beans are removed from the coffee field (Van der Vossen, 2005) and in several cases those contained in the cherry pulp and parchment are lost as well. The topsoil, the 30 cm upper layer, is predominantly rich in organic matter and it is in this layer that the bulk of the feeder roots are found (Snoeck and Vaast, 2004). The conservation of soil fertility and organic matter is essential for sustainable coffee production, especially where farmers apply little or no external inputs. This low input system which is highly dependent on organic matter mineralization for its nutrients, results in low coffee productivity if soil management is poor. In addition, shade trees contribute organic matter, which is important in maintaining soil fertility through its binding effect on soil nutrients and by creating conducive environment for beneficial microorganism like nitrogen fixers. Under high management level, nutrients are supplied by fertilizers, and weeds are managed through application of herbicides. With time, organic matter content of the soil is exhausted and mineral nutrients become unbalanced (Snoeck and Vaast, 2004).

Nitrogen (N) and potassium (K) are the principal nutrients, with K being important in fruit development and N for vegetative growth in coffee. The demand for P is lesser, but it is vital for root, flower bud and fruit development. Calcium (Ca), Mg and other major and micronutrients are often crucial for a balanced nutrition of the coffee plant, but are required in quantities that are usually minimal (Willson, 1985). Nitrogen is the most limiting nutrient in the coffee agro-ecosystem (Evizal et al. 2013) hence productivity of coffee is highly dependent on soil N availability. Under high agronomic management, N is provided by regular and intensive N fertilization to replenish that lost through yields and to ensure vegetative growth of the coffee trees. In contrast, little or no inorganic fertilizers are added under the low input management system. Consequently, N availability is reduced in the soils, which are low in organic matter and this leads to poor coffee growth and low yields (Wrigley, 1988; Pinard et al., 2014). Studies have established that N application enhances growth characteristics such as height, stem girth, length of primary branches and leaf expansion. It also improves coffee bean yields (Njoroge, 1992). The improvement in coffee yield due to N application reportedly leads to a reduction in the proportion of percentage grade ‘A’ beans (Njoroge, 1985). Potassium promotes assimilation of CO_2 and translocation of photosynthates (Willson, 1985). As a fruit crop, coffee has a high demand for potassium especially when fruits are developing and ripening during which time the leaf K content may decrease substantially (Oruko, 1977). While coffee yield responds positively to nutrient inputs, excessive application of fertilizers can lead to nutritional imbalances and toxicities (Castro-Tanzi et al., 2012).

Shade trees in coffee plantations can improve soil fertility through various ways. These include an increase in nutrient supply through N-fixation, reduced leaching by checking runoff, more efficient nutrient cycling by way of decomposition and improvement of soil physical properties thereby enhancing root growth (Buresh and Tian, 1997; Khanna, 1997; Wilson, 1985). The use of leguminous shade trees associated with coffee plantations is a common crop management practice in tropical countries (Baggio et al., 1997). In these systems, N-fixation and nutrient recycling are especially important in enhancing soil fertility and maintaining crop production (Harmand et al., 2007). Leaf accumulation of the major nutrients, except for Ca, was generally positively correlated with soil nutrient content.

Shade reportedly decreases the plant demand on soil nutrients through a reduction in flowering level, promotion of longer internodes, and reduction in number of fruiting nodes (Canell, 1975; Jaramillo-Botero et al., 2010). Conversely, high light intensity promotes a larger number of flower buds per node and higher number of internodes per coffee branch. It is therefore, envisaged that full sun plantations may require high levels of applied inputs to optimize yields; and these inputs are often associated with soil degradation and environmental pollution (Pinard et al., 2014). Furthermore, in Kenya most of the coffee is grown by resource poor small holder farmers who cannot afford the required inputs. Use of trees in coffee may therefore be a viable and economically feasible strategy to enable farmers to sustain their production.

The nutrient content of plant tissues, such as leaves, varies considerably depending on their position in the canopy, as influenced by the amount of exposure to the sun's radiation (Pushparajah, 1994). Light exposure also influences the maturation of coffee berries as shown by Vaast et al. (2006) who reported that coffee berries in full sun did not undergo complete maturation compared to those under shade. They suggested that shade decreased the overall temperature which delayed the maturing process allowing more time for the berries to fill. This implies that there would differences in the nutrient composition of the coffee berries in full sun and those under shade. The study is, therefore, is aimed at determining the effect of *Cordia africana* shade tree on soil nutrient levels and coffee plant nutrient accumulation.

4.3 Materials and Methods

4.3.1 Site

This study was conducted at the Kenya Agricultural and Livestock Research Organization – Coffee Research Institute demonstration (KALRO–CRI) plot in Namwela and two neighbouring farms from year 2010 to 2012. The demonstration plot is under high management while the neighbouring farms are under low and medium management. Namwela is located in Bungoma County at 0° 45'43N 34° 33'42E, 1641 metres above sea level and an average rainfall of 1329 mm. The rainfall pattern is unimodal, starting in March/April and ends in December. The site experiences a dry spell between November and April. The temperatures range from a minimum of 13 °C to a maximum of 27 °C. The soils are mainly humic acrisols which are moderately fertile, sandy and mildly acid.

4.3.2 Experimental treatments and design

The treatments consisted of the shade levels under different agronomic management regimes, namely high, medium and low. The shade level was based on distances from shade tree trunk, 0 – 1.5 m, 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6.0 m (full sun). The treatments were arranged as a 3 x 5 factorial in split plot design. The shade level and agronomic management were assigned as sub and main plot factors, respectively and replicated 7 times. The shade level (amount of light intercepted by the shade trees) was estimated by measuring photosynthetic photon flux density (PPFD) using a Line Quantum Sensor (LI- 191, LICOR Biosciences) at regular and increasing distances from the tree trunk as described by Vaast et al., (2007).

4.3.3 Soil analysis

Soil sampling was carried out during the dry season in February 2010. Representative samples were taken randomly from about 20 points, from a depth of 0 – 30 cm within all the experimental plots at all the sites, using a soil auger. The soil samples were then placed in different buckets and mixed thoroughly for homogenization. The soils were then air dried, after which they were ground using pestle and mortar, and sieved through an 850 µm mesh.

From this, 200 g samples were analysed for the following parameters: pH, total nitrogen (N), total carbon (C), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), phosphorus (P) and base index ratio (Ca+Mg/K). Soil pH was analysed using the $CaCl_2$ method (Anderson and Ingram, 1989); total N was determined by the Kjedahl Method (Motsara and Roy, 2008); P, K, Ca and Mg were analysed using procedures as outlined by Mehlich et al., (1962).

4.3.4 Plant tissue sampling and nutrient analysis

This study was carried out at the KALRO-CRI demonstration plot. Two coffee trees within each shade treatment were randomly selected and all leaves, berries and twigs removed from two selected branches as described by Shwab et al. (2007). The samples were collected from the mid-canopy of the uniform-cropping region of the tree (Coffee Research Institute's Technical Circular No. 202, 2009). The sampling was done before the onset of the rains in February 2009 and 2010. The samples were then cleaned gently with a soft brush, to remove any dust particles.

The leaf, berry and twig samples were separately oven dried at 70 °C for 48 hrs to attain constant weight. The samples were then ground in an electric stainless steel mill (Hummer Mill, Polymix PX-MFC 90D, Kinematica AG, Switzerland) using a 0.5 mm sieve. The cup and blades of the grinding mill were cleaned before grinding each different sample. The samples were then placed back in the oven and dried again to constant weight, and thereafter, stored in glass bottles for analysis. A mixture of nitric acid (HNO_3) and sulphuric acid (H_2SO_4) in a ratio of 9:4 was used for wet digestion of the samples. Approximately 1 g each of ground plant tissue samples were analysed for N, P, K, Ca and Mg. Each sample was placed in 100 ml volumetric flask, 10 ml of the acid mixture added and the content mixed by swirling. The flask was placed on a hotplate in the fume hood and heated up to about 150-200 °C. The heating continued until all the production of red NO_2 fumes stopped and the volume reduced to 3 – 4 ml and became colourless. After cooling the contents, the volume was made up to 15 ml with distilled water and filtered through Whatman No. 1 filter paper. This solution was used for N, P and K determination. The total N in the plant tissue was determined by the Kjedahl Method (Motsara and Roy, 2008). Determination of P was carried out colorimetrically by running on the vanadium phosphomolybdate complex. Potassium was determined on the flame emission channel of the Atomic Absorption Spectrophotometer Analytic JENA AAS Model at wavelength of 766.5 nm (Motsara and Roy, 2008).

To determine the content of calcium and magnesium, about 100 g of the different plant materials were dry-ashed (after pre-drying at 100 – 150 °C for 1 hr in the oven) in 50 ml Pyrex conical flasks at 450 °C in the muffle furnace overnight. Five (5) ml hydrochloric acid (1N HCl) was added and each sample transferred into 20 ml excelo tube. Two (2) ml of strontium chloride solution was added to the digests and made up to volume. The Ca in the digest solution was determined on the flame emission channel using AAS at a wavelength of 422.7 nm. For the determination of magnesium, 10 ml of the digest solutions were transferred into a 20 ml calibrated excelo tube. About 1 ml Strontium chloride solution and was added and diluted to 20 ml. Magnesium content was then determined using AAS at a wavelength of 285.2 nm.

4.3.5 Data analysis

All the data collected were subjected to analysis of variance using CoStat version 6.400 (1998-2008, Co Hort Software). Mean separation was performed using the least significant difference test at $p \leq 0.05$. Pearson's correlation analysis was done using XLSTAT 2015 Version 17.1.

4.4 Results

4.4.1 Soil chemical properties

The pH was significantly $p<0.05$ affected by shade level and agronomic management (Table 4.1). The interaction between shade level and agronomic management had no effect on soil pH. The soil pH decreased with increase in distance from the shade tree trunk (decrease in shade level). Soil under full sun had significantly a lower pH than shaded soil irrespective of distance from shade tree trunk (shade level). The pH for soils under high level agronomic management was significantly lower than for soil under medium agronomic management which, in turn, was significantly lower than for soil under low agronomic management.

Table 4.1: The effect of *Cordia africana* shade levels and agronomic management on soil pH

Distance (m) from shade tree trunk	Soil pH			
	Management level			
	High	Medium	Low	Mean
0 – 1.5	5.06	5.96	6.04	5.69
1.5 – 3.0	5.00	5.80	5.93	5.58
3.0 – 4.5	5.03	5.67	5.94	5.55
4.5 – 6.0	4.84	5.41	5.86	5.37
> 6 (Full sun)	4.80	5.20	5.30	5.10
Mean	4.95	5.61	5.81	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.0653			
$LSD_{0.05}$ (SL)	0.18			
$LSD_{0.05}$ (ML)	0.15			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	4.6			

Key: SL – Shade level, ML – Management level, NS – Not significant, ***significant at 0.1% level

The total carbon content was significantly ($p<0.05$) affected by the shade level and agronomic management (Table 4.2). The interaction between shade level and agronomic management had no significant effect on total carbon content. Soils under shade at 0 – 1.5 m and 1.5 – 3.0 m from shade tree trunk, had higher % C content than soils in full sun. There was no difference in carbon content among soils in full sun, 3.0 – 4.5 m and 4.5 – 6.0 m from shade tree trunk. Total carbon content ranged from 2.44% for soil in full sun to 2.91% for soil at 0 – 1.5 m from the shade tree trunk. The total C was significantly higher under high agronomic management and medium agronomic management than under low management. Carbon content ranged from 1.27% under low agronomic management to 3.45% under high agronomic management. However, the difference in % C between soils under high and medium management was not significant.

Table 4.2: The effect of *Cordia africana* shade level and agronomic management on soil total organic carbon content (%)

Distance (m) from shade tree trunk	Total soil organic carbon (%)			
	Management level			
	High	Medium	Low	Mean
0 – 1.5	3.64	3.55	1.53	2.91
1.5 – 3.0	3.49	3.33	1.45	2.76
3.0 – 4.5	3.42	3.30	1.35	2.69
4.5 – 6.0	3.38	3.28	1.03	2.56
> 6 (Full sun)	3.31	3.05	0.97	2.44
Mean	3.45	3.30	1.27	
P value (SL)	0.04*			
P value (ML)	0.0000***			
P value (SL x ML)	0.99			
$LSD_{0.05}$ (SL)	0.31			
$LSD_{0.05}$ (ML)	0.29			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	18.7			

Key: SL – Shade level, ML – Management level, NS - Not significant, * significant at 5% level, ***significant at 0.1% level

Shade level and agronomic management significantly affected nitrogen content (Table 4.3). The total N was higher in shaded soil than in unshaded soil. Generally, soil nitrogen decreased with increase in distance from shade tree trunk. The total N ranged from 0.10% (full sun) to 0.34% (0 – 1.5 m from the shade tree trunk). The soil under high agronomic management had significantly higher N% than the soil under medium agronomic management which, in turn had higher N% than the soil under low agronomic management. The average total N content ranged from 0.21% (low agronomic management) to 0.36% (high agronomic management).

Table 4.3: The effect of *Cordia africana* shade level and agronomic management on soil total nitrogen content (%)

Distance (m) from shade tree trunk	Soil total nitrogen content (%) Management level			
	High	Medium	Low	Mean
0 – 1.5	0.45	0.30	0.27	0.34
1.5 – 3.0	0.35	0.30	0.23	0.29
3.0 – 4.5	0.38	0.27	0.24	0.30
4.5 – 6.0	0.33	0.26	0.19	0.26
> 6 (Full sun)	0.28	0.21	0.12	0.20
Mean	0.36	0.27	0.21	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.86			
$LSD_{0.05}$ (SL)	0.05			
$LSD_{0.05}$ (ML)	0.04			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	30.2			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Shade level and agronomic management significantly affected the soil P content. However, the interaction between shade and agronomic management was not significant for this parameter (Table 4.4). Shaded soil (0 – 1.5 m and 1.5 – 3.0 m from the shade tree trunk) recorded higher P content than soil in full sun. The average soil P content ranged from 25.2 ppm (full sun) to 48.3 ppm (0 – 1.5 m from the shade tree trunk). The soil under high agronomic management had higher P content than soil under medium agronomic management which, in turn, had higher P content than soil under agronomic low management. The average soil P content ranged from 20.5 ppm (low agronomic management) to 53.1 ppm (high agronomic management).

Table 4.4: The effect of *Cordia africana* shade levels and agronomic management on phosphorus content (ppm)

Distance (m) from shade tree trunk	Soil phosphorus content (ppm) Management level			
	High	Medium	Low	Mean
0 – 1.5	61.7	52.1	31.1	48.3
1.5 – 3.0	55.7	43.6	23.7	41.0
3.0 – 4.5	49.1	30.6	20.3	33.3
4.5 – 6.0	50.3	29.0	19.4	32.9
> 6 (Full sun)	48.5	19.1	8.0	25.2
Mean	53.1	34.9	20.5	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.47			
$LSD_{0.05}$ (SL)	8.4			
$LSD_{0.05}$ (ML)	7.2			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	32.4			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Shade level and agronomic management significantly ($p<0.05$) influenced the soil K content. The interaction between shade level and agronomic management was also significant (Table 4.5). Shaded soil (0 – 1.5 m, 1.5 – 3.0 m and 3.0 – 4.5 m from the shade tree trunk) had higher K content than soil in full sun under high agronomic management. Generally, K content declined with increasing shade level (distance from the shade tree trunk). Under low and medium agronomic management, only 0 – 1.5 m had higher soil K than soil in full sun. The highest K content, 3.11 me %, was recorded at 0 – 1.5 m from shade tree trunk under high agronomic management whereas the lowest K content 0.59 me %, was recorded in soil under low agronomic management level in full sun.

Table 4.5: The effect of *Cordia africana* shade levels and agronomic management on soil potassium content (me %)

Distance (m) from shade tree trunk	Soil potassium content (me %)			
	Management level			
	High	Medium	Low	Mean
0 – 1.5	3.11	1.35	1.06	1.84
1.5 – 3.0	2.48	1.03	0.95	1.49
3.0 – 4.5	1.97	0.82	0.89	1.23
4.5 – 6.0	1.45	0.75	0.74	0.98
> 6 (Full sun)	1.19	0.71	0.59	0.83
Mean	2.04	0.93	0.85	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.0000***			
$LSD_{0.05}$ (SL)	0.23			
$LSD_{0.05}$ (ML)	0.23			
$LSD_{0.05}$ (SL x ML)	0.42			
CV (%)	29.2			

Key: SL – Shade level, ML – Management level, ***significant at 0.1% level

The soil Ca was significantly ($p<0.05$) affected by shade level and agronomic management (Table 4.6). The interaction effect between shade and agronomic management on soil Ca was significant ($p<0.05$). Shaded soils had significantly ($p<0.05$) higher Ca content than soils in full sun under the medium and low agronomic management levels, but there were no significant differences among the shading levels under high agronomic management. The highest soil Ca (26.2 me %) was recorded in full sun under high agronomic management and the lowest (1.7 me %), was recorded in full sun under low agronomic management. Generally, low agronomic management had significantly lower Ca content than medium agronomic management which, in turn, had lower Ca content than soil under high agronomic management.

Table 4.6: The effect of *Cordia africana* shade levels and agronomic management on soil calcium content (me %)

Distance (m) from shade tree trunk	Soil calcium content (me %) Management level			
	High	Medium	Low	Mean
0 – 1.5	24.0	15.9	5.6	15.1
1.5 – 3.0	24.7	21.5	4.6	16.9
3.0 – 4.5	25.1	19.2	4.3	16.2
4.5 – 6.0	25.4	18.6	2.2	15.4
Full sun	26.2	23.2	1.7	17.0
Mean	25.1	19.7	3.7	
P value (SL)	0.2039			
P value (ML)	0.0000***			
P value (SL x ML)	0.0041**			
$LSD_{0.05}$ (SL)	NS			
$LSD_{0.05}$ (ML)	2.33			
$LSD_{0.05}$ (SL x ML)	3.81			
CV (%)	19.7			

Key: SL – Shade level, ML – Management level, NS - Not significant, * *significant at 1% level, ***significant at 0.1% level

The soil Mg content was significantly ($p<0.05$) affected by shade levels, agronomic management and the interaction between shade and agronomic management (Table 4.7). Shaded soils (0 – 1.5 m from the shade tree trunk) had higher Mg content in the high and low management levels, than in full sun. Shading had no effect on soil Mg content under medium agronomic management. The highest soil Mg content (8.17 me %) was recorded at 0 – 1.5 m from the shade tree trunk under high agronomic management and lowest (0.94 me %) in soil under full sun under low agronomic management. Soils under high agronomic management had significantly higher Mg content than soil under medium agronomic management which, in turn, had significantly higher Mg content than soil under low agronomic management.

Table 4.7: The effect of *Cordia africana* shade levels and agronomic management on soil magnesium content (me %)

Distance (m) from shade tree trunk	Soil magnesium content (me %) Management level			
	High	Medium	Low	Mean
0 – 1.5	8.17	5.77	3.88	5.94
1.5 – 3.0	7.80	6.51	2.52	5.61
3.0 – 4.5	7.42	4.84	1.99	4.75
4.5 – 6.0	7.17	5.23	1.32	4.57
> 6 (Full sun)	7.03	5.80	0.94	4.59
Mean	7.52	5.63	2.13	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.0095**			
$LSD_{0.05}$ (SL)	0.59			
$LSD_{0.05}$ (ML)	0.68			
$LSD_{0.05}$ (SL x ML)	1.13			
CV (%)	18.7			

Key: SL – Shade level, ML – Management level, ** significant at 1% level, ***significant at 0.1% level

The cation base ratio index, Ca+Mg/K, was significantly ($p<0.05$) influenced by shade levels, agronomic management and interaction between shade and agronomic management (Table 4.8). The highest base ratio (40.8) was recorded in full sun under medium agronomic management and the lowest, (4.5) was recorded in full sun under low agronomic management. The base ratio index increased with increasing distance from the shade tree trunk (reducing shade level) under the high and medium agronomic management. The distance from the shade tree trunk had no effect on base index ratio under low agronomic management. The base index ratio was higher in medium than in high and low agronomic management across most of the shade levels.

Table 4.8: The effect of *Cordia africana* shade levels and agronomic management on soil base ratio Ca+Mg/K

Distance (m) from shade tree trunk	Soil base ratio Ca+Mg/K Management level			
	High	Medium	Low	Mean
0 – 1.5	11.0	17.9	10.2	13.1
1.5 – 3.0	13.4	31.8	7.6	17.6
3.0 – 4.5	17.8	40.5	7.8	22.0
4.5 – 6.0	22.9	35.2	5.6	21.2
> 6 (Full sun)	27.9	40.8	4.5	24.4
Mean	18.6	33.2	7.1	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.0000***			
$LSD_{0.05}$ (SL)	4.47			
$LSD_{0.05}$ (ML)	6.53			
$LSD_{0.05}$ (SL x ML)	9.51			
CV (%)	36.9			

Key: SL – Shade level, ML – Management level, ***significant at 0.1% level

Shading and the interaction between shade levels and agronomic management level had no effect on soil Na. The level of Na was affected significantly ($p<0.05$) only by management level (Table 4.9). Soil under low agronomic management level had significantly higher Na content than soil under medium management which in turn had lower Na content than soil under high management. However, there was no difference in soil Na content among the shade levels.

Table 4.9: The effect of *Cordia africana* shade level and agronomic management on soil sodium content (me %)

Distance (m) from shade tree trunk	Soil sodium content (me %)			
	Management level			
	High	Medium	Low	Mean
0 – 1.5	0.08	0.05	0.25	0.13
1.5 – 3.0	0.10	0.05	0.24	0.13
3.0 – 4.5	0.10	0.08	0.21	0.13
4.5 – 6.0	0.08	0.06	0.26	0.13
> 6 (Full sun)	0.10	0.02	0.20	0.11
Mean	0.09	0.05	0.23	
P value (SL)	0.84			
P value (ML)	0.0000***			
P value (SL x ML)	0.91			
$LSD_{0.05}$ (SL)	NS			
$LSD_{0.05}$ (ML)	0.01			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	66.8			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

The soil Mn content was significantly influenced by shade level and agronomic management the interaction between shade and agronomic management (Table 4.10). The highest soil Mn (1.30 me %) was recorded in full sun and the lowest (0.43 me %) was recorded at 0 – 1.5 m and 1.5 – 3.0 m away from the shade tree trunk under high agronomic management level. On average, soil under full sun had significantly higher Mn content than soil at 0 – 1.5 m from the shade tree trunk, while soil under medium and low agronomic management had higher Mn content than soil under high agronomic management.

Table 4.10: The effect of *Cordia africana* shade levels and agronomic management on soil manganese content (me %)

Distance (m) from shade tree trunk	Soil manganese content (me %) Management level			
	High	Medium	Low	Mean
0 – 1.5	0.43	1.05	0.91	0.80
1.5 – 3.0	0.43	1.03	0.82	0.76
3.0 – 4.5	0.55	0.89	1.10	0.85
4.5 – 6.0	0.46	1.16	0.80	0.81
> 6 (Full sun)	1.30	1.10	0.60	1.00
Mean	0.63	1.05	0.85	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.0000***			
$LSD_{0.05}$ (SL)	0.11			
$LSD_{0.05}$ (ML)	0.11			
$LSD_{0.05}$ (SL x ML)	0.20			
CV (%)	21.7			

Key: SL – Shade level, ML – Management level, ***significant at 0.1% level

4.4.2 Effect of *Cordia africana* shade on leaf, berry and branch nutrient accumulation

The content of the major elements in the leaves were not affected by the varying shade levels in both season 1 and 2 (Table 4.11). The nitrogen content ranged from 2.97 (full sun) to 3.24% (0 – 1.5 m from the shade tree trunk) and 2.96 (4.5 – 6.0 m from the shade tree trunk) to 3.39% (0 – 1.5 m from the shade tree trunk) in season 1 and 2 respectively.

Table 4.11: Effect of *Cordia africana* shade on nutrient (%) composition of coffee leaves

	Major elements									
	Season 1					Season 2				
Distance (m)	N	P	K	Ca	Mg	N	P	K	Ca	Mg
0 – 1.5	3.24	0.12	2.73	0.42	0.39	3.39	0.18	2.85	0.47	0.35
1.5 – 3.0	3.12	0.13	2.55	0.43	0.34	3.31	0.16	2.73	0.41	0.31
3.0 – 4.5	3.09	0.12	2.65	0.45	0.31	3.23	0.16	2.68	0.43	0.25
4.5 – 6.0	3.11	0.11	2.47	0.46	0.32	2.96	0.15	2.70	0.40	0.27
Full sun	2.97	0.10	2.39	0.35	0.29	3.01	0.16	2.66	0.38	0.28
P value	0.75	0.62	0.17	0.75	0.30	0.14	0.16	0.87	0.87	0.63
$LSD_{0.05}$ (SL)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	7.8	22.5	6.2	25.9	16.5	6.7	9.5	8.74	27.0	29.3

Key: SL – Shade level - based on distance (m), NS - Not significant

The effect of shade on nutrient composition of the coffee berries was not significant in season 1. In season 2, however, shade significantly ($p<0.05$) affected the content of N and P (Table 4.12). The N and P content in coffee berries in full sun was significantly lower than the level recorded in coffee at 0 – 1.5 m and 1.5 – 3.0 m away from the shade tree trunk; however, there was no difference in N content in berries in full sun and the shaded berries at 3.0 – 4.5 m and 4.5 – 6.0 m from shade tree trunk. Overall, the N values ranged from 2.08% (berries in full sun) in season 1 to 2.78% for berries on coffee trees at 0 – 1.5 m from the shade tree trunk in season 2. In season 2, the P level for berries in full sun was significantly ($p<0.05$) different from coffee berries at 0 – 1.5 m, 1.5 – 3.0 m and 3.0 – 4.5 m, but was not different from berries at 4.5 – 6.0 m from shade tree trunk. In season 1, the P content ranged from 0.10% in coffee berries under full sun to 0.25% for berries under shade at 0 – 1.5 m from the shade tree trunk.

Table 4.12: Effect of *Cordia africana* shade on nutrient (%) composition of coffee berries

Major elements										
Distance (m) from tree trunk	Season 1					Season 2				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
0 – 1.5	2.32	0.15	2.55	0.32	0.20	2.78	0.25	2.81	0.22	0.24
1.5 – 3.0	2.24	0.14	2.49	0.20	0.18	2.77	0.23	2.79	0.18	0.26
3.0 – 4.5	2.31	0.12	2.58	0.26	0.21	2.63	0.22	2.55	0.20	0.23
4.5 – 6.0	2.08	0.11	2.37	0.31	0.19	2.41	0.19	2.49	0.21	0.22
Full sun	2.10	0.10	2.40	0.23	0.18	2.43	0.18	2.45	0.21	0.24
P value	0.42	0.20	0.75	0.41	0.90	0.01**	0.03*	0.18	0.91	0.94
$LSD_{0.05}$ (SL)	NS	NS	NS	NS	NS	0.23	0.04	NS	NS	NS
CV (%)	8.4	19.8	9.1	31.8	24.4	4.7	10.3	7.8	25.5	23.8

Key: SL – Shade level - based on distance (m), NS - Not significant, * significant at 5% level, **significant at 1% level

The effect of shade on the nutrient elements of the branches, except for P content in season 1, was not significant in both seasons (Table 4.13). In season 1, the P content was significantly ($p<0.05$) lower in coffee branches under full sun than the branches under shade at 0 – 1.5 m and 1.5 – 3.0 m from the shade tree trunk, but was not different from the branches at 3.0 – 4.5 m and 4.5 – 6.0 m from the shade tree trunk. In season 1, P content ranged from 0.10% for coffee branches in full sun to 0.16% for branches on coffee trees at 1.5 – 3.0 m from the shade tree trunk.

Table 4.13: Effect of *Cordia africana* shade on nutrient (%) composition of coffee branches

	Major elements									
	Season 1					Season 2				
Distance (m)	N	P	K	Ca	Mg	N	P	K	Ca	Mg
0 – 1.5	1.45	0.14	1.54	0.33	0.14	1.44	0.14	1.56	0.32	0.17
1.5 – 3.0	1.42	0.16	1.39	0.31	0.16	1.30	0.12	1.38	0.35	0.15
3.0 – 4.5	1.50	0.13	1.40	0.30	0.12	1.33	0.13	1.35	0.34	0.14
4.5 – 6.0	1.39	0.11	1.36	0.24	0.11	1.31	0.12	1.34	0.31	0.14
Full sun	1.38	0.10	1.37	0.27	0.12	1.27	0.12	1.30	0.30	0.12
P value	0.89	0.03*	0.12	0.75	0.35	0.27	0.63	0.26	0.97	0.42
$LSD_{0.05}$ (SL)	NS	0.04	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	11.8	14.8	5.6	30.4	25.8	6.8	15.8	10.2	29.4	21.2

Key: SL – Shade level - based on distance (m), NS - Not significant, * significant at 5% level

4.4.3 Pearson's correlation between plant nutrient accumulation, yield and soil nutrients

The correlation coefficients for leaf nutrient accumulation, coffee yield, soil nutrient contents and are shown in Tables 4.14. Coffee yield was positively, but non-significantly, correlated with all leaf and soil nutrient contents except soil Ca. Soil N content positively and significantly ($p<0.05$) correlated with N, P and K and Mg accumulation in leaves. The correlation between leaf N and soil Ca was significant ($p<0.05$) but negative. Soil K and Mg significantly ($p<0.05$) and positively correlated with leaf accumulation of P and K. Soil P, K and Mg were significantly and positively correlated with leaf accumulation of Mg. Among the soil nutrients, K was positively and significantly ($p<0.05$) correlated with soil N, P and Mg while Ca was negatively and significantly correlated with N, P, K and Mg.

Table 4.15 shows the relationship between berry nutrient content, coffee yield and soil nutrients. The correlation between berry nutrient contents and coffee yield were not significant. Berry accumulation of N was positively and significantly ($p<0.05$) correlated with berry P, K, Mg and soil K and Mg. However, berry accumulation of K was significantly ($p<0.05$) and negatively correlated with soil Ca.

The correlation between branch accumulation of nutrients, yield and soil nutrient contents are presented in Table 4.16. Branch accumulation of P and Mg were significantly ($p<0.05$) and positively correlated with yield. Soil K and Mg were positively and significantly ($p<0.05$) with branch accumulation of P, Ca and Mg. Correlation between soil Ca and branch accumulation of P, however, was negative but significant ($p<0.05$). Branch accumulation of Mg was positively and significantly ($p<0.05$) correlated with soil P, K and Mg but negatively, though significantly correlated with soil Ca.

The Pearson's correlation between leaf and berry nutrient accumulation are shown in Table 4.17. Leaf N and P accumulation were positively and significantly ($p<0.05$) correlated with berry N, P and K accumulation. Leaf K accumulation was positively and significantly ($p<0.05$) correlated with berry P.

The correlation between branch and leaf nutrient accumulation are shown in Table 4.18. Branch N accumulation was significantly ($p<0.05$) and positively correlated with leaf K, while branch K was significantly ($p<0.05$) and positively correlated with leaf K and Mg. Branch Ca was significantly ($p<0.05$) and positively correlated with leaf N and P whereas branch Mg was significantly ($p<0.05$) and positively correlated with leaf N and P.

The Pearson's correlation coefficients between berry and branch nutrient accumulation are shown in Table 4.19. Berry N content was significantly ($p<0.05$) and positively correlated with branch P and Ca accumulation. Berry P and K content were significantly ($p<0.05$) and positively correlated with branch P, Ca and Mg content. Berry Mg content was significantly ($p<0.05$) and positively correlated with branch P and Ca content.

Table 4.14: Pearson's correlation coefficients for leaf nutrient accumulation, coffee yield and soil nutrient content

Variables	Yield	Leaf N	Leaf P	Leaf K	Leaf Ca	Leaf Mg	Soil N	Soil P	Soil K	Soil Ca
Leaf N	0.78									
Leaf P	0.81	0.99**								
Leaf K	0.57	0.95*	0.90*							
Leaf Ca	0.45	0.70	0.61	0.78						
Leaf Mg	0.67	0.83	0.82	0.81	0.44					
Soil N	0.51	0.92*	0.86	0.99**	0.83	0.76				
Soil P	0.73	0.88	0.86	0.84	0.50	1.00**	0.79			
Soil K	0.80	0.99**	0.98**	0.94*	0.66	0.89*	0.90*	0.93*		
Soil Ca	-0.77	-0.97**	-0.93*	-0.95*	-0.81	-0.85	-0.93*	-0.90*	-0.97**	
Soil Mg	0.81	0.98**	0.97**	0.92*	0.63	0.91*	0.88	0.95*	1.00*	-0.96**

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.15: Pearson's correlation coefficients for berry nutrient accumulation, coffee yield and soil nutrient content

Variables	Yield	Berry N	Berry P	Berry K	Berry Ca	Berry Mg	Soil N	Soil P	Soil K	Soil Ca
Berry N	0.78									
Berry P	0.83	0.95*								
Berry K	0.85	0.98**	0.99**							
Berry Ca	-0.34	-0.09	0.10	-0.05						
Berry Mg	0.68	0.96**	0.83	0.90*	-0.28					
Soil N	0.51	0.82	0.89*	0.83	0.49	0.67				
Soil P	0.73	0.74	0.89*	0.84	0.28	0.55	0.79			
Soil K	0.80	0.93*	0.99**	0.97**	0.16	0.79	0.90*	0.93*		
Soil Ca	-0.77	-0.87	-0.97**	-0.92*	-0.28	-0.69	-0.93*	-0.90*	-0.97*	
Soil Mg	0.81	0.91*	0.99**	0.96**	0.15	0.76	0.88	0.95*	1.00**	-0.96**

*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).

Table 4.16: Pearson's correlation coefficients for branch nutrient accumulation, coffee yield and soil nutrient content

Variables	Yield	Branch N	Branch P	Branch K	Branch Ca	Branch Mg	Soil N	Soil P	Soil K	Soil Ca
Branch N	0.35									
Branch P	0.89*	0.72								
Branch K	0.48	0.83	0.70							
Branch Ca	0.80	0.67	0.95*	0.58						
Branch Mg	0.94*	0.56	0.94*	0.74	0.83					
Soil N	0.51	0.97**	0.80	0.91*	0.69	0.71				
Soil P	0.73	0.64	0.78	0.92*	0.63	0.91*	0.79			
Soil K	0.80	0.80	0.94*	0.89*	0.85	0.94*	0.90*	0.93*		
Soil Ca	-0.77	-0.82	-0.92*	-0.87	-0.76	-0.90*	-0.93*	-0.90*	-0.97**	
Soil Mg	0.81	0.76	0.93*	0.90*	0.83	0.95*	0.88	0.95*	1.00**	-0.96**

*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).

Table 4.17: Pearson's correlation coefficients for leaf and berry nutrient accumulation

Variables	Leaf N	Leaf P	Leaf K	Leaf Ca	Leaf Mg	Berry N	Berry P	Berry K	Berry Ca
Leaf P	0.99**								
Leaf K	0.95*	0.90*							
Leaf Ca	0.70	0.61	0.78						
Leaf Mg	0.83	0.81	0.81	0.44					
Berry N	0.96*	0.98**	0.86	0.60	0.67				
Berry P	1.00**	0.99**	0.93*	0.69	0.84	0.95*			
Berry K	0.98**	1.00**	0.88	0.61	0.78	0.98**	0.99**		
Berry Ca	0.14	0.02	0.43	0.45	0.33	-0.09	0.10	-0.05	
Berry Mg	0.84	0.89*	0.71	0.44	0.47	0.96**	0.83	0.90*	-0.28

*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).

Table 4.18: Pearson's correlation coefficients for branch and leaf nutrient accumulation

Variables	Branch N	Branch P	Branch K	Branch Ca	Branch Mg	Leaf N	Leaf P	Leaf K	Leaf Ca
Branch P	0.72								
Branch K	0.83	0.70							
Branch Ca	0.67	0.95*	0.58						
Branch Mg	0.56	0.94*	0.74	0.83					
Leaf N	0.84	0.96**	0.86	0.89*	0.92*				
Leaf P	0.79	0.97**	0.83	0.93*	0.93*	0.99**			
Leaf K	0.95*	0.84	0.93*	0.73	0.77	0.95*	0.90*		
Leaf Ca	0.79	0.67	0.57	0.49	0.52	0.70	0.61	0.78	
Leaf Mg	0.59	0.72	0.92*	0.55	0.86	0.83	0.81	0.81	0.44

*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).

Table 4.19: Pearson's correlation coefficients for berry and branch nutrient accumulation

Variables	Berry N	Berry P	Berry K	Berry Ca	Berry Mg	Branch N	Branch P	Branch K	Branch Ca
Berry P	0.95*								
Berry K	0.98**	0.99**							
Berry Ca	-0.09	0.10	-0.05						
Berry Mg	0.96**	0.83	0.90*	-0.28					
Branch N	0.79	0.80	0.76	0.48	0.70				
Branch P	0.97**	0.97**	0.99**	-0.12	0.89*	0.72			
Branch K	0.73	0.85	0.78	0.52	0.56	0.83	0.70		
Branch Ca	0.98**	0.88*	0.95*	-0.29	0.98**	0.67	0.95*	0.58	
Branch Mg	0.87	0.94*	0.94*	-0.09	0.74	0.56	0.94*	0.74	0.83

*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).

4.5 Discussion

4.5.1 Effect of shade and agronomic management level on soil properties

In the current study, the total soil organic carbon increased with increase in shade levels. Similarly, Dossa et al., (2008) found that total C content under shaded coffee was higher than that for coffee grown in full sun. This is further supported by Evizal et al., (2012) who found that shaded coffee agro-ecosystems had higher soil organic C and total litter biomass (litter fall, coffee and shade tree pruning, and weed biomass). The higher soil C content may be attributed to the higher vegetative growth, hence higher litter fall and slower rate of decomposition under shade that leads to higher accumulation of organic matter in the soil. This view is corroborated in studies by Harmand et al., (2007) and Ehrenbergerová et al., (2015) who found that total carbon stock for coffee in agroforestry systems was markedly higher than for coffee monoculture systems in full sun. They similarly attributed the increase in total C to the increase in plant biomass and litter and hence C sequestration. Harmand et al., (2007) further reported that the change of coffee monoculture to agroforestry system caused a mean annual increment in aerial biomass ranging from 1 to 3.1 ton C ha^{-1} $year^{-1}$. The foregoing suggests that a shaded coffee system has the potential to sequester carbon and thereby mitigate of the consequences of climate change. Total C is often taken as the key pointer of soil quality and agronomic sustainability owing to its bearing on other physical, chemical and biological indicators of soil quality (Snoeck and Vaast, 2004; Reeves, 1997).

The total N, P, K, Ca and Mg levels were higher in soils under shade than in soils under full sun across all agronomic management levels. The concentration of the soil nutrients tended to increase with increase in shading level. Similarly, Pinard et al., (2014) reported that non-leguminous trees increased Ca, Mg and K concentrations in the soil. The positive effect on soil nutrients may be attributed to litter fall from the shade tree, *Cordia africana*, which provides good mulch and improves the soil physical and chemical properties (Orwa et al. 2009). These results agree with the general understanding that the presence of trees positively influences soil nutrient content (Jose, 2009). The ability of many trees to utilize nutrient pools deeper in the soils than crops would normally be able to access leads to increased nutrient capture efficiency. These nutrients are assimilated into the biomass of the trees and returned to the soil surface over time through litter fall, decomposition and mineralization processes thus making them available to the crops (Nair et al., 1999). Dossa et al. (2008) further submitted that given the possibility for competition between coffee and shade trees particularly under low soil fertility, shade trees should be pruned to increase organic matter and nutrient addition to the soil. In contrast, De Souza et al. (2012) observed no difference in soil properties between shade and full sun.

In the current study, *Cordia africana* shade increased N and P content in coffee berries and P content in branches. Shade, however, had no effect on the accumulation of major nutrients in coffee leaves. Pushparajah, (1994) observed considerable variation in the nutrient content of plant tissues, such as leaves, in relation to their position in the canopy as influenced by the amount of exposure to the sun rays. Generally, soil N was positively correlated with leaf, berry and branch nutrient accumulation of the major nutrients namely N, P, K, Ca and Mg. It is well established that adequate supply of N stimulates rapid plant development through the proliferation in number of leaves, number of nodes and branches per plant (Willson, 1985; Fahl et al., 1994; Carelli et al., 2006). This implies that the more N availability approaches the optimal content in the soil, the more the other major elements would increasingly be required to complete the metabolic processes that promote growth. This may explain the positive correlations of soil N with the other parameters.

In this study, soil Ca was negatively correlated with leaf, berry and branch accumulation of N, P, K, Ca and Mg. Likewise, Ramalho et al., (1995) observed associated increases in the concentrations of K^{+}, Mg^{2+} and Na^{+} in leaves and roots, with the decrease in calcium concentration. Likewise, Silva et al., (2013) found a negative correlation between foliar Ca and coffee yield variables. This may be explained by the role that calcium plays as a secondary messenger, in regulating various cell and plant functions, where it assists in nutrient uptake. Therefore, the negative correlation between soil Ca and other plant nutrients may be that, as it depletes, the uptake of other nutrients is enhanced.

Soils under high agronomic management were more acidic than those under medium agronomic management which, in turn, were more acidic than that under low agronomic management. The change in soil pH may be attributed to the application of inorganic fertilizer. This is in agreement with Clark et al., (1998) who reported a higher soil pH under low input system than under conventional system where fertilizers such as diammonium phosphate (DAP) and urea were applied. Total N, total carbon, exchangeable K, Ca, Mg and P were higher under high agronomic management than under medium and low agronomic management. This may be explained by the frequent and intensive fertilizer applications under high agronomic management to improve crop growth and yield. In contrast, the application of less than recommended rates of inorganic fertilizers under the medium agronomic management and none at all under the low agronomic management could have led to lower soil nutrients. Nitrogen is the most limiting nutrient in the coffee agro-ecosystem (Evizal et al., 2013) hence the productivity of coffee is highly dependent on soil N availability.

Total C was twice as high under high and medium agronomic management as under low agronomic management. This may be attributed to the higher vegetative growth that contributed to the higher organic carbon content under high and medium agronomic management compared to the low agronomic management level. In Chapter Five of this study, the significantly higher vegetative growth and yield under high agronomic management than under medium and low agronomic management has been demonstrated. Comparable observations were made by Wrigley (1988) and Pinard et al., (2014) who reported poor coffee growth under low input system was as a result of low soil organic matter.

4.6 Conclusion

Shading with *Cordia africana* increased soil pH and soil nutrient contents of total C, N, P, K, Mg and Mn, regardless of the agronomic management, but had no effect on soil Ca and Na. Shading resulted in higher accumulation of N and P in coffee berries and P in coffee branches. However, shade had no significant effect on the accumulation of other major nutrients in coffee leaves.

CHAPTER FIVE: EFFECT OF *Cordia africana* SHADE AND AGRONOMIC MANAGEMENT ON GROWTH AND YIELD OF ARABICA COFFEE

5.1 Abstract

Coffee's an important export crop in Kenya, however, the sector has been experiencing some challenges among them being high cost of production, decline in soil fertility associated with falling levels of soil organic matter, depletion of soil nutrients and mono-cropping. Studies carried out elsewhere have shown that use of shade improves yields and quality especially under low input and adverse weather conditions, without loss in coffee quality. In Kenya, information on the effect of *Cordia africana* shade on coffee production is quite limited. A study was, therefore, conducted to investigate the impact of *Cordia africana* shade and agronomic management level on growth, yield and % grade 'A' beans of coffee variety K7. The trials were set up at the Kenya Agricultural and Livestock Research Organization's Coffee Research Institute (KALRO-CRI) demonstration farm and at two smallholder coffee farms in Namwela, Bungoma County. The three farms represented high, medium and low agronomic management level treatments, respectively. The different shading levels were based on the distances from the trunk of the shade tree: 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m and > 6 m (full sun), equivalent to 80, 70, 50, 30 and 0% shade levels, respectively. The experimental design was a split plot, with agronomic management as main plot treatment and shading level as the sub-plot treatment. Shade levels and agronomic management had significant effects on the length of primary branches, number of nodes on primary branches, coffee yield and % Grade 'A' beans. Coffee yields were significantly higher under high agronomic management level than under medium and low agronomic management levels. Shaded coffee had significantly higher clean bean yields than un-shaded coffee under medium and low management levels. The % grade A beans among shading levels in high and

low management levels were not different. At higher shading levels, 80% and 70% (0 – 1.5 m, and 1.5 – 3.0 m from shade tree trunk respectively), coffee had significantly higher % Grade ‘A’ coffee beans than under un-shaded conditions. These findings suggest that shading can be used to enhance coffee yields without loss in raw bean quality, especially under smallholder low input conditions.

5.2 Introduction

The coffee sector plays a significant role in Kenya’s economy. Besides contributing to foreign exchange earnings, it also provides employment, household incomes and food security. The Coffee Research Foundation (CRF) estimates that 600,000 households derive their livelihood directly from coffee farming while nearly 200,000 households are either in permanent or seasonal employment (CRF, 2010a). Most of the coffee in Kenya (USAID, 2010), as in many areas of the world (Lin, 2007), is grown by small scale farmers under rain-fed conditions and in a mono-cropping system. This production system currently faces several constraints which include limited land availability, drought, declining soil fertility and high production costs mainly due to high costs of agrochemical inputs and labour (CRF, 2010a).

Coffee originated from the shaded forests of Southern Western Ethiopia where it is thought to have developed as an under-storey crop (Wintgens, 2004). The area has an altitudinal range of 1600 – 2800 m, with average annual temperatures of 20°C, rainfall of 1600-2000 mm with a cool dry season of 3-4 months (DaMatta, 2004). According to DaMatta (2004), early plantations were shaded using over-storey trees in order to simulate its natural habitat since coffee was considered shade-obligatory. However, it was soon established that coffee could be grown without shade, especially under optimal conditions, but with high amounts of agrochemical inputs (Beer et al., 1998). This open grown, intensive production system is considered unsustainable as result of the unstable and low market prices, reduction in longevity of coffee plants, soil degradation and ground water pollution (Bote and Struik, 2011). Hence, there is a need for new production systems which would not only guarantee increased farm profitability and stability but also put greater emphasis on crop mixtures and system diversification. The integration of shade, timber, fruit and other trees is one such strategy that could achieve this (Bote and Struik, 2011; Vaast et al., 2006).

Several studies (Somporn et al., 2012; Vaast et al., 2007; Beer et al., 1998) carried out in regions such as Asia and Central America have shown that shade has several potential advantages. Under sub-optimal conditions, shade trees protect the coffee trees by moderating the effects of adverse climatic conditions, thereby providing a more suitable micro-climate for coffee production (Vaast et al., 2005). Shade trees help to recycle soil nutrients from deep layers in the soil to the coffee rooting top soil through litter fall, which acts as mulch that preserves soil moisture and reduces soil erosion by reducing raindrop impact. The litter, on decomposition, provides organic matter improving soil fertility and physical properties (Amoah et al., 1997). This shade tree-coffee system may further utilize the soil nutrients and water more efficiently than in a coffee monocrop system. It has been observed that shading increases coffee bean size (Somporn et al., 2012; Geromel et al., 2008; Vaast et al., 2006; Muschler, 2004). Shade also reportedly reduces the portion of rejects which include diseased, mummified or dried berries. In Costa Rica, Muschler, (1998) reported that rejects accounted for up to 10% in the un-shaded samples and less than 1% under shade. On the other hand, Pinard et al. (2014) found that shade did not increase or improve the final quality grading of green coffee beans; neither did it delay coffee berry maturation nor reduce alternate bearing pattern. Shade trees may also compete for light, water and nutrients with coffee trees and can alter conditions for incidences of pests and diseases (Staver et al., 2001; DaMatta, 2004; Mouen Bedimo et al., 2012). As a consequence of the multidimensional and diverse interactions, the shade effect on coffee production often differs according to sites, coffee varieties and shade tree species (Beer et al. 1998; Vaast et al. 2007; Hagar et al. 2011).

In East Africa, studies on the effect of shade on coffee production are disjointed and quite dated (Tapley, 1961; McClelland, 1935; Sturdy, 1935). As demonstrated in the foregoing, shade is thought to be beneficial under sub optimal conditions that include unfavourable climate and low inputs. This study was, therefore, conducted to determine the effect of agronomic management and shade levels on coffee growth, yield and quality.

5.3 Materials and Methods

5.3.1 Description of study sites

This study was conducted at the KALRO-CRI demonstration plot in Namwela and at two surrounding small holder farms within the area from January 2010 to December 2012. The sites chosen had similar climatic and soil conditions due to their close proximity, being within a 5 km radius. Namwela is located in Bungoma County at 0° 45’43N 34° 33’42E, 1641 m above sea level and receives an average rainfall of 1329 mm; average maximum and minimum temperatures of 27°C and 13.1°C respectively. The soils are moderately fertile, sandy and mildly acid humic acrisols (Jaetzold et al., 2005). The annual rainfall and mean maximum and minimum temperature data recorded during the trial are shown in Appendix 1. The highest rainfall of 1485.4 mm was received in 2010, followed by 1235.5 mm in 2011 and 1165.5 mm in 2012.

5.3.2 Coffee and shade tree variety

In all the sites, the traditional coffee variety K7 spaced at 2.74 m x 2.74 m was used in the study. The K7 cultivar is a selection from “French Mission” coffee. This variety is the most commonly grown in the study area. The cultivar has resistance to some races of coffee leaf rust (CLR) and partial resistance to coffee berry disease (CBD).

The shade tree variety used, *Cordia africana* Lam, is a small to medium sized evergreen tree that grows up to 30 m. It is heavily branched with a spreading umbrella shaped or rounded crown which provides excellent shade for tree crops (Orwa et al., 2009). It is the predominant shade tree used in Bungoma County.

5.3.3 Experimental treatments and design

The treatments consisted of five shade levels, based on the distances of coffee plants from the trunk of the shade tree: 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m and >6 m (full sun), equivalent to 80, 70, 50, 30 and 0% shade level; and three management levels (high, medium and low). The treatments were arranged as a 3 x 5 factorial in split plot design. The shade level and management level were assigned as sub and main plot factors, respectively, and replicated 7 times. Each replicate comprised one shade tree surrounded by coffee plants. The effects of the shading levels were evaluated by selecting four coffee plants, in an east-west orientation, for each of the four distances from the shade tree trunk; 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m. For the treatments in full sun treatments, recordings were made on four plants randomly selected from a block of 36 coffee plants in the un-shaded plots.

5.3.4 Agronomic management level

The agronomic management levels were categorized into three (high, medium and low) depending on field operations and externally applied inputs as described by Mugo (2010). Based on these criteria, the demonstration plot was under high agronomic management level where the coffee trees were managed using all the recommended practices (CRF, 2013) for optimum production. The coffee trees used in the study were established in 1955 and were in the 4th year of the productive cycle (CRF, 2013). The main crop is focused on the March to April flowering and therefore NPK compound fertilizers, 20:10:10, were applied earlier in October (6 months before flowering) at the rate of 250 g/coffee tree. Foliar applications of Boron and Zinc were also applied, at the rate of 3 kg/ha, 3 months before flowering. After the main flowering in March/April, the first round of Calcium Ammonium Nitrate (CAN) fertilizer at the rate of 100 g/tree was applied. Two more rounds of CAN applications were made at 4 weeks interval giving a total of 300 g/tree per annum, (3 equal split applications). Pruning of the coffee trees was undertaken in January of 2010 and 2011. This involved the removal of unwanted branches to concentrate growth of the desired branches. Major insect pests such as Antestia bugs and thrips were controlled using Dursban 480 EC (active ingredient: chlorpyrifos) at the rate of 1000 ml/Ha. Weeds were managed by application of Roundup® herbicide (glyphosate 36%) which was applied during the rainy period when the weeds were young. The *Cordia africana* shade trees were established in the same year as the coffee trees. Under medium agronomic management level, the coffee was in its 5th year of production after change of cycle, whereas the *Cordia africana* shade was planted in 1957. The external inputs applied included farm yard manure at the rate of 6 kg/tree and 20:10:10 NPK compound fertilizers at the rate of 150 g/tree. For control of insect pests the farmer occasionally applied insecticides, such as Durban® 480 EC at the rate of 1000 ml/Ha (20 ml in 20 litre knapsack). The coffee was routinely intercropped with common bean (*Phaseolus* *vulgaris* L.). Under the low management level, there was no application of external inputs at all. The coffee was also in its 5th year of production, after change of cycle, and the *Cordia africana* shade was established in 1959. The farm was also routinely intercropped with common bean.

5.3.5 Coffee growth and bean yield

Data collected included primary branch length extension, total number of nodes and clean coffee bean yield. The coffee primary branch growth was taken as the average increase in the length of six primaries per plot. The primaries, selected from the middle canopy, had initially been tagged at three nodes from the tip. The measurements were recorded every three months for a period of one year. The difference in primary length between two consecutive recording dates was the actual increase in primary length. The total number of nodes per primary was obtained as the average number of nodes per primary.

To determine clean coffee bean yield, fully ripe cherries, as indicated by the bright red colour of the skin, were harvested from the four effective trees in each treatment. The fresh weight of cherries was taken at each harvest. The cherries were processed using standard wet processing procedures (CRF, 2010b; Mburu, 2004). The parchment was hulled to produce clean coffee.

5.3.6 Coffee grade

The green coffee bean size was determined using a coffee grader (Wm McKinnon, Aberdeen Scotland). The proportion of green coffee retained by a screen size of > 6.75 mm, referred to as grade ‘A’ beans, was calculated.

5.3.7 Data analysis

All the data collected were subjected to analysis of variance using CoStat version 6.400 (1998-2008, Co Hort Software). Mean separation was done using the least significant difference test at $p \leq 0.05$. Regression analysis, using XLSTAT 2015 Version 17.1, was conducted to establish the relationship between coffee bean yield and physiological parameters.

5.4 Results

5.4.1 Coffee growth, yield and raw bean quality

Shade levels and agronomic management had significant ($p < 0.05$) effects on primary branch length extension (Table 5.1). However, interaction between shade and agronomic management had no effect on the primary branch length extension. Primary branch extension was significantly higher at 0 – 1.5 m from the shade tree trunk (equivalent to 80% shade) than under full sun and at all other distances from the shade tree trunk in 2010 and 2011 (Table 5.1 and 5.2). Primary branch extension was significantly lower in full sun than in most of the shade treatments in 2010 and 2011. A significantly higher primary branch extension was observed for coffee under high agronomic management than under medium and low agronomic management levels. No difference in primary branch length extension was observed between medium and low management. The primary branch extension ranged from 24.3 to 34.8 cm in 2010 and from 31.8 to 46.5 cm in 2011.

Table 5.1: The effect of *Cordia africana* shade and agronomic management on mean primary branch length extension (cm), January– December 2010

Distance (m) from shade tree trunk	Mean primary branch length extension (cm) Management level			
	High	Medium	Low	Mean
0 – 1.5	40.3	30.8	33.4	34.8
1.5 – 3.0	37.6	30.5	26.2	31.4
3.0 – 4.5	34.8	26.7	24.1	28.5
4.5 – 6.0	32.7	22.1	23.8	26.2
> 6 (Full sun)	32.8	21.5	18.5	24.3
Mean	35.6	26.3	25.2	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.4390			
$LSD_{0.05}$ (SL)	3.0			
$LSD_{0.05}$ (ML)	3.3			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	16.6			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Table 5.2: The effect of *Cordia africana* shade and agronomic management on mean primary branch length extension (cm), January – December 2011

Distance (m) from shade tree trunk	Mean primary branch length extension (cm) Management level			
	High	Medium	Low	Mean
0 – 1.5	61.9	40.7	37.0	46.5
1.5 – 3.0	56.9	40.0	36.7	44.5
3.0 – 4.5	57.3	35.0	31.8	41.4
4.5 – 6.0	48.4	36.5	29.6	38.2
> 6 (Full sun)	41.1	32.0	22.4	31.8
Mean	53.1	36.8	31.5	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.7803			
$LSD_{0.05}$ (SL)	6.2			
$LSD_{0.05}$ (ML)	6.5			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	25.0			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Shade levels and agronomic management had significant ($p<0.05$) effects on the total number of nodes per coffee branch (Table 5.3 and 5.4). However, there was no interaction effect between shade level and the agronomic management. Generally, the number of nodes increased significantly as the distance away from the shade tree trunk increased in both years. In 2010, coffee under full sun recorded a higher number of nodes than coffee at all shade levels, except that at 4.5 – 6.0 m from the shade tree trunk (equivalent to 30% shade). In 2011, coffee under full sun had significantly higher number of nodes than shaded coffee regardless of the intensity of shade. Total number of nodes per branch was significantly lower under low level management than under medium and high agronomic management levels in 2010 and 2011 (Table 5.3 and 5.4). Medium agronomic management had a lower number of nodes than high agronomic management in 2011.

Table 5.3: The effect of *Cordia africana* shade and agronomic management on total number of nodes per plant, January– December 2010

Distance (m) from shade tree trunk	Total number of nodes per plant Management level			
	High	Medium	Low	Mean
0 – 1.5	8.6	7.3	5.7	7.2
1.5 – 3.0	8.3	8.6	6.9	7.9
3.0 – 4.5	10.1	9.4	7.1	8.9
4.5 – 6.0	11.4	9.6	8.2	9.7
Full sun	12.0	10.0	8.1	10.0
Mean	10.1	9.0	7.2	
P value (SL)	0.0000***			
P value (ML)	0.0004***			
P value (SL x ML)	0.6250			
$LSD_{0.05}$ (SL)	1.0			
$LSD_{0.05}$ (ML)	1.1			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	19.2			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Table 5.4: The effect of *Cordia africana* shade and agronomic management on total number of nodes per plant, January– December 2011

Distance (m) from shade tree trunk	Total number of nodes per plant Management level			
	High	Medium	Low	Mean
0 – 1.5	9.7	8.4	6.3	8.1
1.5 – 3.0	9.9	8.9	6.6	8.5
3.0 – 4.5	9.6	9.1	8.4	9.0
4.5 – 6.0	11.0	9.6	8.3	9.6
Full sun	14.0	10.0	9.0	11.0
Mean	10.8	9.2	7.7	
P value (SL)	0.0002***			
P value (ML)	0.0000***			
P value (SL x ML)	0.3341			
$LSD_{0.05}$ (SL)	1.3			
$LSD_{0.05}$ (ML)	0.8			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	22.5			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Shade levels and agronomic management had significant ($p<0.05$) effects on coffee yields in 2010 and 2011 (Tables 5.5 and 5.6). However, the interaction between shade level and agronomic management was significant only in 2010. The coffee yields under high management level were significantly higher than that under medium and low management levels in 2010 (Table 5.5). Under medium management, coffee at 0 – 1.5 m and 1.5 – 3.0 m from the shade tree trunk had significantly higher bean yield than coffee in full sun. Coffee yield was significantly higher under high management level than under medium and low management levels across all the shade levels. No difference was observed between medium and low management levels in yield across all the distances from the tree trunk. On average, shaded coffee yielded significantly ($p<0.05$) higher than coffee under full sun. The yield advantage of shaded coffee over coffee under full sun varied from 9.7% (4.5 – 6 .0 m from shade tree) to 54% (1.5 – 3.0 m from shade tree) in 2010 (Table 5.5) and 50.5% (0 – 1.5 m from shade tree) to 70.8% (1.5 – 3.0 m from shade tree) in 2011 (Table 5.6). There were no significant differences in yield of shaded coffee among the different shading levels. Coffee yield under high management level was 2.4 and 3.2 times the yield under medium and low management levels, respectively. On average, the yields recorded under high, medium and low management level were 1282, 608 and 432 kg/ha, respectively in 2010 and 1333, 545 and 423 kg/ha in 2011 respectively. On average, the coffee yield gap between high and low agronomic management ranged from 850 kg/ha in 2010 to 910 kg/ha in 2011.

Table 5.5: The effect of *Cordia africana* shade and agronomic management on coffee yield (kg/ha) – 2010

Distance (m) from shade tree trunk	Coffee yield (kg/ha) Management level			
	High	Medium	Low	Mean
0 – 1.5	1327	765	446	846
1.5 – 3.0	1589	819	492	967
3.0 – 4.5	1094	644	477	738
4.5 – 6.0	1032	544	492	689
Full sun	1365	266	252	628
Mean	1282	608	432	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.0005***			
$LSD_{0.05}$ (SL)	133.1			
$LSD_{0.05}$ (ML)	222.5			
$LSD_{0.05}$ (SL x ML)	302.9			
CV (%)	28			

Key: SL – Shade level, ML – Management level, ***significant at 0.1% level

Table 5.6: The effect of *Cordia africana* shade and agronomic management on coffee yield (kg/ha) - 2011

Distance (m) from shade tree trunk	Coffee yield (kg/ha) Management level			
	High	Medium	Low	Mean
0 – 1.5	1403	485	426	772
1.5 – 3.0	1342	699	586	876
3.0 – 4.5	1441	637	460	846
4.5 – 6.0	1455	599	433	829
> 6 (Full sun)	1021	306	211	513
Mean	1333	545	423	
P value (SL)	0.0000***			
P value (ML)	0.0000***			
P value (SL x ML)	0.7940			
$LSD_{0.05}$ (SL)	148.1			
$LSD_{0.05}$ (ML)	180.8			
$LSD_{0.05}$ (SL x ML)	NS			
CV (%)	31.4			

Key: SL – Shade level, ML – Management level, NS - Not significant, ***significant at 0.1% level

Shade levels and agronomic management had significant ($p<0.05$) effects on percentage grade 'A' beans in both season 1 (Table 5.7) and season 2 (Table 5.8). A significant interaction for % grade 'A' was observed between shade levels and agronomic management. In full sun, the coffee generally had lower percentage of grade 'A' beans. Coffee in full sun recorded significantly ($p=0.05$) lower % grade 'A' beans than shaded coffee at all distances from the tree trunk under low management, shaded coffee at 1.5 – 3.0 m and 4.5 – 6.0 m from shade tree trunk under medium management, and shaded coffee at 1.5 – 3.0 m and 3.0 – 4.5 m away from shade tree trunk, under high management. Shading improved % grade 'A' relative to full sun by a range of 44.5% to 78.5% under low agronomic management, 3.1 to 12.8% under medium agronomic management and -2.3% to 7.1% under high agronomic management. There were no differences in % grade 'A' beans among the agronomic management in shaded coffee at 0 – 1.5 m, 1.5 – 3.0 and 3.0 – 4.5 m from the shade tree trunk in 2011. However, coffee in full sun and that at 4.5 – 6.0 m, from shade tree trunk, had higher % grade 'A' beans under high and medium agronomic management than coffee under low agronomic management (Table 5.8).

Table 5.7: The effect of *Cordia africana* shade and agronomic management on % grade 'A' beans - 2010

Distance (m) from shade tree trunk	% grade 'A' beans Management level			
	High	Medium	Low	Mean
0 – 1.5	84.5	87.2	90.8	87.5
1.5 – 3.0	87.8	86.5	80.5	85.0
3.0 – 4.5	88.5	85.0	80.7	84.7
4.5 – 6.0	76.6	85.6	81.5	81.2
> 6 (Full sun)	78.9	80.2	71.0	76.7
Mean	83.3	84.9	80.9	
P value (SL)	0.0000***			
P value (ML)	0.0196*			
P value (SL x ML)	0.0033**			
$LSD_{0.05}$ (SL)	3.63			
$LSD_{0.05}$ (ML)	4.03			
$LSD_{0.05}$ (SL x ML)	6.21			
CV (%)	7.12			

Key: SL – Shade level, ML – Management level, * significant at 5% level, ** significant at 1% level, ***significant at 0.1% level

Table 5.8: The effect of *Cordia africana* shade and agronomic management on % grade 'A' beans - 2011

Distance (m) from shade tree trunk	% grade 'A' beans Management level			
	High	Medium	Low	Mean
0 – 1.5	82.9	81.7	87.1	83.9
1.5 – 3.0	83.2	87.2	84.9	85.1
3.0 – 4.5	77.5	79.7	73.2	76.8
4.5 – 6.0	79.2	86.4	70.5	78.7
> 6 (Full sun)	76.9	77.3	48.8	66.7
Mean	80.0	82.5	72.9	
P value (SL)	0.0000***			
P value (ML)	0.0001***			
P value (SL x ML)	0.0000***			
$LSD_{0.05}$ (SL)	4.42			
$LSD_{0.05}$ (ML)	3.31			
$LSD_{0.05}$ (SL x ML)	7.60			
CV (%)	9.16			

Key: SL – Shade level, ML – Management level, ***significant at 0.1% level

Regression analysis revealed no significant relationships between coffee yield and photosynthetically active radiation (Figure 5-1), leaf temperature (Figure 5-2), transpiration rate (Figure 5-3), stomatal conductance (Figure 5-4), photosynthetic rate (Figure 5-5).

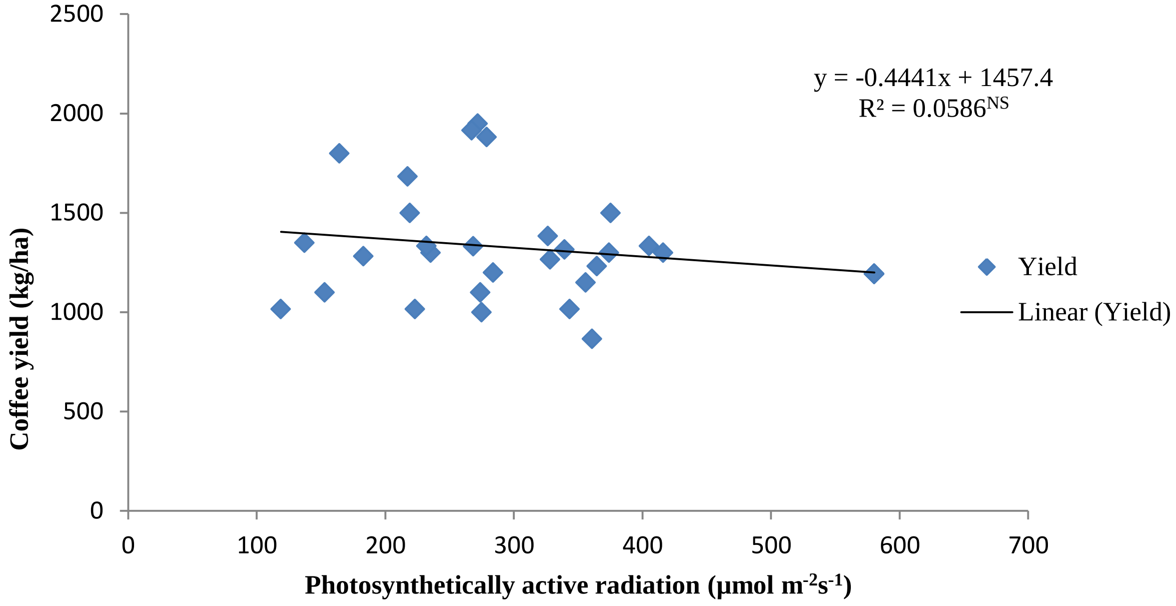


Figure 5-1: Linear regression analysis curve showing the relationship between photosynthetically active radiation and coffee yield at the Namwela Demo plot. NS – Not significant

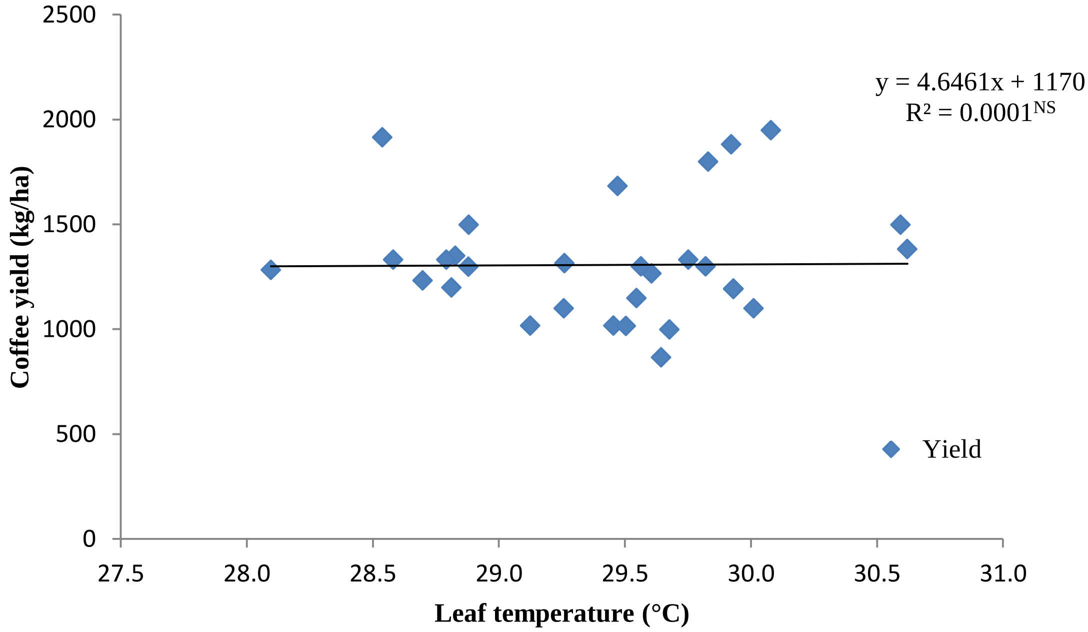


Figure 5-2: Linear regression analysis curve showing the relationship between leaf temperature (°C) and coffee yield (kg/ha) at the Namwela Demo plot. NS – Not significant

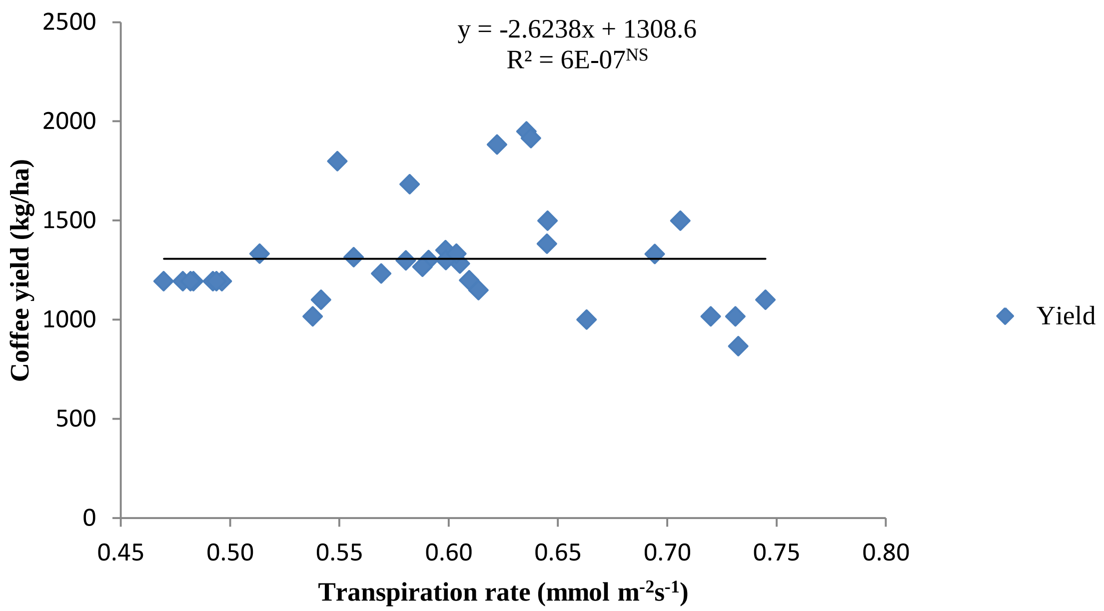


Figure 5-3: Linear regression analysis curve showing the relationship between transpiration rate (µmol $m^{-2}s^{-1}$) and coffee yield (kg/ha) at the Namwela Demo plot. ^{NS} – Not significant

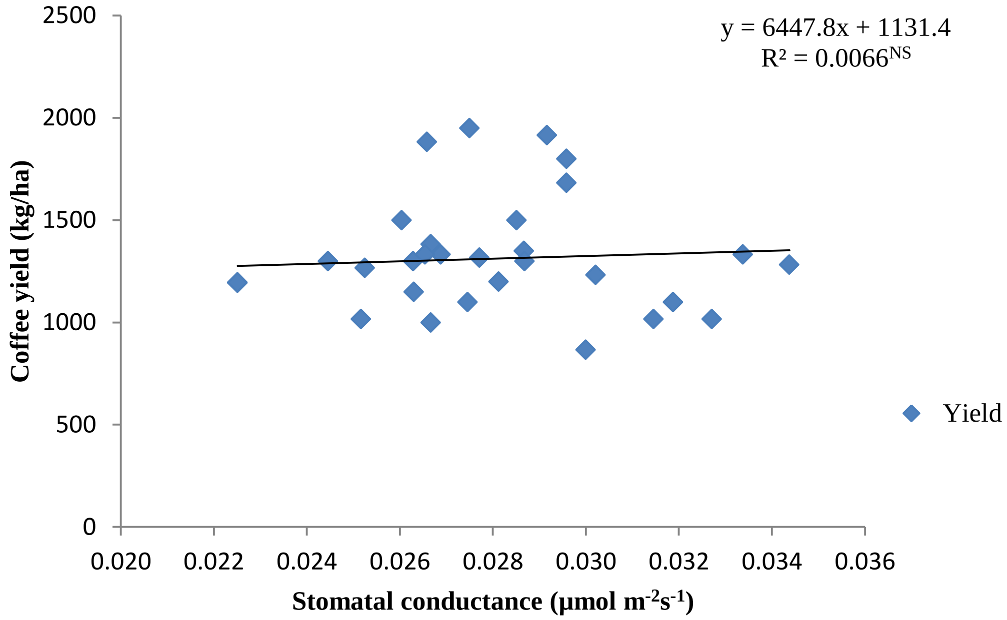


Figure 5-4: Linear regression analysis curve showing the relationship between stomatal conductance (µmol $m^{-2}s^{-1}$) and coffee yield (kg/ha) at the Namwela Demo plot. ^{NS} – Not significant

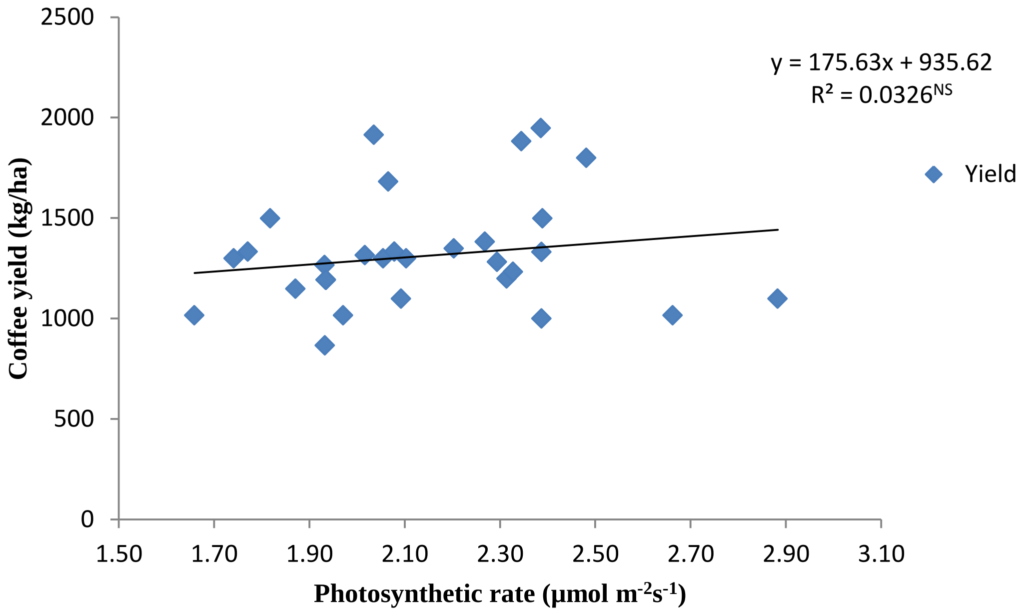


Figure 5-5: Linear regression analysis curve showing the relationship between photosynthetic rate (µmol $m^{-2}s^{-1}$) and coffee yield (kg/ha) at the Namwela Demo plot. ^{NS} – Not significant

5.5 Discussion

The number of nodes increased with decrease in shade level, with coffee under full sun registering a higher number of nodes than coffee under shade. This is explained by coffee's physiological response to shade. In shaded situations, under optimal production conditions, light is hypothesised as the limiting factor. High light level produces higher number of flower buds per node and higher number of nodes per coffee branch (Youkhana and Idol, 2010). Conversely, branch length growth increased with increasing shade level with full sun recording the lowest branch length growth. Previous studies by Kimemia (2004) have also shown that shade promoted higher vegetative growth in coffee. Muschler, (2004) observed that with comparable nutrition, shaded plants tended to be larger, more robust and had higher leaf retention compared to plants in full sun. This effect was more distinct under marginal conditions for the production of coffee. On the other hand, shade favours longer nodes and reduces number of internodes (Vaast et al., 2007; Cannell, 1975). Cannell (1975) further indicated that the foremost component of yield was the number of nodes formed. The major adverse effect shade has on coffee yield appears to be lower flower initiation hence a lower number of fruitful nodes on a branch (Franck, 2005). As explained by Cannell (1985), coffee produces a small number of flowers in shaded environment and, therefore, it has not evolved satisfactory mechanisms to maintain its fruiting load proportional to the available nutrients when grown in full sunshine. This may explain the higher coffee yield obtained under shade in low input conditions.

As would be expected, coffee plants under high management levels recorded better growth than those under medium and low management levels. Under high management levels, the primary branch growth was higher and total nodes per branch were more than those under medium and low management. This was attributed to better nutrition, through applied fertilizers and protection against insect pests and diseases. Similar findings have been reported by Njoroge (1992) and Willson (1985) who observed that growth characteristics such as plant height, length and total shoots of primary branches, leaf area and total nodes were enhanced with the application of N alone or in combination with P and K.

In terms of production, coffee under high management level out-yielded coffee under medium and low management level in both crop years. Under medium and low level management regimes shaded coffee had significantly higher yields than coffee in full sun. In contrast, shade had no effect on coffee yield under high management. Similarly, Vaast et al., (2007) found that coffee under sub-optimal conditions benefitted more from shade. Somporn et al., (2012) and Youkhana and Idol (2010) also reported an increase in bean yield and 1000-bean weight as shade level increased. Shaded plantations may therefore require lower levels of inputs than un-shaded plantations under the same climatic conditions. However, further studies need to be carried out to determine the most appropriate shading levels, shade trees and their management.

In the current study, the yield gap between well managed coffee and poorly managed coffee varied from 850 kg/ha in 2010 to 910 kg/ha in 2011. Yield gaps between farms on different management levels on the one hand and between farms and research stations still exist (Karanja, 1992; USAID, 2010; Okibo and Mwangi, 2013) suggesting a huge potential for the improvement of coffee production in Kenya. The Kenya National Bureau of Statistics (Economic Survey, 2011) in years 2005 to 2010 showed that the estates sector, with an average 6-year yield of 548.4 Kg/ha clean coffee, was 2.5 times higher than the small holder co-operative sector (218.2 Kg/ha clean coffee). Studies by USAID (2010) showed that the average annual clean coffee production, from 2004 to 2009 was 289 kg/ha. Under research conditions, yields of 15 kg/tree are routinely achieved (CRF, 2012), whereas the average yield per tree for estates is about 3 kg and 1.2 kg for cooperative sector. The yield gaps may be attributed mainly to the lack of investment by the small-holder producer, who cannot afford costly farm inputs which has led to reduced coffee productivity and poor quality. However, in the current study, the productivity of shaded coffee under low agronomic management was 25% higher than coffee in full sun. The percentage grade ‘A’ was also higher under shade than in full sun. This finding has important implications in that the promotion of shade in coffee has the potential to improve coffee productivity without the need for heavy capital investment.

5.6 Conclusion

Shade promoted higher vegetative growth regardless of the agronomic management level. Use of shade, especially under medium and low agronomic management level, resulted in higher yields and higher percentage grade 'A' coffee beans. This study shows that shade can be used to boost coffee yields without loss in raw coffee quality, primarily under low input conditions. Therefore, the main challenge is to develop cost-effective technologies that would enhance productivity while enhancing or maintaining the quality for which Kenya coffee is renowned. Such simple and sustainable production systems such as use of shade, is what is required to be developed and disseminated to farmers.

CHAPTER SIX: EFFECT OF *Cordia africana* SHADE AND AGRONOMIC MANAGEMENT ON BIOCHEMICAL COMPONENTS OF ARABICA COFFEE

6.1 Abstract

Coffee cup quality is based on categorization of various factors that are correlated to the biochemical content of roasted coffee beans. Although the environment is essential in determining the expression of the biochemical components, studies on how they are affected by shade and agronomic management are scarce. A study was, therefore, conducted to evaluate the effect of *Cordia africana* shade and agronomic management on the biochemical components of coffee beans. The shade level was based on distances from shade tree trunk, 0 – 1.5 m, 1.5 – 3.0 m, 3.0 – 4.5 m, 4.5 – 6.0 m and > 6.0 m which were equivalent to 80, 70, 50, 30 and 0 %(full sun), respectively. The study was carried out at the KALRO-CRI demonstration plot in Bungoma County, representing high management level, and two small holder farms neighbouring the Institute plot, representing medium and low management levels, respectively. Fully ripe cherries were harvested, wet processed and the wet parchment dried to moisture content of 10.5 to 11%. Caffeine, trigonelline, total chlorogenic acids (CGA), oil and sucrose were determined. The results showed that biochemical components were affected significantly shade and management levels. Caffeine content ranged from 1.47% dry weight (dwb) basis under high agronomic management, to 0.59% dwb under low agronomic management. Highest mean oil content of 18.99% dwb, was obtained under high agronomic management, and the lowest, 15.79% dwb, was recorded under low agronomic management. Mean trigonelline content ranged from 1.54% dwb under high agronomic management level in shade and lowest, 0.56% dwb obtained under low management. The mean sucrose content ranging from the highest, 11.76% dwb and the lowest, 7.43% dwb, were all obtained under high agronomic management. Mean chlorogenic acid content ranged

from the lowest, 4.82% dwb under low management level to the highest, 9.59% dwb in full sun under high management level. Most of the biochemical components were positively correlated with shade and management levels. This presented the possibility of manipulating the two parameters to enhance the quality of coffee.

6.2 Introduction

Coffee is a perennial evergreen tropical plant, which belongs to the family *Rubiceae* and the genus *Coffea* (Davies et al., 2006). Raw coffee beans comprise an extensive variety of diverse chemical compounds which interrelate during coffee processing to produce an end product that is even more variable and intricate in structure (Clifford, 1985). The distinct flavour of brewed coffee is undoubtedly the main motivation for its widespread acceptance and almost worldwide demand as a stimulating beverage (Petracco, 2001). The beverage quality is based on the description of several factors including taste and aroma (Kathurima et al., 2009) which are associated with biochemical contents of coffee beans.

Coffee quality is the result of intricate interactions between the environment, the agronomic management and the coffee plant (Somporn et al., 2012). In the coffee bean, the biochemical composition is inherent (Montagnon et al., 1998; Leroy et al., 2006; Mayoli and Gitau, 2012) and plant growth conditions (Viani, 2001). The biochemical compounds give distinctive odour or taste to edible plants and offer adaptive properties to plants such as contributing to resistance to diseases and pests (Dessalegn, 2005; Gichimu et al., 2014). The key biochemical compounds in coffee are caffeine, oils, trigonelline, sucrose and chlorogenic acids (Farah et al., 2006; Gichimu et al., 2014).

Climate, altitude, and shade have a profound effect on flowering, bean biochemical composition and maturity through their effect on temperature, availability of light and water. Shade, or conditions that imply lower air temperatures such as higher elevations, delay the maturity of coffee berries permitting adequate time for complete bean filling (Vaast et al., 2006), giving in beans that are heavier and more intense in flavour than those grown under lower altitudes or in full sunlight. The slower ripening process, therefore, is essential in ensuring high cup quality, probably by ensuring the full expression of all biochemical phases needed for the development of the beverage quality (Silva et al., 2005). Vaast et al., (2006) observed that shade resulted in an increase in size and improvement in the biochemical composition of the coffee bean through delayed ripening by one month. Other authors (Muschler, 2004; Geromel et al. 2008; Bosselmann et al., 2009; Bote and Struik, 2011; Somporn et al., 2012) have reported similar positive effects of shade on coffee biochemical composition. In contrast, Avelino et al., (2007) found that coffees produced from unshaded trees produced better cup quality than shaded, which was appreciated more by tasters, and the results were corroborated with biochemical data.

Shade also reportedly reduces the portion of rejects which include diseased, mummified or dried berries. In Costa Rica, Muschler (1998) reported that discards accounted for up to 10% in the full sun samples and below 1% under shade. In the current study, as presented in Chapter 4 of this thesis, the shaded coffee produced higher % grade ‘A’ beans than coffee in full sun. Although coffee biochemical quality attributes are intrinsic, the environment, which includes agronomic management, is important in their manifestation (Leroy et al., 2006). Caffeine content, for example, is genetically defined but it is also influenced by external factors (Pearl et al., 2004). Good growing conditions, which include proper pruning and nutrition, tends to produce larger coffee beans with better flavour (Wintgens, 2004). In South

America, Dessalegn (2005) reported that coffee grown with substantial application of nitrogen fertilizer had higher caffeine content, than that from unfertilized fields. Therefore, this study was conducted to evaluate the effect of shade and management levels on the biochemical components of coffee beans.

6.3 Materials and Methods

6.3.1 Study site

This study was conducted at the KALRO–CRI demonstration plot in Namwela and two surrounding small holder farms within the area from year 2010 to 2012. Namwela is located in Bungoma County at 0o 45’43N 34o 33’42E, 1641 metres above sea level, an average rainfall of 1329 mm. The sites chosen had similar climatic and soil conditions due to their proximity. The three farms represented high, medium and low management level treatments.

6.3.2 Experimental treatments and design

The treatments were shade and agronomic management levels. The different shading levels were based on the distances from the trunk of the shade tree: 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m and > 6 m (full sun). The experimental design was a split plot, with management level as main plot treatment and shade level as the sub-plot. The shading level was estimated by measuring the Photosynthetic Photon Flux Density (PPFD) in μmol m^{-2} s^{-1} using a Line Quantum Sensor (LI-COR Biosciences) and expressing it as a percentage of that obtained in full sun as described by Vaast et al. (2007). The agronomic management levels were categorized depending on field operations and externally applied inputs as described by Mugo (2010). Based on these criteria, a coffee plot under high management level was managed using all the recommended practices by Coffee Research Foundation (CRF, 2013) for optimum production. Under medium management level, the external inputs applied included farmyard manure and inorganic fertilizers; and pesticides (insecticides and fungicides for the control of insect pests and diseases respectively). Under the low management level, there was no application of external inputs.

6.3.3 Processing of samples

Fully ripe cherries were harvested from four trees in each of the plots in each site during the year 2010/11and 2011/12 seasons. The cherries were bulked and wet processed using standard procedures (Mburu, 2004). The cherry samples were pulped, fermented, washed and the wet parchment dried to final moisture content of 10.5 to 11%. The parchment coffee was hulled and graded based on size, shape and density (Gichimu et al., 2012) and grade AB was used for the subsequent analysis in the study. Fifty (50) grams of dry coffee beans per treatment from each of the sites were frozen at -80°C and later ground to <0.5mm particle size in liquid nitrogen using an analytical mill (Model A10 IKA work inc. Wilmington, NC, USA).

6.3.4 Biochemical analysis

Caffeine, trigonelline and total chlorogenic acids (CGA) were extracted concurrently from 3 g of green coffee powder using ethanol and acetone (24:1v/v) and shaking in the dark for 24 hours. Caffeine, trigonelline and CGA were analysed using a HPLC system (KNEUR) equipped with a Supel Co. Discovery column and a diode array detector at three wavelengths, 278 nm for caffeine, and 266 nm for trigonelline and 324 nm for CGA. Sucrose was extracted from green coffee powder using the method of Osborne and Voogt (1978) with modifications. About 2.5 g of the green coffee powder was weighed and put into a round bottomed flask. Extraction was done for one hour in 100 ml of 96% ethanol (AR) under reflux. The extract was cooled and filtered through Whatman filter paper number 42 and evaporated to dryness. Sucrose was recovered with 10 ml de-ionized water and 2 ml of the extract mixed thoroughly with 2 ml Diethyl ether (AR) left to settle and the top layer discarded. This was repeated three times. One millilitre of the clarified extract was mixed with 1 ml of acetonitrile and filtered through a 0.45 µm micro filter (Chromafil). Sucrose was analysed using a HPLC system (KNEUR) equipped with a Eurospher 100-5 NH_2 column and a refractive index detector. The mobile phase was acetonitrile HPLC grade (SCHARLAU) 75%, and distilled water 25% at a flow rate 1 ml/min under ambient temperature. Caffeine, trigonelline, CGA and sucrose were identified by comparing the retention times of standards and their concentrations calculated from peak areas using calibration equations. Crude oil was analysed following the Association of Official Analytical Chemists (AOAC, 1995) method.

6.3.5 Data analysis

The biochemical data obtained were subjected to analysis of variance at 5% level of significance using Costat version 6.400 (1998-2008, Co Hort Software) statistical program. Least significant difference (LSD) was used to separate the means. Correlation and regression analysis was done using XLSTAT 2015 Version 17.1.

6.4 Results

Shade levels and agronomic management significantly affected caffeine content % (dry weight basis) in season 1 and 2 (Table 6.1). The interaction between shade levels and agronomic management had a significant ($p=0.05$) effect on caffeine content only in the first season. In season 1, shaded coffee had significantly higher caffeine content than coffee under full sun across the management levels. Increase in shade level under medium and low management led to an increase in caffeine content but different shade levels at high agronomic management had similar caffeine content. Caffeine content was not affected by agronomic management under high (80%) shade level. Caffeine content was significantly lower under low management than under medium and high agronomic management across all the shade levels except at 0 – 1.5 m from shade tree trunk. On average, in both seasons, high agronomic management level had significantly higher caffeine content than medium agronomic management level which, in turn, had higher caffeine content than the low agronomic management level.

Table 6.1: Mean caffeine content (% dry weight basis) in green coffee under different levels shade and agronomic management

	Caffeine content (% dry weight basis) Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	1.25	1.26	1.15	1.22	1.44	1.35	1.17	1.32
1.5 – 3.0	1.21	1.17	0.91	1.10	1.47	1.39	1.17	1.34
3.0 – 4.5	1.26	1.11	0.61	0.99	1.34	1.35	1.17	1.29
4.5 – 6.0	1.20	1.02	0.62	0.95	1.35	1.30	1.15	1.27
Full sun	1.01	0.82	0.59	0.81	1.31	1.28	1.16	1.25
Mean	1.19	1.08	0.78		1.38	1.33	1.16	
P value (ML)	0.0034**				0.0040**			
P value (SL)	0.0000***				0.0025**			
P value (ML x SL)	0.0000***				0.1084			
$LSD_{0.05}$(ML)	0.08				0.04			
$LSD_{0.05}$ (SL)	0.05				0.04			
$LSD_{0.05}$ (ML x SL)	0.10				NS			
CV (%)	3.77				2.64			

Key: ML – Management level, SL – Shade level; NS - Not significant, ** significant at 1% level

Shade levels and agronomic management significantly ($p<0.05$) influenced the mean oil content (% dry weight basis) (Table 6.2). However, significant interactions between shade and agronomic management levels were only observed in season 1. In season 1, high management level had higher oil content than medium and low agronomic management levels across the shading levels. However, there no was significant (p<0.05) difference in oil content between medium and low agronomic management levels except at 4.5 – 6.0 m away from the shade tree trunk in which the former outperformed the latter. In season 2, the highest mean oil content, 18.77% dwb was recorded under high agronomic management and the lowest, 17.72% dwb, was recorded under low agronomic management level. Shaded coffee, on average, recorded higher mean oil content than coffee grown under full sun.

Table 6.2: Mean oil content (% dry weight basis) in green coffee under different shade levels and agronomic management

	Oil content (% dry weight basis) Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	17.57	16.42	16.59	16.86	18.99	18.20	18.41	18.53
1.5 – 3.0	17.62	16.36	16.51	16.83	18.80	18.16	18.04	18.33
3.0 – 4.5	17.07	16.25	16.20	16.51	18.97	18.48	17.82	18.42
4.5 – 6.0	16.78	16.67	15.81	16.42	18.83	18.18	17.41	18.14
Full sun	16.71	15.94	15.79	16.15	18.27	18.30	16.94	17.84
Mean	17.15	16.33	16.18		18.77	18.26	17.72	
P value (ML)	0.0100*				0.0038*			
P value (SL)	0.0001***				0.0281*			
P value (ML x SL)	0.0125*				0.1768			
$LSD_{0.05}$ (ML)	0.32				0.20			
$LSD_{0.05}$ (SL)	0.22				0.42			
$LSD_{0.05}$ (ML x SL)	0.44				NS			
CV (%)	1.05				1.85			

Key: ML – Management level, SL – Shade level; NS - Not significant, * significant at 5% level, ***significant at 0.1% level

Shade level significantly (p<0.05) influenced trigonelline content in season 1 and season 2. Agronomic management levels affected the trigonelline content only in season 1 (Table 6.3). However, there were significant (p<0.05) interactions between shade and agronomic management in both seasons. In season 1, agronomic management level had no effect on trigonelline content in coffee grown under at 0 – 1.5 m, 1.5 – 3.0 m and 3.0 – 4.5 m from shade tree trunk (80, 70 and 50% shade respectively). However, coffee under low agronomic management level had lower trigonelline content than coffee under high and medium agronomic management in full sun and at 4.5 – 6.0 m from shade tree trunk (50% shade level). On average, the increase in shading level across the agronomic management led to an increase in the trigonelline content.

In season 2, agronomic management had no effect on trigonelline across the shading levels except at 0 – 1.5 m and 1.5 – 3.0 m from the shade tree trunk (80 and 70% shade, respectively). Shaded coffee had higher trigonelline content than coffee in full sun in both seasons. The trigonelline content, in season 2, ranged from 1.54% dwb under high agronomic management (0 – 1.5 m from the shade tree trunk) to 1.08% dwb under medium agronomic management (full sun) and in season 1, it ranged from 1.20% dwb under medium agronomic management level to 0.56% dwb under low management level in full sun (Table 6.3).

Table 6.3: Mean trigonelline content (% dry weight basis) in green coffee under different shade levels and agronomic management

	Trigonelline content (% dry weight basis)							
	Management level							
Distance (m) from	Season 1				Season 2			
shade tree trunk	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	1.16	1.20	1.10	1.15	1.54	1.47	1.27	1.43
1.5 – 3.0	1.06	1.03	0.97	1.02	1.29	1.44	1.19	1.31
3.0 – 4.5	1.04	1.04	0.95	1.01	1.29	1.18	1.21	1.23
4.5 – 6.0	1.03	1.02	0.64	0.90	1.16	1.15	1.16	1.16
Full sun	0.87	0.75	0.56	0.73	1.14	1.08	1.11	1.11
Mean	1.03	1.01	0.84		1.28	1.26	1.19	
P value (ML)	0.0352*				0.1054			
P value (SL)	0.0000***				0.0000***			
P value (ML x SL)	0.0276*				0.0265*			
$LSD_{0.05}$ (ML)	0.12				NS			
$LSD_{0.05}$ (SL)	0.08				0.08			
$LSD_{0.05}$ (ML x SL)	0.17				0.15			
CV (%)	6.85				4.94			

Key: ML – Management level, SL – Shade level; NS - Not significant, * significant at 5% level, ***significant at 0.1% level

Shade level and agronomic management significantly ($p<0.05$) influenced the sucrose content (Table 6.4). The interaction between shade and agronomic management significantly affected this parameter only in season 2. In the first season, shaded coffee at all distances from the shade tree trunk had lower sucrose content than coffee in full sun. The higher shade level (0 – 1.5 m from tree trunk) had higher sucrose content than coffee at 4.5 – 6.0 m from shade tree trunk. Coffee under high agronomic management had higher sucrose content than coffee under medium agronomic management which in turn had higher sucrose content than coffee under low agronomic management. In season 2, increase in shade level reduced sucrose content under high agronomic management. High agronomic management had significantly higher sucrose content than medium and low agronomic management in both seasons. The sucrose content ranged from 7.43% to 11.76% dwb level at 0 – 1.5 m from shade tree trunk and in full sun, respectively, under high agronomic management in season 2 (Table 6.4).

Table 6.4: Mean sucrose content (% dry weight basis) in green coffee under different levels shade and agronomic management

	Sucrose content (% dry weight basis)							
	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	8.47	8.16	7.70	8.11	7.43	9.58	8.03	8.35
1.5 – 3.0	8.63	8.44	8.19	8.42	8.52	9.24	8.29	8.68
3.0 – 4.5	8.39	8.19	8.05	8.21	9.22	9.94	8.05	9.07
4.5 – 6.0	8.89	8.09	8.57	8.52	11.16	9.40	9.17	9.91
Full sun	9.41	8.92	8.48	8.94	11.76	9.76	9.29	10.27
Mean	8.76	8.36	8.20		9.62	9.58	8.57	
P value (ML)	0.0026**				0.0108*			
P value (SL)	0.0008***				0.0000***			
P value (ML x SL)	0.2419				0.0001***			
$LSD_{0.05}$ (ML)	0.09				0.38			
$LSD_{0.05}$ (SL)	0.31				0.48			
$LSD_{0.05}$ (ML x SL)	NS				0.81			
CV (%)	2.96				4.10			

Key: ML – Management level, SL – Shade level; NS - Not significant, * significant at 5% level, **significant at 1%, ***significant at 0.1% level

Shading level significantly ($p<0.05$) affected the content of chlorogenic acids in both seasons (Table 6.5). In both seasons, shaded coffee had lower chlorogenic acid content than coffee under full sun. Agronomic management influenced the chlorogenic acids content in season 1 only. There was significant interaction between shade levels and agronomic management in season 2. Coffee under high agronomic management had higher chlorogenic content than medium and low management level. In season 2, management level had no effect on chlorogenic acid under 0 – 1.5 m and 1.5 – 3.0 m, 3.0 – 4.5 m and 4.5 – 6.0 m from shade tree trunk. However, under full sun, high management level had significantly higher chlorogenic acids than medium and low management levels.

Table 6.5: Mean chlorogenic acid content (% dry weight basis) in green coffee under different shade levels and agronomic management

	Chlorogenic acid content (% dry weight basis) Management level							
	Season 1				Season 2			
Distance (m)	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	6.10	5.20	4.82	5.37	6.38	7.20	5.43	6.34
1.5 – 3.0	6.41	6.16	5.44	6.00	6.77	7.26	6.91	6.98
3.0 – 4.5	6.33	5.98	6.00	6.10	7.97	7.12	7.52	7.54
4.5 – 6.0	6.48	6.25	5.64	6.12	8.34	7.38	7.41	7.71
Full sun	6.89	6.37	6.38	6.55	9.59	7.51	7.33	8.14
Mean	6.44	5.99	5.66		7.81	7.29	6.92	
P value (ML)	0.0236*				0.1371			
P value (SL)	0.0012**				0.0001***			
P value (ML x SL)	0.4987				0.0080**			
$LSD_{0.05}$ (ML)	0.37				NS			
$LSD_{0.05}$ (SL)	0.43				0.56			
LSD (ML x SL)	NS				1.31			
CV (%)	5.63				6.10			

Key: ML – Management level, SL – Shade level; NS - Not significant, * significant at 5% level, **significant at 1%, ***significant at 0.1% level

6.4.1 Correlation coefficients between biochemical variables, shade and management levels

The correlation coefficients of biochemical variables showing effect of management levels are shown in Table 6.6. Management was positively and significantly ($p<0.05$) correlated with caffeine and oil content. Caffeine was positively and significantly correlated with oil, trigonelline and chlorogenic acids. Oil was positively and significantly ($p<0.05$) correlated with trigonelline and chlorogenic acids. Sucrose and chlorogenic acids were positively and significantly ($p<0.05$) correlated.

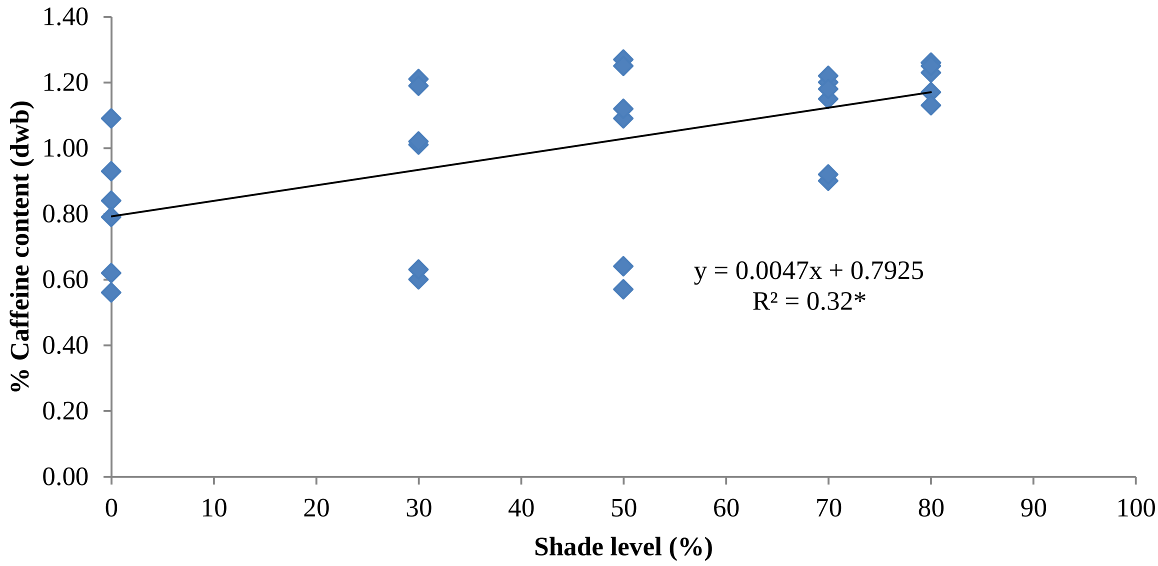
Linear regression relationship between shade levels and biochemical components indicated that shade levels had positive and significant effect on the bean contents of caffeine, oil and trigonelline (Figures 1, 2 and 3) and significant and negative effect on sucrose and chlorogenic acids content.

Table 6.6: Pearson's correlation coefficients of biochemical variables and agronomic management

Variables	Management	Caffeine	Oil	Trigonelline	Sucrose
Caffeine	0.56**				
Oil	0.41**	0.81**			
Trigonelline	0.27	0.85**	0.79**		
Sucrose	0.35	0.29	0.38	0.06	
CGA	0.35	0.41*	0.58**	0.27	0.83**

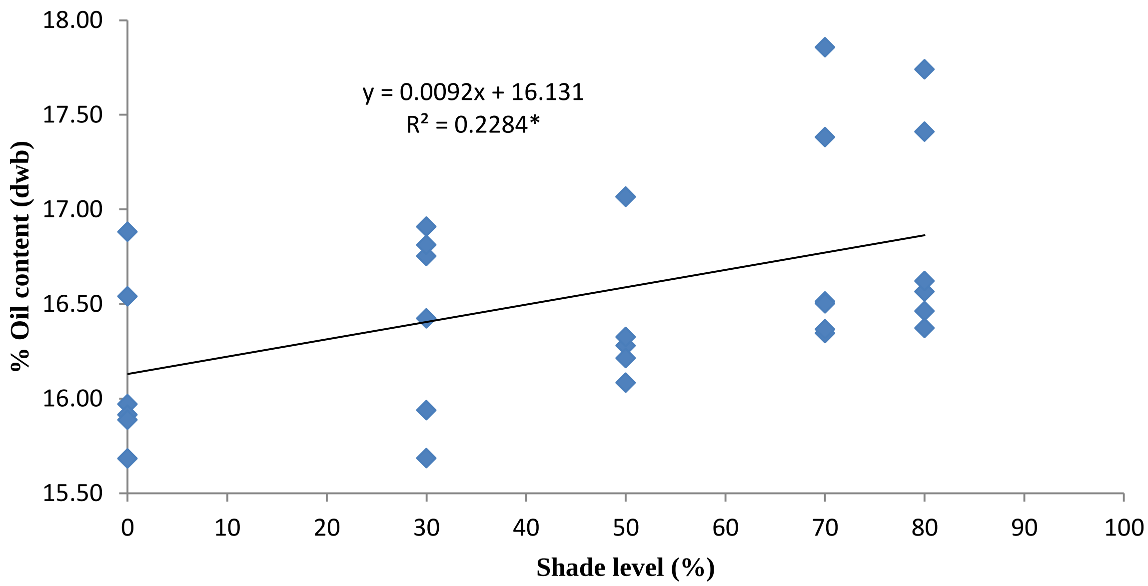
*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).



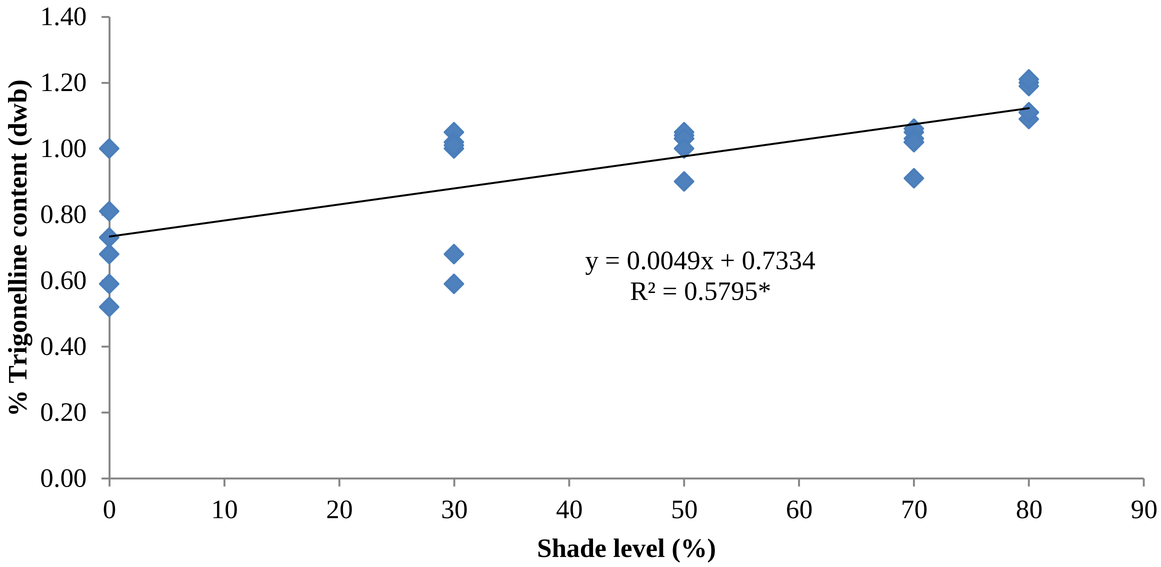
*significant at p=0.05

Figure 6-1: Linear regression curve describing the relationship between shade level and % caffeine content (dwb).



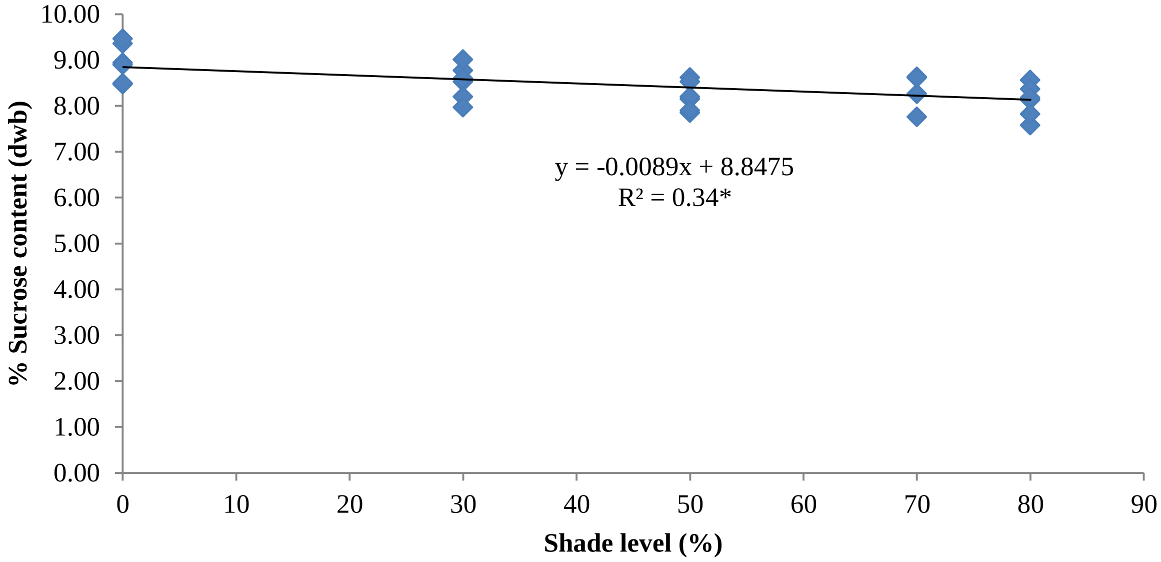
*significant at p=0.05

Figure 6-2: Linear regression curve describing the relationship between shade level and % oil content (dwb).



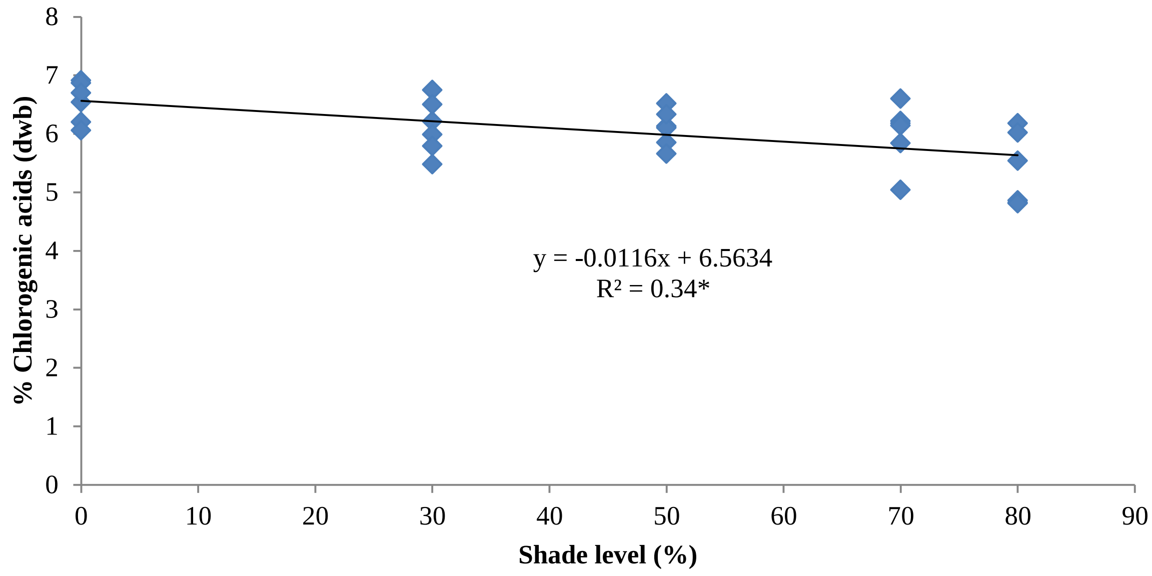
*significant at p=0.05

Figure 6-3: Linear regression curve describing the relationship between shade level and % trigonelline content (dwb).



*significant at p=0.05

Figure 6-4: Linear regression curve describing the relationship between shade level and % sucrose content (dwb).



*significant at p=0.05

Figure 6-5: Linear regression curve describing the relationship between shade level and % chlorogenic acids content (dwb).

6.5 Discussion

Shade levels significantly influenced biochemical components in this study. Shaded coffee had higher caffeine content than coffee in full sun. The caffeine level increased with increase in shade level. Similar findings have been reported by Morais et al., (2006), Vaast et al., (2006: 2007), and Guyot et al., (1996). The caffeine content ranged from 0.59% to 1.47% (dwb), which was within the range reported in other studies (Kathurima, 2013).

Shaded coffee consistently recorded higher oil content than coffee grown in full sun. The oil content generally increased with increase in shade level. This may be explained by a slowdown in the ripening process which led to better bean filling and complete fat synthesis as postulated by Vaast et al., (2006). Several studies have also shown a positive correlation between shade and oil content (Morais et al., 2006; Vaast et al., 2007; Decazy et al., 2003).

Avelino et al., (2007), on other hand, reported higher oil content in sun grown coffee. The contrast may be attributed to the use of Caturra and Catuai coffee varieties. The oil content ranged from 15.79% to 18.99% in this study. This was within the oil levels reported by other workers, for example, 10.12% to 18.75% (Kathurima (2013), 15% in green Arabica coffee (Speer and Kolling-Speer (2001; 2006) and 14.07% to 15.47% in a traditional coffee cultivar Caturra grown under different elevations in Central America (Bertrand et al., 2006).

Shaded coffee had higher trigonelline content than coffee grown in full sun. On the contrary, Vaast et al., (2007) recorded higher trigonelline values in full sun while Kathurima and Njoroge (2012) found that shade had no effect on the level of trigonelline. The levels of trigonelline ranged from a high of 1.54% dwb recorded under high agronomic management, under maximum shade, during the second season to a low of 0.56% dwb recorded in low management in full sun. Varying levels of trigonelline on dry weight basis have been reported by several authors. These include: 1.52% to 2.9% (Mazzafera, 1991), 1% to 1.94% (Martin et al., 1998), 0.88% to 1.77% (Ky et al., 2001) and 0.50% to 1.10% (Kathurima, 2013).

Shaded coffee had significantly lower chlorogenic acids content than coffee in full sun. This is similar to the findings reported by Vaast et al., (2006) and Vaast et al., (2005). In contrast, Somporn et al., (2012) and Morais et al., (2006) observed a higher chlorogenic acid content in shade grown coffee. The effect of total CGA on sensory characteristics is rather controversial. Kathurima (2013) found that, in some genotypes, high CGA levels produced harsh flavour while in others it did not have any negative impact. In that study only total chlorogenic acids were analysed without looking into the different specific fractions of the acid. Moreira et al. (2001) associated individual contents of chlorogenic acid with bad coffee.

Farah et al. (2006) found 3, 4-dicaffeoylquinic acid levels in green coffee correlating strongly with high quality. The fact that coffees with high total chlorogenic acids had equally good flavour underscores the importance of analysing specific chlorogenic acid fractions in coffee.

The shaded plants had lower sucrose content in coffee beans than those in full sun. The effect of shade on sucrose content in mature coffee remains controversial since it depends on the coffee cultivar. In this study, a traditional cultivar K7 was used. Using Catuai cultivar of *C. arabica* grown in shade, Guyot et al., (1996) reported an increase in sucrose content while for Catimor cultivar of *C. arabica*, Vaast et al., (2006) observed a negative correlation between sucrose content and shade. Sucrose is significantly degraded during bean roasting but remains markedly present in roasted grains at concentrations of 0.4 – 2.8% dwb and is believed to contribute to beverage sweetness (Guyot et al., 1996).

Agronomic management significantly influenced biochemical components in this study. High agronomic management increased caffeine content. Under the high agronomic management, N fertilizers were applied as recommended and this probably led to higher caffeine content than under the lower level agronomic management where little or no inputs were applied at all. This was further reinforced by the strong and positive correlation between management level and caffeine content. Excess nitrogen, reportedly, increases caffeine content (Wintgens, 2004). This has been supported by Gonthier et al., (2011) who found that caffeine concentration in phloem exudates was greater in high-N fertilized plants relative to intermediate and low-N plants. However, leaf, stem, root and total overall caffeine concentration and content did not differ across N treatments. The finding by Gonthier et al., (2011) suggested that the caffeine content was strongly regulated genetically and the environment was not as important. The high management level recorded the highest oil content and this could be explained by the positive effect of fertilizer application on bean size and weight. Studies by Wintgens, (2004) and Lara-Estrada and Vaast, (2007) showed that there was a higher accumulation of fat matter in green coffee beans with adequate plant nutrition. In the current study, trigonelline content generally increased with increase in management level. This is in contrast to the findings by Lara-Estrada and Vaast, (2007) who reported that fertilization increased bean size and weight but caused a reduction in trigonelline concentration. This is probably due to the dilution effect that showed that as the volume of the bean increased the concentration of trigonelline reduced.

In this study, there was an increase in chlorogenic acids (CGA) levels with increase in management levels, though the effect was significant only in the second season. In contrast, other workers have reported that agricultural practices were less important, compared to species or maturation, in determining the chlorogenic acid content (Clifford, 1985; Varnam and Sutherland, 1994; Flament, 2002; Farah et al., 2005). Higher sucrose content was observed under high than under medium and low management levels in this study. Comparable results were reported by Lara-Estrada and Vaast (2007) who found that fertilization increased sucrose content.

The biochemical components all showed positive correlations among each other. Caffeine, oil and trigonelline were strongly and positively correlated. Lara-Estrada and Vaast, (2007) and Gichimu et al., (2014) also reported positive correlations among the biochemical components except for caffeine which was negatively correlated with chlorogenic acids, trigonelline and lipids.

6.6 Conclusion

Shade increased caffeine, oil and trigonelline contents while it reduced the chlorogenic acids and sucrose contents of coffee bean. High agronomic management increased the contents of caffeine, oil, trigonelline, sucrose and chlorogenic acids in coffee beans. However, further studies need to be carried out to determine how the different biochemical components interact to influence cup quality.

CHAPTER SEVEN: BEVERAGE QUALITY OF COFFEE UNDER *Cordia africana* SHADE AND DIFFERENT AGRONOMIC MANAGEMENT CONDITIONS

7.1 Abstract

Beverage quality is a major determinant of consumer preferences. It is influenced by genetic and the production environment. However, in Kenya, there is inadequate information on the effect of shade and agronomic management levels on the beverage quality. This study was, therefore, conducted on three farms representing high, medium and low agronomic management levels. The shade levels were based on the distances from the shade tree trunk: 0 – 1.5 m, 1.5 – 3 m, 3 – 4.5 m, 4.5 – 6 m and > 6 m equivalent to 80, 70, 50, 30 and 0% (full sun) shade level, respectively. Under low management level no external inputs were applied. Fragrance/aroma, flavour, aftertaste, acidity, body, balance and overall sensory characteristics were assessed by a panel of seven judges. The beverage quality attributes, except for acidity and balance, were not influenced by shade levels or management. Nonetheless, trends showed that most of the variables had better scores under shade than in full sun. Shade correlated positively with all beverage quality attributes. This indicates that shading, under low management, could compensate for the inadequate application of external inputs to some degree.

7.2 Introduction

There has been an emergence of a market for quality coffee (*Coffea arabica* L) which explains the increasing interest in research on environmental factors and local production systems that affect quality (Avelino et al., 2007; Oberthur et al., 2011). The international specialty coffee industry has succeeded, as shown in the increasing numbers of small to medium roasters of high quality coffee beans and many chains of high-class coffee houses, providing evidence that consumers are more discerning of beverage quality and are willing to pay for it (Pendergrast, 1999). The distinct flavour of brewed coffee is undoubtedly the main reason for its worldwide acceptance as a refreshing beverage (Petracco, 2001). Coffee beverage quality, which is closely linked to its flavour and aroma, is an important attribute of coffee that generates consumer satisfaction (Muschler, 2001; Agwanda et al, 2003; Chalfoun et al, 2013). It is also referred to as liquor or cup quality and is used to set its price (Gichimu et al., 2012).

The green coffee beans contain a many different chemical compounds which react and interact at all stages of coffee processing to produce an end product with an even greater variety and intricacy of structure (Clifford, 1985; Buffo and Frere, 2004). The desirable aroma and taste of brewed coffee is, however, formed during roasting of green coffee beans. The beverage quality is based on the classification of numerous factors such as fragrance, flavour, aftertaste, acidity, body, balance, overall and total score (Kathurima et al., 2009). Coffee beverage quality is judged organoleptically by skilled coffee tasters (van der Vossen, 1985; Agwanda, 1999).

Although physical and beverage quality attributes of coffee bean are inherent factors, the environment, which includes agronomic management, are crucial in determining their expression (Bertrand et al., 2006; Leroy et al., 2006; Gichimu et al., 2014). A coffee tree in good growing conditions tends to produce larger beans with better flavour (Wintgens, 2004). Climate, altitude, and shade have a considerable influence on flowering, bean expansion, and ripening through their effect on temperature, light and water (Carr, 2001; Decazy et al., 2003). Shade, or conditions that provide lower air temperatures such as higher elevations, delay the ripening process of coffee berries giving more time for whole bean filling (Vaast et al., 2006), resulting in bigger beans that are heavier and more intense in flavour than those grown under lower altitudes or under full sunlight. The slower maturation process, therefore, is essential in ensuring high cup quality, by guaranteeing the full manifestation of all the biochemical steps needed for the development of the beverage quality (Silva et al., 2005). Other authors have reported that shade increased coffee bean size and enhanced beverage quality (Muschler, 2004; Geromel et al. 2008; Bote and Struik, 2011; Somporn et al., 2012). Kathurima et al., (2012) recognized the significant contribution of the shade to the increased premium grades, AA and AB, which are highly valued in the coffee trade in Kenya but found no clear gain on the sensory quality parameters. In the present study, shade was found to contribute to higher percentage grade 'A' under all agronomic management levels (Chapter 4 of this thesis). Studies have also shown that different shade tree species affect the sensory quality differently. Yadessa et al., (2008) demonstrated that coffee under *Acacia abysinnica* and *Cordia africana* shade were more acidic, had better flavour and overall beverage quality than those under *Albizia gummifera* and *Albizia schimperiana* shade.

Excessive use of nitrogen has been reported to reduce bean density and quality. In South America, Dessalegn (2005) reported that coffee grown with intensive application of nitrogen fertilizer had thinner, lighter and poorer body than that from fields where no fertilizer was applied. A high concentration of calcium and potassium in beans has been associated with a bitter taste while no correlation has been reported between phosphorus and the physical and organoleptic quality of the bean (Northmore, 1965). A study by Foote, (1963) showed that nutrient deficiencies may decrease cup flavour. In contrast, Pochet (1990) demonstrated a very clear and positive link between the organoleptic qualities and low soil fertility. Da Matta (2004) indicated that the advantage in use of shade increases as the environment becomes more marginal for coffee production. In Kenya, studies on the effect of shade and management levels on the beverage or cup quality are limited. This study was therefore, conducted to evaluate the effect of shade and management levels on beverage quality of coffee.

7.3 Materials and Methods

7.3.1 Study site

This study was conducted at the Kenya Agricultural and Livestock Research Organization – Coffee Research Institute demonstration (KALRO–CRI) plot in Namwela and two surrounding small holder farms, which represented high, medium and low management level treatments, respectively. Namwela is located in Bungoma County at 0° 45’43N 34° 33’42E, 1641 meters above sea level and receives an average rainfall of 1329 mm per annum. The sites chosen had similar climatic and soil conditions due to their proximity.

7.3.2 Experimental treatments and design

The main treatments were five (5) shade and three (3) management levels. The different shading levels were based on the distances of coffee plant the shade tree trunk of: 0 – 1.5 m (80% shade), 1.5 – 3 m (70% shade), 3 – 4.5 m (50% shade), 4.5 – 6 m (30% shade) and full sun (0% shade). The shading level (%) was estimated by measuring the Photosynthetic Photon Flux Density (PPFD) in µmol m^{-2} s^{-1} using a Line Quantum Sensor (LI-COR Biosciences) and expressing it as a percentage of that obtained in full sun as described by Vaast et al. (2007). The experimental design was a split plot, with management level as main plot treatment and shade level as the sub-plot. The sub-plot treatments were replicated seven times. The management levels were categorized depending on field operations and externally applied inputs as described by Mugo (2010). Based on these criteria, a coffee plot under high management level was managed using all the recommended practices by Coffee Research

Foundation (CRF, 2013) for optimum production. Under medium management level, the external inputs applied included farmyard manure and inorganic fertilizers; and pesticides (insecticides and fungicides for the control of insect pests and diseases respectively). Under the low management level, there was no application of external inputs at all.

7.3.3 Processing of samples

Fully ripe cherries were harvested from four trees in each of the five treatments in each site during the year 2010/11 and 2011/12 seasons. The cherries were bulked and wet processed using standard procedures (Mburu, 2004). The cherry samples were pulped, fermented, washed and the wet parchment dried to final moisture content of 10.5 to 11%. The parchment coffee was hulled and graded based on size, shape and density (Gichimu et al., 2012) and grade AB was used for the subsequent analysis in the study.

7.3.4 Roasting and sensory evaluation

Roasting of green coffee was done to attain a medium roast using a Probat laboratory roaster within 24 hours of evaluation and coffee allowed to rest for at least eight hours. Samples were weighed out to the predetermined ratio of 8.25 g per 150 ml of water. Sensory evaluation procedure (Appendix 2) as described by Lingle (2001) was followed. Fragrance/aroma, flavour, aftertaste, acidity, body, balance and overall (this reflects the holistically integrated rating of the sample as perceived by the individual panellist) sensory characteristics were assessed and scored together with three process control parameters (uniformity, clean cup and sweetness) by a panel of seven trained judges on a 10 – point scale, where 1 represents very poor score and 10 is outstanding score (Appendix 3). All the sensory parameters including the process control parameters were added to constitute the total score which is a reflection of the broad quality performance of a particular coffee. This presents the total score as a key characteristic for evaluating the sensory quality performance.

7.3.5 Data analysis

The sensory data obtained were subjected to analysis of variance at 5% level of significance using Costat version 6.400 (1998-2008, Co Hort Software) statistical program. The least significant difference (LSD) test (at p=0.05) was used to separate the means.

7.4 Results

Shade levels affected the fragrance of coffee significantly in season 2, whereas agronomic management had a significant effect in season 1 (Table 7.1). The interaction between shade and agronomic management had no significant effect on fragrance. Shaded coffee had significantly higher fragrance scores than coffee in full sun in season 2. In season 1, coffee under low management level had significantly higher scores for fragrance than that under medium management; however it was not different from coffee under high agronomic management. Average fragrance scores varied from 7.43 to 7.64 in season 1 and 7.51 to 7.77 in season 2.

Table 7.1: Fragrance scores of coffee under different shade and management levels

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.64	7.57	7.64	7.62	7.64	7.82	7.86	7.77
1.5 – 3.0	7.57	7.54	7.57	7.56	7.57	7.68	7.61	7.62
3.0 – 4.5	7.54	7.54	7.57	7.55	7.57	7.64	7.75	7.65
4.5 – 6.0	7.61	7.50	7.61	7.57	7.64	7.61	7.64	7.63
> 6 (Full sun)	7.46	7.46	7.54	7.49	7.43	7.57	7.54	7.51
Mean	7.56	7.52	7.59		7.57	7.66	7.68	
P value (ML)	0.0277*				0.0747			
P value (SL)	0.1068				0.0005***			
P value (ML x SL)	0.9897				0.6684			
$LSD_{0.05}$ (ML)	0.05				NS			
$LSD_{0.05}$ (SL)	NS				0.11			
$LSD_{0.05}$ (ML x SL)	NS				NS			
CV (%)	2.03				2.34			

Key: ML – Management level, SL – Shade level; Score: 1 = very poor and 10 = outstanding for fragrance; NS - Not significant, * significant at 5% level, ***significant at 0.1% level

Shade level significantly affected the flavour in both seasons but the effect of agronomic management was only significant in season 2 (Table 7.2). No interaction between shade and agronomic management was observed in both seasons. In season 1, shaded coffee (0 – 1.5 m and 1.5 – 3.0 m away from shade tree trunk), had higher flavour scores than coffee in full sun. In season 2, coffee under low agronomic management level had better flavour scores than coffee under high agronomic management level. Shaded coffee (all shade levels) had higher scores than coffee in full sun.

Table 7.2: Flavour scores of coffee under different shade levels and agronomic management

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.75	7.61	7.64	7.67	7.71	7.75	7.64	7.70
1.5 – 3.0	7.61	7.71	7.71	7.68	7.68	7.64	7.71	7.68
3.0 – 4.5	7.54	7.50	7.64	7.56	7.75	7.71	7.86	7.77
4.5 – 6.0	7.43	7.50	7.57	7.50	7.57	7.71	7.86	7.71
> 6 (Full sun)	7.43	7.46	7.54	7.48	7.50	7.57	7.57	7.55
Mean	7.55	7.56	7.62		7.64	7.68	7.73	
P value (ML)	0.1848				0.0099**			
P value (SL)	0.0029**				0.0018**			
P value (ML x SL)	0.7343				0.2660			
$LSD_{0.05}$ (ML)	NS				0.05			
$LSD_{0.05}$ (SL)	0.12				0.10			
$LSD_{0.05}$ (ML x SL)	NS				NS			
CV (%)	2.67				2.29			

Key: ML – Management level, SL – Shade level; Score: 1 = very poor and 10 = outstanding for flavor; NS - Not significant, ** significant at 1% level

Shade and management levels had no effect on the aftertaste in both seasons (Table 7.3). The aftertaste scores ranged from 7.52 for coffee under full sun in season 1 to 7.70 for shaded coffee, at 3.0 – 4.5 m away from shade tree trunk, in season 2; the ranges for management level were from 7.53 for coffee under medium management in season 1 to 7.71 for coffee under low management in season 2.

Table 7.3: After taste scores of coffee under different shade levels and agronomic management

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.71	7.54	7.61	7.62	7.68	7.54	7.64	7.62
1.5 – 3.0	7.57	7.61	7.64	7.61	7.61	7.68	7.71	7.67
3.0 – 4.5	7.61	7.46	7.54	7.68	7.68	7.61	7.82	7.70
4.5 – 6.0	7.61	7.54	7.54	7.57	7.57	7.57	7.71	7.62
> 6 (Full sun)	7.50	7.50	7.57	7.52	7.43	7.71	7.68	7.61
Mean	7.60	7.53	7.58		7.59	7.62	7.71	
P value (ML)	0.2661				0.0968			
P value (SL)	0.3183				0.5671			
P value (ML x SL)	0.7592				0.3196			
$LSD_{0.05}$ (ML)	NS				NS			
$LSD_{0.05}$ (SL)	NS				NS			
$LSD_{0.05}$ (ML x SL)	NS				NS			
CV (%)	2.34				2.81			

Key: ML – Management level, SL – Shade level; Score: 1 = very poor and 10 = outstanding for aftertaste; NS – Not significant at p<0.05

Shading level significantly (p<0.05) affected the acidity of the coffee in both seasons, while the effect of management was only significant in season 1 (Table 7.4). The interaction effect on acidity was significant in season 2. In season 1, shaded coffee (all levels) had higher acidity than coffee in full sun. Average acidity scores varied from 7.60 (full sun) to 7.77 (0 – 1.5 m from the shade tree trunk). In season 2, shade generally reduced acidity scores under medium agronomic management but had inconsistent effects under high and low agronomic management.

Table 7.4: Acidity scores of coffee under different shade levels and agronomic management

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.75	7.71	7.86	7.77	7.79	7.61	7.64	7.68
1.5 – 3.0	7.71	7.61	7.71	7.68	7.79	7.82	7.79	7.80
3.0 – 4.5	7.79	7.64	7.68	7.70	7.86	7.82	7.89	7.86
4.5 – 6.0	7.79	7.71	7.86	7.79	7.61	7.79	7.89	7.76
> 6 (Full sun)	7.57	7.54	7.68	7.60	7.57	7.75	7.71	7.68
Mean	7.72	7.64	7.76		7.72	7.76	7.78	
P value (ML)	0.05*				0.2478			
P value (SL)	0.0020**				0.0008***			
P value (ML x SL)	0.8148				0.0147*			
$LSD_{0.05}$ (ML)	0.09				NS			
$LSD_{0.05}$ (SL)	0.10				0.09			
$LSD_{0.05}$ (ML x SL)	NS				0.17			
CV (%)	2.12				1.98			

Key: ML – Management level, SL – Shade level; Score: 1 = very flat to 10 = very bright for acidity (Appendix 3); NS - Not significant, * significant at 5% level, **significant at 1% level, ***significant at 0.1% level

Shade levels and agronomic management did not affect the body of the coffee beverage in both seasons (Table 7.5). The values for body of coffee beverage ranged from 7.61 for both low and medium agronomic management in season 1 to 7.71 for coffee under low agronomic management in season 2; the values for coffee beverage body ranged from 7.57 for coffee under full sun in season 1 to 7.72 for shaded coffee, at 3.0 – 4.5 m from the shade tree trunk, in season 2.

Table 7.5: Body of coffee beverage under different shade levels and agronomic management

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.68	7.54	7.64	7.62	7.61	7.71	7.68	7.67
1.5 – 3.0	7.64	7.61	7.54	7.60	7.75	7.64	7.71	7.70
3.0 – 4.5	7.57	7.57	7.61	7.58	7.68	7.68	7.79	7.72
4.5 – 6.0	7.64	7.75	7.71	7.70	7.68	7.61	7.75	7.68
> 6 (Full sun)	7.57	7.57	7.57	7.57	7.57	7.68	7.64	7.63
Mean	7.62	7.61	7.61		7.66	7.66	7.71	
P value (ML)	0.9617				0.3019			
P value (SL)	0.2667				0.5580			
P value (ML x SL)	0.8717				0.6300			
$LSD_{0.05}$ (ML)	NS				NS			
$LSD_{0.05}$ (SL)	NS				NS			
$LSD_{0.05}$ (ML x SL)	NS				NS			
CV (%)	2.73				2.24			

Key: ML – Management level, SL – Shade level; Score 1 = very thin and 10 = very heavy for body; NS – Not significant at p<0.05

Shade levels had no significant effect on the balance of the coffee beverage, however, management level had a significant ($p<0.05$) effect in both seasons (Table 7.6). The coffee under low management level had higher balance scores than coffee under high agronomic management. Average balance scores varied from 7.57 to 7.72.

Table 7.6: Balance scores of coffee beverage under different shade levels and agronomic management

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.64	7.54	7.61	7.60	7.61	7.61	7.68	7.63
1.5 – 3.0	7.54	7.57	7.64	7.58	7.57	7.64	7.68	7.63
3.0 – 4.5	7.54	7.54	7.61	7.56	7.61	7.61	7.71	7.64
4.5 – 6.0	7.46	7.50	7.61	7.52	7.54	7.64	7.68	7.62
>6 (Full sun)	7.39	7.54	7.61	7.51	7.46	7.64	7.57	7.56
Mean	7.51	7.54	7.62		7.56	7.63	7.66	
P value (ML)	0.0460*				0.0366*			
P value (SL)	0.2699				0.3657			
P value (ML x SL)	0.4907				0.7713			
$LSD_{0.05}$ (ML)	0.08				0.08			
$LSD_{0.05}$ (SL)	NS				NS			
$LSD_{0.05}$ (ML x SL)	NS				NS			
CV (%)	1.94				1.90			

Key: ML – Management level, SL – Shade level; Score: 1 = very poor and 10 = outstanding for balance; NS - Not significant, * significant at 5% level

Shade level significantly ($p \leq 0.05$) affected the overall score of the coffee beverage in both seasons, while the effect of agronomic management level was only significant in season 1 (Table 7.7). There no interaction between the shade levels and agronomic management in both seasons. In both season 1 and 2, coffee under the low agronomic management level had higher overall scores than medium and high agronomic management levels. There was, however, no significant difference in overall score between coffee under medium and high agronomic management level. Shaded coffee, at all levels, recorded higher scores for the overall than full sun coffee. There was no significant difference in overall scores among the shade levels in the shaded coffee (Table 7.7).

Table 7.7: Overall scores of coffee under different shade levels and agronomic management

Distance (m) from shade tree trunk	Management level							
	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	7.54	7.50	7.64	7.56	7.64	7.71	7.86	7.74
1.5 – 3.0	7.61	7.54	7.68	7.61	7.71	7.71	7.75	7.72
3.0 – 4.5	7.46	7.50	7.54	7.50	7.75	7.64	7.86	7.75
4.5 – 6.0	7.43	7.61	7.61	7.55	7.54	7.64	7.86	7.68
> 6 (Full sun)	7.39	7.50	7.46	7.45	7.36	7.54	7.64	7.51
Mean	7.49	7.53	7.59		7.60	7.65	7.79	
P value (ML)	0.0659				0.0029**			
P value (SL)	0.050*				0.0052**			
P value (ML x SL)	0.6333				0.6525			
LSD $_{0.05}$ (ML)	NS				0.10			
LSD$_{0.05}$ (SL)	0.11				0.13			
LSD$_{0.05}$ (ML x SL)	NS				NS			
CV (%)	2.28				2.92			

Key: ML – Management level, SL – Shade level; Score: 1 = very poor and 10 = outstanding for preference; NS - Not significant, * significant at 5% level, **significant at 1% level

Shade levels and management significantly ($p<0.05$) affected the total score for coffee beverage in both seasons. Coffee under low agronomic management had a higher total score than coffee under high agronomic management level. No interaction effect between shade and agronomic management was observed for this score in both seasons (Table 7.8). In both seasons, coffee under shade (0 – 1.5, 1.5 – 3.0, 3.0 – 4.5 m from the shade tree trunk) had higher total score than coffee under full sun. The total score ranged from 82.67%, for coffee in full sun, to 83.43%, for coffee at 0 – 1.5 m from the shade tree trunk, in season 1. In season 2, the score ranged from 82.77% for coffee in full sun to 84.07% for coffee at 1.5 – 3.0 m from the shade tree trunk, in season 2.

Table 7.8: Total score (%) of coffee berries under different shade levels and agronomic management

	Management level							
Distance (m) from shade tree trunk	Season 1				Season 2			
	High	Medium	Low	Mean	High	Medium	Low	Mean
0 – 1.5	83.14	83.57	83.57	83.43	83.68	83.21	84.68	83.86
1.5 – 3.0	83.64	83.18	83.36	83.39	83.68	83.93	84.61	84.07
3.0 – 4.5	83.11	83.00	83.57	83.23	83.89	83.79	83.82	83.83
4.5 – 6.0	82.50	83.11	83.21	82.94	83.43	82.57	83.79	83.26
Full sun	82.29	82.71	83.00	82.67	82.32	82.54	83.46	82.77
Mean	82.94	83.11	83.34		83.40	83.21	84.07	
P value (ML)	0.0429*				0.0043**			
P value (SL)	0.0095**				0.0010**			
P value (ML x SL)	0.6016				0.6096			
$LSD_{0.05}$ (ML)	0.31				0.47			
$LSD_{0.05}$ (SL)	0.48				0.66			
$LSD_{0.05}$ (ML x SL)	NS				NS			
CV (%)	0.94				1.29			

Key: ML – Management level, SL – Shade level; NS - Not significant, * significant at 5% level, **significant at 1% level

7.5 Correlation among shade, agronomic management and sensory variables

Shade was positively and significantly correlated with acidity and body (Table 7.9). Positive but non-significant correlation was observed between shade and fragrance, flavour, aftertaste, balance and the overall score. Agronomic management was significantly and negatively correlated with balance and the overall score. The correlation between management level and the other sensory variables were also negative but non-significant. All the sensory variables had significant and positive correlations between them except, that of fragrance and acidity whose correlation, while positive, was non-significant.

Table 7.9: Pearson's correlation coefficients of sensory variables showing effect of shade and management levels

Variables	Shade	Management	Fragrance	Flavour	Aftertaste	Acidity	Body
Management	0.000						
Fragrance	0.168	-0.291					
Flavour	0.217	-0.279	0.578**				
Aftertaste	0.084	-0.236	0.482**	0.668**			
Acidity	0.471**	-0.198	0.315	0.532**	0.661**		
Body	0.394*	-0.152	0.504**	0.496**	0.526**	0.499**	
Balance	0.122	-0.596**	0.650**	0.793**	0.703**	0.536**	0.439**
Overall	0.263	-0.458*	0.698**	0.774**	0.657**	0.536**	0.673**

*. Correlation is significant at 5% level (2-tailed).

**. Correlation is significant at 1% level (2-tailed).

7.6 Relationship between sensory and biochemical variables

The correlation coefficients between sensory and biochemical variables are shown in Table 7.10 Caffeine had a positive correlation with all sensory variables although none was significant. Oil had a positive and significant (p=0.05) correlation with all sensory variables except acidity and balance which were not significant. Trigonelline was also positively and significantly correlated with fragrance, flavour, aftertaste and overall. Correlation between trigonelline with acidity, body and balance, while positive, were not significant. Sucrose was negatively correlated with all sensory variables, however, none was significant. Chlorogenic acids were positively but non-significantly correlated with flavour, aftertaste and body. Chlorogenic acids were negatively correlated with fragrance, acidity, balance and overall score though none was significant.

Table 7.10: Pearson's correlation coefficients between sensory and biochemical variables

Variables	Caffeine	Oil	Trigonelline	Sucrose	CQA
Fragrance	0.278	**0.416***	**0.536***	-0.190	-0.132
Flavour	0.302	**0.428***	**0.522***	-0.195	0.064
Aftertaste	0.292	**0.385***	**0.395***	-0.278	0.047
Acidity	0.188	0.224	0.239	-0.310	-0.073
Body	0.230	**0.425***	0.317	-0.010	0.222
Balance	0.021	0.265	0.283	-0.315	-0.113
Overall	0.223	**0.425***	**0.491***	-0.284	-0.026

**. Correlation is significant at the 0.01 level (2-tailed)

7.7 Discussion

Coffee is a beverage where flavour is the leading quality parameter and a major motivation for consumer preference (Clarke, 1987; Marin et al., 2008). In this study, coffee under *Cordia africana* shade had higher scores for flavour, acidity and total score than coffee in full sun. Similar findings were reported by Vaast et al., (2006; 2007) who found that positive characteristics such as beverage acidity and preference were better for coffee produced under shade of timber trees. They further observed that negative characteristics such as astringency and bitterness were higher for beverage from coffee grown in full sun. The delayed maturity between the cherry pulp and bean caused by shade is suggested as one of the reasons explaining perceived differences in beverage quality between shaded coffee and that grown in full sun. The delayed ripening leads to complete berry maturation that promotes the development of high quality coffee flavour (Montavon et al., 2003).

Yadessa et al., (2008), working with different shade trees, demonstrated that *Acacia abyssinica* and *Cordia africana* produced coffee beans that were acidic, with better flavor than those produced by *Albizia schimperiana* and *Albizia gummifera*. In contrast, Bosselmann et al., (2009) reported that sensory characteristics were adversely affected by shade. They found that shade, at high altitude, had an unfavourable effect on fragrance, acidity, body, sweetness and preference of the beverage. These conflicting findings may be due to the different cultivars used in these different studies. The management levels had an effect on balance and total score in both seasons; however, the effect on fragrance, flavour and overall preference were not consistent. Generally, coffee under low management levels had higher scores for acidity, balance and total score in both seasons; it also had higher scores for fragrance in season 1, flavour in season 2 and overall preference than medium and high management levels. This observation was reinforced by the negative correlation between management levels and all sensory variables. Earlier studies by Amorim et al, (1973), showed that coffee beans harvested in plots where N and K were applied gave a significantly lower quality beverage. Dessalegn (2005) demonstrated that coffee grown with intensive application of nitrogen fertilizer had lighter, poorer, and thinner body than that from fields that were not fertilized. Cannell (1985) reported that yield had an adverse effect on beverage acidity as a result of competition for carbohydrates among coffee berries especially under high production. Similarly, Pochet (1990) found a clear and positive link between coffee organoleptic qualities and low soil fertility. Findings by Vaast et al., (2006) furthermore illustrated the antagonistic relationship between coffee tree productivity and bean size and quality. In contrast, Lara-Estrada and Vaast (2007) reported a positive influence of fertilization on the coffee bean size and organoleptic characteristics. The increase in bean size and weight resulted in higher fat accumulation and lower trigonelline concentration that led to a better aroma, flavor and overall score. Comparable results have been reported in other studies (Franca et al. 2005; Decazy et al. 2003). As Da Matta (2004) established, in a study of eco-physiological limitations of coffee, the gains in use of shade increase as the environment becomes suboptimal for coffee cultivation.

7.8 Conclusion

This study shows that the use of shade, in Kenya, can lead to production of high quality coffee. The coffee under low management had, as good as or better scores for various sensory variables than those under medium or high management. Trends showed that most of the variables had better scores in shade than in full sun. All sensory variables were positively correlated with shade which suggested that use of shade could improve beverage quality under all management levels.

CHAPTER EIGHT: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

8.1 Discussion

Shaded coffee had higher PAR values in the dry than in rainy period. The PAR was generally higher, above 200 µmol $m^{-2}s^{-1}$, in the shade than that reported by Vaast et al., (2006) who showed that the photosynthetic photon flux density (PPFD) of inner and middle leaves of all branch levels in shaded coffee was below 200 µmol quanta $m^{-2}s^{-1}$, while sun leaves were well above this value. This study showed that shade reduced the PAR; however this did not seem to affect the photosynthetic rate. The trends showed, nonetheless, that shaded coffee recorded higher values for photosynthetic rates than coffee in full sun. Earlier studies showed that photosynthetic rates of coffee were higher at intermediate shade levels than in full sun in climatic conditions of the tropics. The higher rates of photosynthesis in shaded coffee may partly explain the higher vegetative growth, for instance, longer primary branch length extension and generally higher yields than in full sun coffee. Plants adjust their developmental processes in reaction to variations in light intensity to optimize their fitness. Vegetative growth has been shown to respond to shade intensity as shown in higher vegetative growth under dense (60%) shade of *Terminalia ivorensis* compared to lighter shade (30 to 40%) of *Eucalyptus deglupta* (Vaast et al., 2007). In contrast, the number of nodes was higher in full sun than in shaded coffee. The reason may be that shade largely inhibits the flower initiation and intensity in coffee. Boyer (1968) and Cannell (1975) showed that shade promoted longer internodes but reduced number of fruiting nodes. In this study, photosynthetic rates were generally quite low ranging from 4.33 µmol $m^{-2}s^{-1}$ in the rainy season to 1.10 µmol $m^{-2}s^{-1}$. These could be attributed to the high leaf temperatures ranging from 25.8 to 38 °C in the dry season and 24.9 to 30.6°C in the rainy season. Chaves et al. (2008) observed that coffee leaves showed low photosynthetic rate, mostly below 2.5µmol m^{-}

$^{2}s^{-1}$, regardless of light treatment. They attributed this to chronic photoinhibition in the cool dry season and discrete, dynamic photoinhibition during the rainy warm season. Temperature is the climatic factor with greatest influence on the physiology of Arabica coffee plants; the ideal mean annual range for this species is 18 to 21°C however it can tolerate day temperatures of 30°C. Temperature above the optimum as found in this study may have been caused by short direct sun flecks that pass through the shade trees as observed, in a similar study, by Mayoli and Gitau (2012).

In the morning hours, there were generally no significant differences between transpiration rates in the shaded and full sun coffee, except during the rainy period in second season. Transpiration rates were greater in shaded coffee from midday onwards, than in full sun coffee. This partly contradicts findings by van Kanten and Vaast (2006) who found that coffee in full sun transpired more, on leaf area basis, than coffee under shade. However, the same authors found that, even though the coffee under full sun transpired more than shaded coffee, the daily water use was higher under shade than full sun due to the larger leaf area index in shaded coffee. The higher transpiration in the dry season compared to that in the rainy could probably be due to a high evaporative demand in the dry season. The higher transpiration rates in shaded coffee, in the morning may be explained by the higher stomatal conductance in the morning hours. Guiterrez et al. (1994) also showed, in Hawaii, that stomatal conductance was high in the morning and decreased with the increase in VPD and solar radiation. Wormer (1965) reported full stomatal closure in coffee plants at high temperatures and further observed a linear reduction in stomatal opening with the increase in VPD and solar radiation.

The results of this study also demonstrated the advantage of using shade under limited or no input situations. The coffee bean yields obtained under shade were significantly higher than that in full sun, in medium and low management levels. Yields under agronomic high management were higher than under medium and low management levels and this was understandably attributed to the use of all the recommended practices, including fertilization, for coffee production (CRF, 2013). Under high management, the coffee bean yield, though generally higher under shade, was not significantly different from that obtained in full sun.
The results also show that the benefits of shade are not limited to sub-optimal conditions as the use of shade was seen to improve the raw bean quality in term of % grade ‘A’ beans regardless of the management level.

Shaded coffee had higher content of caffeine, trigonelline and oil, all of which have been linked to high quality coffee. This was confirmed when the three component were positively and significantly correlated with fragrance/aroma, flavour, aftertaste and overall score. Trugo (1984) showed that derivatives of trigonelline are important to the coffee aroma. Furthermore, oil was positively and significantly related with the body of the coffee brew. Caffeine that has been linked to, a lesser extent, to good quality was also positively correlated, though non-significantly, to all the sensory attributes. On the other hand, sucrose and chlorogenic acids that have been associated with poor beverage quality were higher in coffee under full sun than in shaded coffee.

It has been projected that climate change will increase temperatures and alter rainfall patterns (amounts and frequency). As a result, coffee cultivation may move from traditional areas to non-traditional areas. Similarly, the demand for high quality, sustainably grown coffee continues to grow worldwide. It is therefore important for coffee producers to know where coffee will grow in future and how the suitability of these areas will vary with time. It is important for small-holder farmers, whose livelihoods are highly vulnerable to effects of climate change, to appreciate its likely impacts and develop adaptive strategies (Läderach et al., 2011). It has been established that Arabica coffee is a climate sensitive species that would be negatively impacted by climate change (Davis et al. 2012). Adding shade in the coffee systems is an adaptation strategy that farmers can use. As shown in the current study showed shaded coffee leaves had lower temperatures especially during hot midday sun and higher temperature during the cooler morning.

8.2 Conclusions

The study revealed that shade had potential in alleviating adverse weather conditions and thereby providing a suitable micro climate for coffee production. Under shaded conditions, leaf temperatures were generally lower while transpiration rates and stomatal conductance were higher than in full sun. The soil contents of most major plant nutrients were higher under shade than in full sun, regardless of the management level. Shade further enhanced the accumulation of N and P in coffee and P in coffee branches. However, shade had no significant effect on accumulation of major nutrients in coffee leaves. Shade promoted higher vegetative growth and higher yields especially under low input conditions. The percentage grade ‘A’ was also higher under shade than in full sun. Significant and positive correlations between shade and biochemical components further demonstrated that shade could be used to enhance coffee quality. The trends revealed that sensory variables with desirable traits had better scores in the shade than in full sun. Further, all the sensory variables were positively correlated with shade regardless of the agronomic management level. The growing interest for shade coffee is due to its potential contribution to sustainability and diversity of production systems as well as coffee quality. This study clearly showed that shade is useful especially under low input conditions. Under optimal ecological conditions for coffee cultivation shade can be used to enhance coffee quality and also mitigate the effects of climate change.

8.3 Recommendations

1. Further research need to be carried out to model the effects of shade on microclimate, coffee physiology, productivity and quality to provide adequate recommendations for extension services and farmers on the choice and management of shade tree species according to different ecological zones.
2. Further studies could be carried out to evaluate the effect of shade on disease and insect pest dynamics
3. This study has shown that shade trees have a positive effect on coffee yield and quality even under optimal conditions. There is need for policy makers, therefore, to promote the growing of coffee under shade.
4. There is need to study the impact of the inclusion of trees in coffee systems on the livelihoods of small holder farmers.
5. A study to assess the influence of shade on soil moisture dynamics needs to be conducted.
6. Studies could be conducted to assess the effect of shade using a wide range of trees and coffee varieties in different locations.

REFERENCES

Agwanda, C.O. 1999. Flavour: an ideal selection criterion for the genetic improvement of liquor quality in Arabica coffee. In the Proceedings of 18th International Scientific Colloquium on Coffee, pp. 383-389. Helsinki, Finland.

Agwanda, C.O., Baradat P., Eskes A.B., Cilas C., and Charrier A. 2003. Selection for bean and liquor qualities within related hybrids of Arabica coffee in multi-local field trials. Euphytica 131: 1-14.

Alemu, M.M. 2015. Effect of shade on coffee crop production. Journal of Sustainable Development 8(9): 66 – 70.

Amoah, F.M., Osei-Bonsu K. and Oppong F.K. 1997. Response of improved Robusta Coffee to location and management practices in Ghana. Experimental Agriculture 33:103 – 111.

Amorim, H. V., Teixeira, A. A., Moraes, R. S., Reis, A. J., Gomes, F. Pimentel and Malavolta, E. 1973. Estudos sobre a alimentação mineral do cafeeiro XXVII. Efeito da adubação N, P e K no teor de macro e micro nutrientes do fruto e na qualidade da bebida do café. Anais da Escola Superior de Agricultura Luiz de Queiroz 30: 323-333.

Anderson, J.M. and Ingram, T.S.I (eds). 1989. Tropical soil biological and fertility. A handbook of methods. CAB International, Oxford, UK 221pp.

AOAC-Association of Official Analytical Chemists 1995. Official methods of analysis of AOAC International (16th Ed.) Gaithersburg, MD, USA: AOAC International.

Araujo, W.L., Dias P.C., Moraes G.A., Celin E.F., Cunha R.L., Barros R.S. and DaMatta F.M. 2008. Limitations to photosynthesis in coffee leaves from different canopy positions. Plant Physiology and Biochemistry 46 (10): 884 – 890.

Avelino J., Barboza, B., Davrieux, F. and Guyot, B. 2007. Shade effects on sensory and chemical characteristics of coffee from very high altitude plantations in Costa Rica. In: Second International Symposium on Multi-Strata agroforestry systems with perennial crops: Making ecosystems services count for farmers for farmers, consumers and the environment, September 17-21, 2007 Turrialba, Costa Rica.

Baggio, A., Caramori P., Androcioli Filho A. and Montoya L. 1997. Productivity of Southern Brazillian coffee plantations shaded by different stocking of *Grevillea robusta*, Agroforestry Systems. http://dx.doi.org/10.1023/A:1005814907546

Baliza, D. P., Cunha, R. L., Guimarães, R. J., Barbosa, J. P. R. A. D., Ávila, F. W. and Passos, A. M. A. 2012. Physiological characteristics and development of coffee plants under different shading levels. Revista Brasileira de Ciências Agrárias, 7(1) 37 – 43.

Barradas, V and Fanjul L. 1986. Microclimatic characterization of shaded and open-grown coffee (*Coffea arabica*) plantations in Mexico. Agricultural and Forestry Meteorology. 38: 101 – 112.

Beer, J., 1987. Advantages, disadvantages and desirable characteristics of shade trees for coffee, cocoa and tea. Agroforestry Systems 5: 3 – 13.

Beer, J., Mushler R., Kass D. and Sommariba E. 1997. Timber yielding trees as shade for coffee. Boletin PROMECAFE76/77: 5 – 7.

Beer, J., Muschler, R., Kass, D. and Somarriba, E. 1998. Shade management in coffee and cacao plantations. Agroforestry Systems 38: 139–164.

Belay, A. (2010). Measurement of integrated absorption cross-section, oscillator strength and number density of caffeine in coffee beans by integrated absorption coefficient technique. Food Chemistry 121: 585-590.

Bertrand, B., Vaast, P.H., Alpizar, E., Etienne, H., Davrieux, F. and Charmetant, P. 2006. Comparison of bean biochemical composition and beverage quality of Arabica hybrids involving Sudanese-Ethiopian origins with traditional varieties at various elevations in Central America. Tree Physiology 26:1239–1248.

Bosselmann, A. S., Dons, K., Oberthur, T., Smith-Hall, C., and Ræbild, A. 2009. The influence of shade trees on coffee quality in small holder agroforestry systems in southern Columbia. Agriculture, Ecosystems and Environment 129(1): 253-260.

Bote A.D. and Struik, P.C. 2011. Effects of shade on growth, production and quality of coffee (*Coffea arabica*) in Ethiopia. Journal of Horticulture and Forestry 3 (11): 336-341.

Boyer J. 1968. Influence de l’ombrage artificial sur la croissance végétative, la floraison et la fructification des caféiers Robusta Café Cacao Thé XII – 4 302-319.

Buck, L., Lassoie, J.P. and Fernandes, E.C.M. 1999. Agroforestry in Sustainable Agricultural Systems.CRC Press, Boca Raton, FL.

Buffo, R. A., and Freire, C. C. 2004. Coffee flavour: An overview. Flavour and Fragrance Journal, 19: 99–104.

Buresh, R.J. and G. Tian 1997. Soil improvement by trees in sub-Saharan Africa. Agroforestry Systems 38: 51–76.

Camargo, M. B. 2010. The impact of climatic variability and climate change on Arabica coffee crop in Brazil. Bragantia 69: 239-247.

Cambrony H.R. 1992. Coffee growing – CTA Wageningen, The Netherlands and Macmillan Press Ltd. London. 119pp

Cannell M.G.R. 1975. Crop physiology aspects of coffee bean yield – a review. Journal of Coffee Research 5: 7 – 20.

Cannell, M.G.R. 1985. Physiology of the coffee crop. In Coffee: Botany, Biochemistry and Production of Beans and Beverage. Eds. N.M. Clifford and K.C. WilsonCroom Helm, London. 305 – 374.

Cantergiani, E., Brevar, H., Amado, R., Krebs, V., Feria-Morales, A. and Yeetizian, C. 1999. Proceedings of 18th International Colloq Coffee. Helsinki.

Carelli, M. L. C., Fahl, J. I., Trivelin, P.C.O. and Queiroz-Voltan R.B. 1999. Carbon isotope discrimination and gas exchange in *Coffea* species grown under different irradiance regimes. Revista Brasileira de Fisiologia Vegetal, 11(2): 63 – 68.

Carelli, M. L. C., Fahl, J. I. and Ramalho, J. D. C. 2006. Aspects of nitrogen metabolism in coffee plants. Brazilian Journal of Plant Physiology, 18: 9-21.

Carr, M.K.V. 2001. Review paper: the water relations and irrigation requirements of coffee. Experimental Agriculture, 37: 1 – 36.

Castro-Tanzi S., Dietsch T., Urena N., Vindas L. and Chandler M. 2012. Analysis of management and site factors to improve the sustainability of small-holder coffee production in Tarrazú, Costa Rica. Agriculture, Ecosystems and Environment 155: 172– 181.

Cavatte, P.C., Oliveira A.A.G., Morais L.E., Martins S.C.V., Sanglard L.M.V.P. and DaMatta F.M. 2012. Could shading reduce the negative impacts of drought on coffee? A morphological analysis. Physiologia Plantarum 144: 111-122.

Chalfoun, S.M., Pereira, M.C., Carvalho, G.R., Pereira, A.A., Savian, T.V. and dos Santos Botelho, D.M. 2013. Sensorial characteristics of coffee (*Coffea arabica* L.) varieties in the Alto Paranaiba Region. Coffee Science, Lavras 8(1): 43 – 52.

Chaves A.R.M, Ten-Caten A., Pinheiro H.A., Ribeiro A. and DaMatta F.M. 2008. Seasonal changes in photoprotective mechanisms of leaves from shaded and unshaded field grown coffee (*Coffea arabica* L.) trees. Trees 22: 351- 361.

Clark, S.M., Horwath W.R., Shennan C. and Scow K.M. 1998. Changes in soil chemical properties resulting from organic and low-input farming practices. Agronomy Journal 90: 662 – 671.

Clarke, R. J. 1987. Grading, storage, pre-treatments and blending. In R. J. Clarke & R. Macrae (Eds.), Coffee volume 2: technology (pp. 35–58). Amsterdam: Elsevier Applied Science.

Clarke, R. J., and Vitzthum, O. G. 2001. Coffee Recent Developments. Blackwell Science Ltd. Pp 257.

Clifford M.N. 1985. Chlorogenic acid. In: RJ Clarke and R MaCrae (eds), Coffee Elselvier Applied Science. London. 1:153-202.

CRF, 2010a. Coffee Research Foundation, Strategic Plan 2010 – 2014.

CRF, 2010b. Coffee Research Foundation, Standard Coffee Processing Procedures. Technical Circular Number 204.

CRF, 2012. Annual Report, Coffee Research Foundation.

CRF, 2013. Coffee Production Handbook. JM Minai (ed). Coffee Research Foundation.

CRF. 2014. Coffee Research Foundation, Annual Report. JM Minai (ed).

Crowe, T. J. 2004. Coffee Pests in Africa. *In*: Coffee: growing, processing, sustainable production: A guide book for growers, processors, traders and researchers. Ed. J. Wintgens. Wiley-VCH, Weinhein, Alemania, pp 421-458.

DaMatta, F.M., 2004. Ecophysiological constraints on the production of shaded and unshaded coffee: a review. Field Crops Research 86: 99 -114.

DaMatta, F. M., Cunha, R. L., Antunes, W. C., Martins, S. C. V., Araujo, W. L., Fernie, A. R. and Moraes, G. A. B. K. 2008. Field-grown coffee trees source–sink manipulation alters photosynthetic rates, independently of carbon metabolism, via alterations in stomatal function. New Phytologist, 178: 348–357.

DaMatta F.M. and Ramalho, J.D.C. 2006. Impacts of drought and temperature stress on coffee physiology and production: a review. Brazilian Journal of Plant Physiology 18: 55-81.

DaMatta, F. M., Ronchi, C.P., Maestri M., and Barros R.S. 2007. Ecophysiology of coffee growth and production. Brazilian Journal of Plant Physiology 19(4): 485 – 510.

DaMatta, F. M., Ronchi, C.P., Maestri M., and Barros R.S. 2010. Coffee: environment and crop physiology. In: DaMatta, F.M. (ed), Ecophysiology of Tropical Tree Crops. Nova Science Publishers, New York, USA, pp 181-216.

Davies, A.P., Gole T.W., Baena S. and 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.doi:10.1371/journal.pone.0047981

Davies, A.P., Govaerts, R., Bridson, D.M. and Stoffelen, P. 2006. Air, annotated taxonomic conspectus of genus *Coffea* (*Rubiaceae*). Botannical Journal of the Linnean Society 152: 465-512.

Decazy, F., Avelino, J., Guyot, B., Perriot, J.J., Pineda, C. and Cilas, C. 2003. Quality of different Honduran coffees in relation to several environments. Journal of Food Science 68 (7): 2356 – 2361.

Descroix, F. and Snoeck, J. 2004. Environmental factors suitable for coffee cultivation. In: Coffee: growing, processing, sustainable production: A guide book for growers, processors, traders and researchers. Ed. J. Wintgens. Wiley-VCH, Weinhein, Alemania, pp 164 – 177.

De Souza, H.N., De Goede R.G.M., Brusaard L., Cardoso I.M., Duarte E.M.G., Fernandes R.B.A., Gomes L.C. and Pulleman M.P. 2012. Protective shade, tree diversity and soil properties in agroforestry systems in Atlantic rainforest biome. Agriculture, Ecosystems and Environment 146: 179 – 196.

Dessalegn, Y. B. 2005. Assessment of cup quality, morphological, biochemical and molecular diversity of *Coffea arabica* L. genotypes of Ethiopia. PhD Thesis, University of Free State, South Africa.

Dossa, E.L., Fernandes E.C.M., Reid W.S. and Ezui K. 2008. Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. Agroforestry Systems 72: 103 – 115.

Economic Survey. 2011. Kenya National Bureau of Statistics.

Ehrenbergerová, L., Cienciala E., Kučera A., Guy L and Habrová H. 2015. Carbon stock in agroforestry coffee plantations with different shade trees in Villa Rica, Peru. Agroforestry Systems 90(3): 433-445.

Evizal R., Prijambada I.D., Widada J., Widianto D. and Tohari. 2013. Diversity of legume nodulating bacteria as key variable of coffee agro-ecosystem productivity. Global Journal of Pests, Diseases and Crop Protection 1(1): 35 – 40.

Evizal, R., Tohari, Prijambada I.D., Widada J. and Widianto D. 2012. Soil bacterial diversity and productivity of coffee - shade tree agro-ecosystems. Journal of Tropical Soils 17(2): 181-187.

Fahl, J.I., Carelli, M.L.C., Vega, J., and Magalhães, A.C. 1994. Nitrogen and irradiance levels affecting net photosynthesis and growth of young coffee plants (*Coffea arabica* L.). Journal of Horticultural Science, 69(1):161-169,

Farah, A., Franca, A. S., Mendonca, J. C. F. and Oliveira, S. D. 2005. Composition of green and roasted coffee of different cup qualities. Lebensmittel-Wissenschaft and Technologie (LWT) – Food Science and Technology, 38: 709-715.

Farah, A., Monteiro, M. C., Calado, V., Franca, A. S. and Trugo, L. C. 2006. Correlation between cup quality and chemical attributes of Brazilian coffee. Food Chemistry, 98:373–380.

Feldhake C. 2001. Microclimate of a natural pasture under planted *Robinia pseudoacacia* in Central Appalachia, West Virginia. Agroforestry Systems. 53: 297 - 303

Flament, V. 2002. Coffee flavor chemistry. England: John Wiley and Sons, Ltd. 396p.

Folstar, P. (1985). Lipids. In: R.J. Clarke, and R., Macrae, (Eds.). Coffee: Chemistry, London, Elsevier Applied Science. pp. 203-222.

Foote, H.E. 1963. Factors affecting cup quality in Coffee. Coffee and Cacao Journal 5:248-249.

Franca, A.S., Mendonca, J. C. F. and Oliveira S. D. 2005. Composition of green and roasted coffees of different cup qualities. Lebensmittel-Wissenschaft and Technologie (LWT)-Food Science and Technology 38: 709–715.

Franck, N. 2005. Effet de la charge en fruits et de l'ombrage sur l'assimilation carbone´e, la croissance et la production du cafe´ier (*Coffea arabica* L.). Thése de Doctorat, ENSA, Montpellier, pp 165.

Franck, N. and Vaast P. 2009. Limitation of coffee leaf photosynthesis by stomatal conductance and light availability under different shade levels. Trees 23: 716 – 769.

Franck, N., Vaast, P., Génard, M. and Dauzat, J. 2005. Soluble sugars mediate sink feedback down-regulation of leaf photosynthesis in field-grown coffee of *Coffea arabica*. Tree Physiology 26: 517-525.

Freitas, R.B. de, Oliveira, L.E.M. de, Delú Filho, N. and Soares, A.M. 2003. Influêcia de diferentes níveisde sombreamento no comportamento fisiológico de cultivares de café (*Coffea arabica* L.) Ciência e Agrotecnologia 27 (4): 804 – 810.

Friend, D.J.C. 1984. Shade adaptation of photosynthesis in *Coffea arabica*. Photosynthesis Research 5(4): 325 – 334.

Gates, D.M., 1968. Transpiration and leaf temperature. Annual Review of Plant Biology 19: 211–238.

Geromel, C., Ferreira L.P., Davrieux F., Guyot B., Ribeyre F., Scholz M.B. dos S, Pereira L.F.P., Vaast P., Pot D., Leroy T., Filho A.A., Vieira L.G.E., Mazzafera P. and

Marraccini. 2008. Effects of shade on the development and sugar metabolism of coffee (*Coffea arabica* L.) fruits. Plant Physiology and Biochemistry 46: 569-579.

Gichimu, B.M. Gichuru, E.K., Mamati, G.E. and Nyende, A.B. 2012. Selection within *Coffea arabica* cv. Ruiru 11 for high cup quality. African Journal of Food Science 6(8): 456-464.

Gichimu, B.M., Gichuru, E.K., Mamati, G.E. and Nyende, A.B. 2014. Biochemical composition within *Coffea arabica* cv Ruiru 11 and its relationship with cup quality. Journal of Food Research 3 (3): 31-44.

Ginz, M. and Enhelhardt, U.H. (2000). Analysis of bitter fractions of roasted coffee by LC-ESI- MS- new chlorogenic acid derivatives. In: Proceedings of 16th International Scientific Colloquium on Coffee, Kyoto, Japan. pp. 248–252.

Gonthier, D.J., Witter, Spongberg, A.L. and Philpott, S.M. 2011. Effect of N fertilization on caffeine production in coffee (*Coffea arabica*). Chemoecology 21: 123-130.

Guiterrez, M.V., Meinzer F.C. and Grantz D.A. 1994. Regulation of transpiration in coffee hedgerows on an Ultisol in southern Cameroon. Agroforestry Systems, 64: 73-82.

Guyot, B., Manez, J.C., Perriot, J.J. Giron, J. Villain, L. 1996. Influence de l’altitude et de l’ombrage sur la qualite´ des cafe´s arabica, Plant. Rech. De´v. 3 (1996) 272e280.

Hagar J., Barrios M., Bolaños M., Merlo M., Moraga P., Munguia R., Ponce A., Romero S., Soto G., Staver C., Virginio E. de M.F. 2011. Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. Agroforestry Systems 82: 285 – 301.

Harmand JM, Hergoualc'h K, De Miguel S, Dzib B, Siles P, and Vaast P. 2007. Carbon sequestration in coffee agroforestry plantations of Central America. In Proceedings of the 21st ASIC Colloquium; Montpellier; ASIC; Paris, pp. 1071-1074.

Hernandez, A.D.P., Cock J.H. and El-Sharkawy M.A., 1989. The responses of leaf gas exchange and stomatal conductance to air humidity in shade-grown coffee, tea and cacao plants as compared with sunflower. Brazilian Journal of Plant Physiology 1(2): 155 – 161.

Hietz, P. (2005). Conservation of vascular epiphyte diversity in Mexican coffee plantations. Conservation Biology 19: 391-399

Huner, N.P.A., Öquist G., Sarhan F.1998. Energy balance and acclimation to light and cold. Trends in Plant Science 3: 224 -230.

Huxley, P. 1999. Tropical Agroforestry. Blackwell Science, Oxford, UK.

ISO International Standard, 5492 (2008). Sensory analysis – Vocabulary, Second edition, published in Switzerland.

Jaetzold, R., Schmidt, H., Hornetz, B. and Shisanya, C. 2005. Farm Management Handbook of Kenya Vol. II– Natural Conditions and Farm Management Information –2nd Edition, Part A, West Kenya Subpart A1Western Province.

Jaramillo-Botero, C., Santos R.H.S., Martinez H.E.P., Cecon P.R. and Fardin M.P. 2010. Production and vegetative growth of coffee under fertilization and shade levels. Scientia Agricola (Piracicaba, Brazil) 67 (6): 639- 645.

Jose S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Systems 76: 1 – 10.

Jassogne, L., Läderach P. and Van Asten P. 2013. The impact of climate change on coffee in Uganda. Lessons from a case study in the Rwenzori Mountains. Oxfam Research Reports.

Karanja, A.M. 1992. Coffee production and profitability in the small holder sector in Kenya. Kenya Coffee 57: 1375 – 88.

Karunaratne, P.M.A.S., Mohotti, A.J., Nissanka, S.P. and Gunasinghe, W.A.D.S.K. 2003. Effect of shade in minimizing photoinhibition of photosynthesis of high grown tea (*Camellia sinensis* L.O. Kuntze) in Sri Lanka. Tropical Agricultural Research 15: 133 – 143.

Kasai M. 2008. Effect of growing soybean plants under continuous light on leaf photosynthetic rate and other characteristics concerning biomass production. Journal of Agronomy 7: 156 – 162.

Kathurima, C.W. 2013. Characterization of the diversity of coffee genotypes in Kenya by genetic, biochemical and beverage quality profiles. PhD Thesis. Jomo Kenyatta University of Agriculture and Technology.

Kathurima, C.W., Gichimu, B.M., Kenji, G.M., Muhoro, S.M. and Boulanger, R. 2009. Evaluation of beverage quality and green bean physical characteristics of selected Arabica coffee genotypes in Kenya. African Journal of Food Science 3(11): 365-371.

Kathurima, C. W., Kenji, G. M., Muhoho, S. M., Boulanger, R., Gichimu, B. M., and Gichuru, E. K. 2012. Genetic diversity among commercial coffee varieties, advanced selections and museum collections in Kenya using molecular markers. International Journal of Biodiversity and Conservation 4(2): 39-46.

Kathurima, C.W. and Njoroge, E. 2012. Effect of different shade regimes on coffee quality. In the Proceedings of the International Conference on Coffee Science (ASIC) – 11-16 November 2012, San Jose, Costa Rica.

Khanna, P.K. 1997. Comparison of growth and nutrition of young monocultures and mixed stands of *Eucalyptus globules* and *Acacia mearnsii*. Forest Ecology and Management 94(1–3): 105–113.

Kimemia, J.K. 1998. Studies on green manure application and intercropping in *Coffea arabica* L. production. PhD Thesis, University of Nairobi.

Kimemia, J.K. 2004. Effect of shade on the growth and yield of young Arabica coffee trees in Kenya. ASIC Proceedings 11-15 October, 2004. Bangalore, India.

Kimemia J.K. and Kaminchia N.N. 1994. Arabica Coffee management in Kenya. Kenya Coffee 59: 1811-1816.

Kimemia J.K. and Njoroge J.M. 1988. Effect of shade on coffee – a review. Kenya Coffee 387 – 391.

Kirkpatrick TW. 1935. The climate and eco-climates of coffee plantations. Amani (Kenya): East African Agricultural Research Station.

Kumar, D. and Tieszen, L.L. 1980. Photosynthesis in *Coffea arabica*. I. Effects of light and temperature. Experimental Agriculture 16: 13-19.

Ky C.L., Louarn J., Dussert S., Guyot B., Hamon S., Noirot M. 2001. Caffeine, trigonelline, chlorogenic acids and sucrose diversity in wild *Coffea arabica* L. and *C. canephora* P. accessions. Food Chemistry 75: 223-230.

Läderach, P., M. Lundy, A. Jarvis, J. Ramirez, E. Prez-Portilla, K. Schepp, and A. Eitzinger. 2011. Predicted impact of climate change on coffee supply chains. The economic, social and political elements of climate change. Part 4, 703–723.

Lara-Estrada, L. and Vaast, P. 2007. Effects of altitude, shade, yield and fertilization on coffee quality (*Coffea arabica* L. Caturra) produced in agroforestry systems of the Northern Central Zones of Nicaragua. The Second International Symposium on Multi-Strata Agroforestry Systems with Perennial Crops, Turialba, Costa Rica.

Larcher, W. 2003. Gas exchange in plants. In: Larcher W (ed) Physiological plant ecology, 4th edn. Springer, Berlin, pp 91 – 139.

Leakey, R.R.B. 1999. Agroforestry for biodiversity in farming systems. In: Collins, W.W., Qualset, C.O. (eds), Biodiversity in Agroecosystems. CRC Press, Boca Raton, FL, USA, pp 127 – 145.

Leroy, T., F. Ribeyre, B. Bertrand, P. Charmetant and M. Dufour. 2006. Genetics of coffee quality. Brazilian Journal of Plant Physiology 18: 229 – 242.

Lin B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agricultural and Forest Meteorology 144: 85 – 94.

Lingle, T.R. 2001. The Coffee Cuppers Handbook. A Systematic Guide to the Sensory Evaluation of Coffee's Flavour, 3rd Ed. Specialty Coffee Association of America.

Luo Y., Reynolds J., Wang Y., Wolfe D. 1999. A search for predictive understanding of plant responses to elevated [CO_2]. Global Change Biology 5: 143-156.

Lusk C., Reich P.B., Montgomery R.A., Ackerly D.D., Cavender-Bares J. 2008. Why evergreen leaves so contrary about shade? Trends in Ecology and Evolution 23: 299-303.

Maestri, M. and Barros R.S. 1977. Coffee In: Alvim P.T. and Kowslowski T.T. (eds), Ecophysiology of Tropical crops. Academic Press, New York, USA, pp 249 – 278.

Marin, K., Pozrl, T., Zlatic, E. and Plestenjak, A. 2008. A new aroma index to determine the aroma quality of roasted and ground coffee during storage. Food Technology and Biotechnology 46 (4): 442 – 447.

Martin, M.J., Pablos, F. and Gonzales, A.G. 1998. Discrimination between Arabica and Robusta green coffee varieties according to their chemical composition. Talanta 46 (6): 1259 -1264.

Matos, F.S., Wolfgramm R., Gonclaves F.V., Cavatte P.C., Ventrella M.C. and DaMatta F.M. 2009. Phenotypic plasticity in response to light in coffee tree. Environmental and Experimental Botany 67: 1781 -1787.

Mayoli R.N. and Gitau K.M. 2012. The effects of shade trees on the physiology of Arabica coffee. African Journal of Horticultural Science 6: 35 – 42.

Mazzafera, P. 1991. Trigonelline in coffee. Phytochemistry 30:2309–2310.

Mburu, J.K. 2004. The current recommendations for the processing of high quality and safe coffee in Kenya. In the Proceedings of 20th International Scientific Colloquium on Coffee, pp 509-512. Bangalore India.

McClelland, T.L., 1935. Coffee shade in Kenya. East African Agricultural and Forestry Journal 1 (2): 107-118.

Mehlich, A., Pinkerton A., Robertson W. and Kempton R. 1962. Mass analysis methods of soil fertility and evaluation. Scott Agricultural Laboratories. Ministry of Agriculture, Nairobi.

Miguel, P. and Toledo V.M. 1999. Review: Biodiversity conservation in traditiona coffee systems of Mexico. Conservation Biology 13(1): 11- 21.

Mohotti, A.J. and Lawlor, D.W. 2002. Diurnal variation of photosynthesis and photoinibition in tea: effects of irradiance and nitrogen supply during growth in the field. Journal of Experimental Botany 53(367): 313 – 322.

Montagnon, C., Guyot, B., Cilas, C. and Leroy, T. 1998. Genetic parameters of several biochemical compounds from ground coffee, *Coffea canephora*. Plant Breeding 117: 576–578.

Montavon, P., Duruz, E., Rumo, G., and Pratz, G. 2003. Evolution of green coffee profiles with maturation and relationship to coffee cup quality. Journal of Agriculture, Food and Chemistry 51: 2328–2334.

Monteith , J.L., Ong C.K. and Corlett J.E., 1991. Microclimatic interaction in agroforestry system. Forest Ecology Management 45: 31 – 44.

Morais, H., Caramori P.H., Ribeiro A.M. de Arruda., Gomes J.C. and Koguishi M.S. 2006. Microclimatic characterization and productivity of coffee plants grown under shade of pigeon pea in Southern Brazil. Pesquisa Agropecuária Brasileira 41(5): 763 – 770.

Moreira, R.F.A., Trugo, L.C., De Maria, C.A.B., Matos, A.G.B., Santos, S.M., and Leite J.M.C. 2001. Discrimination of Brazilian Arabica green samples by chlorogenic acid composition. American Archives of nutrition, 51:95-99.

Motsara, M.R. and Roy R.N. 2008. Guide to laboratory establishment for plant nutrient analysis. Fertilizer and Plant Nutrition Bulletin 19, Food and Agriculture Organization of the United Nations, Rome, Italy.

Mouen Bedimo, J. A, Bieysse, D., Njiayouom, I., Deumeni, J. P., Cilas, C., and Nottéghem, J. L. 2007. Effect of cultural practices on the development of Arabica coffee berry disease, caused by *Colletotrichum kahawae*. European Journal of Plant Pathololology 119: 391-400.

Mouen Bedimo, J.A., Dufour B.P., Cilas C. and Avelino J. 2012. Effets des arbres d'ombrage sur les bioagresseurs de *Coffea arabica*. Cahier Agricultures 21: 89 – 97.

Mugo, H.M. 2010. Integration of soil fertilizers, selective insecticides and predacious mites for the management of coffee insect pests in Kenya. PhD thesis, University of Nairobi.

Muller R.A., Berry D., Avelino J. and Bieysse D. 2004. Coffee Diseases. In: Wintgens, N., editor). Coffee: Growing, Processing, Sustainable Production. Wiley-VCH Verlag GmbH & Co. KGaA. p. 491-545.

Mumin, M. A., Akhter, K. F., Abedin, M. Z., & Hossain, M. Z. (2006). Determination and characterization of caffeine in tea coffee and soft drink by solid phase extraction and HPLC. Malaysian Journal of Chemistry 8(1), 045- 051.

Muschler, R.G. 1998. Tree crop compatibility in Agroforestry: production and quality of coffee grown under managed tree shade in Costa Rica. PhD Dissertation, University of Florida, Gainsville, FL.

Muschler, R.G. 2001. Shade improves quality in suboptimal coffee zone of Costa Rica. Agroforestry Systems51: 131-139.

Muschler, R.G. 2004. Shade Management and its effect on coffee growth and quality. In: Coffee: growing, processing, sustainable production: A guide book for growers, processors, traders and researchers. Ed. J. Wintgens. Wiley-VCH, Weinhein, Alemania, pp 391–418.

Mussatto, S.I., Machado, E.M., Martins, S. and Texeira, J.A. 2011. Production, composition and application of coffee and its industrial residues. Food and Bioprocess Technology 4: 661 – 672.

Nair, P., Buresh, R., Mugendi, D. and Latt, C. 1999. Nutrient cycling in tropical agroforestry systems: myths and science. In L. Buck, J. Lassoie, & E. Fernandes (Eds.), Agroforestry in Sustainable Agricultural Systems (pp. 1-33). CRC PRess.

Njoroge, J.M. 1992. Studies on fertilization, plant density, training, replacement methods of established coffee and intercropping food crops with Coffea arabica L. cv "Ruiru". PhD Thesis, University of Nairobi.

Njoroge, J.M. 1985. Effects of methane gas, plant residues, cattle manure and artificial fertilizers on coffee yield and quality in Kenya. Acta Horticulturae 158: 273 – 282.

Njoroge, J.M. and Kimemia J.K. 1993. Current observations and future trends in coffee intercropping studies in Kenya. Outlook in Agriculture 22: 43 – 48.

Northmore, J.M. 1965. Some factors affecting the quality of Kenya coffee 15. Turialba, Costa Rica, 184–193.

Nunes, M. A., Ramalho, J. C. and Dias, M. A. 1993. Effect of nitrogen supply on the photosynthetic performance of leaves from coffee plants exposed to bright light. – Journal of Experimental Botany 44: 893-899.

Nunes, M.A., Bierhuizen J.F., Ploegman C., 1968. Studies on productivity of coffee; I. Effect of light, temperature, and CO_2 concentration on photosynthesis of *Coffea arabica*. Acta Botanica Neerlandica, 17: 93 – 102.

Nutman, F.J. 1937. Photosynthesis of coffee leaves under natural conditions. Annals of Botany 1(3): 353 – 367.

Oberthur, T., Laderach, P., Posada, H., Fisher, M.J., Samper, L., Illera J., Collet, L., Moreno, E., Alarcón, R., Villegas, A., Usma, H., Perez, C. and Jarvis, A. 2011. Regional relationships between inherent coffee quality and growing enironment for denomination of origin labels in Nariño and Cauca, Colombia. Food Policy 36: 783–794.

Okibo, B.W. and Mwangi, J.K. 2013. Effects of liberalization on coffee production in Kenya. European Journal of Business and Management 5(3): 29 – 45.

Oliveira V.F., Zaidan, L.B.P., Braga, M.R., Aidar, M.P.M. and Carvalho, M.A.M. 2010. Elevated CO_2 atmosphere promotes plant growth and inulin production in the cerrado species *Vernonia herbacea*. Functional Plant Biology 37: 223-231.

Ong, C., C. Black, J. Wallace, A. Khan, L. Lott, N. Jackson, S. Howard and S.D.M. 2000. Productivity, microclimate and water use in *Grevillea robusta* – based agroforestry systems on hillslopes in semi-arid Kenya. Agriculture Ecosystems and Environment 80: 121-141.

Oruko, B.A. 1977. Yield response of Arabica coffee to fertilizers in Kenya – a review. Kenya Coffee 42: 227 – 39.

Orwa, C., Mutua A., Kindt R., Jamnadass R. and Anthony S. 2009. Agroforestree Database: a tree reference and selection guide version 4.0. (http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp)

Osborne, D.R. and Voogt, P. 1978. Carbohydrates, In: the analysis of nutrients in foods, Academic Press Inc. London Ltd. (pp 130-150).

Paulos D. and Tesfaye S. 2000. Some ecological parameters occurring in the major coffee growing areas of southwestern and southern Ethiopia. Proceedings of the workshop on control of Coffee Berry Disease (CBD) in Ethiopia. Addis Ababa, 13-15 August 1999. 533 -539.

Pearl, H.M., Nagai, C., Moore, P.H., Steiger, D.L., Osgood, R.V. and Ming, R. 2004. Construction of a genetic map for Arabica coffee. Theoretical and Applied Genetics 108:829–835.

Pendergrast, M. 1999. Uncommon grounds. Basic Books, New York 458pp.

Perfecto, I., Mas, A., Dietsch, T.V. and Vandermeer, J., 2003. Species richness along an agricultural intensification gradient: a tri-taxa comparison in shade coffee in southern Mexico. Biodiversity Conservation 12, 1239 – 1252.

Perfecto I., Vandermeer J., Mas A. and Pinto L.S. 2005. Biodiversity, yield, and shade coffee certification. Ecological Economics 54(4):435-446.

Petracco, M. 2001. Technology IV: Beverage Preparation: Brewing Trends for the New Millennium. In R.J. Clarke and Vitzthum O.G., eds. Coffee Recent Developments, Blackwell Science Ltd cap.7, p.140-164.

Pinard, F., Boffa J.M. and Rwakagara E. 2014. Scattered shade trees improve low-input smallholder Arabica coffee productivity in the Northern Lake Kivu region of Rwanda. Agroforestry Systems 88(4): 707-718.

Pochet, P. 1990. The quality of coffee from plantet to cup. Agricultural publications, Brussels, Belgium.

Pompelli M.F., Martins S.C., Antunes W.C., Chaves A.R. and DaMatta F.M. 2010. Photosynthesis and photoprotection in coffee leaves is affected by nitrogen and light availabilities in winter conditions. Journal of Plant Physiology 167(13):1052-60.

Pregitzer, K.S. and King J.S. 2005. Effects of soil temperature on nutrient uptake. In Nutrient Acquisition by Plants. H. Bassiri Rad (Ed.) Ecological Studies 181: 277 – 310.

Pushparajah, E. 1994. Leaf analysis and soil testing for plantation tree crops. International Workshop, Leaf Diagnosis and soil testing as a guide to crop fertilization. September 12-17 1994, International Board for Soil Research and Management (IBSRAM) Bangkhen, Bangkok 10900, Thailand.

Ramalho, J.C., Rebelo M.C., Santos M.E., Luísa Antunes M. and Nunes M. A. 1995. Effects of calcium deficiency on *Coffea arabica*. Nutrient changes and correlation of calcium levels with some photosynthetic parameters. Plant and Soil 172 (1): 87-96.

Ramalho, J.C., Pons T.L., Groeneveld H.W. and Nunes M.A. 1997. Photosynthetic responses of *Coffea arabica* leaves to a short-term high light exposure in relation to N availability . Physiologia Plantarum 101: 229-239.

Ramalho, J. C., Rodrigues, A. P., Semedo, J. N., Pais, I. P., Martins, L. D., Simões-Costa, M. C. and DaMatta, F. M. (2013). Sustained photosynthetic performance of *Coffea* spp. under long-term enhanced [CO_2]. *PLOS ONE*,*8*(12), e82712. http://doi.org/10.1371/journal.pone.0082712

Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil and Tillage Research 43: 131-167.

Romero-Alvarado Y., Soto-Pinto L., García-Barrios L. and Barrera-Gaytán J.F. 2002. Coffee yields and soil nutrients under the shades of *Inga* sp. vs. multiple species in Chiapas, Mexico. Agroforestry Systems 54(3):215-224.

Ronquim J.C., Prado C.H.B.A., Novaes P., Fahl J.I. and Ronquim C.C. 2006. Carbon gain in *Coffea arabica* during clear and cloudy days in the wet season. Experimental Agriculture 42: 147-164.

Schaller M., Schroth G., Beer J. and Jimenez F. 2003. Species and site characteristics that permit the association of fast-growing trees with crops: the case of *Eucalyptus deglupta* as coffee shade in Costa Rica. Forest Ecology and Management 175(1-3): 205-215.

Shwab, G.J., Lee C.D. and Pearce R. 2007. Sampling plant tissue for nutrient analysis. University of Kentucky Cooperative Extension Service. Available online at: http://www.ca.uky.edu/agc/pubs/agr/agr92/agr92.pdf

Siles P. (2007). Hydrological processes (water use and balance) in a coffee (*Coffea arabica* L.) monoculture and a coffee plantation shaded by *Inga densiflora* in Costa Rica. Doctor of Science Thesis, University Henri Poincaré (Nancy I)

Siles P., Harmand J.M. and Vaast P. 2010. Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. Agroforestry Systems 78: 269-286.

Siles P.D.G. and Vaast P. 2002. Comportamiento fisiológico del café asociado *Eucalyptus deglupta, Terminalia ivorensis* y sin sombre. Agroforestería en las Américas 9(35-36): 44-49.

Silva, E.A., Mazzafera, P., Brunini, O., Sakai, E., Arruda, F.B., Mattoso, L.H.C., Carvalho, C.R.L. and Pires, R.C.M. 2005. The influence of water management and environmental conditions on the chemical composition and beverage quality of coffee beans. Brazilian Journal of Plant Physiology 17:229-238.

Silva, S.A., Lima J.S.S. and Bottega E.L. 2013. Yield mapping of Arabic coffee and their relationship with plant nutritional status. Journal of Soil Science and Plant Nutrition 13(3): 556 – 564.

Snoeck, D. and Vaast P. 2004. Importance of organic matter and biological fertility in coffee soil. In "Coffee: Growing, Processing, Sustainable Production" Jean Nicolas Wintgens (ed) WILEY-VCH Verlag GmbH & Co. KGaA. Weinheim. Pp 371 – 383.

Somarriba E, Harvey C.A., Samper M., Anthony F., Gonzalez J., Staver C. and Rice R.A. 2004. Introduction: the role of agroforestry in biodiveesity conservation in tropical landscapes In: G Schroth, GAB da Fanseta, CA Harvey, C Gascon, HL Vasconcelos & AN Izac (eds) Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press. Washington, pp 198-226

Somporn, C., Kamtuo A., Theerakulpisut P. and Siriamornpun S. 2012. Effect of shading on yield, sugar content, phenolic acids and antioxidant property of coffee beans (*Coffea arabica* L. cv Catimor) harvested from north-eastern Thailand. Journal of the Science of Food and Agriculture 92: 1956 – 1963.

Soto-Pinto L., Perfecto Y., Castilio-Hernandez J., and Caballero-Nieto J. 2000 Shade effect on coffee production at the northern Tzeltal zone of the State of Chiapas, Mexico. Agriculture, Ecosystems and. Environment 80: 61–69.

Souza H.Nd., de Goede R.G.M., Brussaard L., Cardoso I.M., Duarte E.M.G., Fernandes R.B.A., Gomes L.C. and Pulleman M.M. 2012. Protective shade, tree diversity and soil properties in coffee agroforestry systems in the Atlantic Rainforest biome. Agriculture, Ecosystems and Environment 146(1):179-196.

Speer, K. and Kolling-Speer I. 2001. Lipids. In R. J. Clarke, O. G. Vitzthum (Eds), Coffee: Recent Developments (pp. 33–49). Blackwell Science, Oxford (UK).

Speer, K., and Kölling-Speer, I. 2006. The lipid fraction of the coffee bean. Brazilian Journal of Plant Physiology 18(1): 201-216.

Sridevi V. and Giridhar P. 2013. Influence of altitude variation on trigonelline content during ontogeny of *Coffea canephora* fruit. Journal of Food Studies 2(1): 62-74.

Staver C., Guharay F., Monterroso D. and Muschler R.G. 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agroforestry Systems 53: 151 – 170.

Sturdy, D., 1935. Observations on Coffee under artificial shade at Selian estate, Arusha. 1931-35. East African Agricultural Journal 1: 135-139.

Tapley, R.G., 1961. Crinkly leaf of coffee in Tanganyika. Kenya Coffee 26: 156 – 157.

Trugo, L. C. 1984. HPLC in coffee analysis – PhD Thesis. University of Reading, England.

United States Agency for International Development (USAID), 2010. Kenya Coffee Industry Value Chain analysis. Profiling the actors, their interactions, costs, constraints and opportunities. Prepared by Chemonics International Inc.

Vaast P, Bertrand B, Perriot J J, Guyot B and Génard M. 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. Journal of Science, Food and Agriculture 86: 197-204.

Vaast P, R. van Kanten, P. Siles, B. Dzib, N. Franck, J. Harmand and M. Genard. 2005. Shade: a key factor for coffee sustainability and quality. Proceeding of the 20th International Congress on Congress Research (ASIC) Bangalore, India. Pp 887 – 896.

Vaast P, van Kanten R, Siles P, Angrand J, and Aguilar A. 2007. Biophysical Interactions between timber trees and Arabica coffee in suboptimal conditions of Central America. S. Jose and A M Gordon (eds). Towards Agroforestry Design: An Ecological Approach. Pp 135-148.

Van der Vossen, H.A.M. 1985. Coffee selection and breeding. In: M.N. Clifford and K.C. Willson (Eds.), Coffee botany, biochemistry and production of beans and beverage, Croom Helm, London. 49 – 96.

Van der Vossen, H.A.M. 2005. A critical analysis of the agronomic and economic sustainability of organic coffee production. Experimental Agriculture 41: 449–473.

Van Kanten R., and Vaast, P. 2006. Transpiration of Arabica coffee and associated shade tree species in suboptimal low-altitude conditions of Costa Rica. Agroforestry Systems 67: 187 – 202.

Variyar P. S., Ahmad, R., Bhat R., Niyas, N., & Sharma, A. 2003. Flavoring components of raw munsoned Arabica coffee and their changes during radiation process. Journal of Agriculture and Food Chemistry 51: 7945-7950.

Varnam, H.A. and Sutherland, P.J. 1994. Beverage technology chemistry and microbiology. New York: Chapman and Hall. Pp 191-254.

Viani, R. 2001. Global perspectives in coffee quality improvement. In: Proceedings of the International Scientific Symposium on coffee. Bangalore, India. pp. 120-127.

Wallace, J. S. 1996. The water balance of mixed tree–crop systems. In Tree–crop interactions – a physiological approach (ed. C. K. Ong and P. A. Huxley). Wallingford, UK: CAB International. pp 189–123.

Walters, R.G. 2005. Towards an understanding of photosynthetic acclimation. Journal of Experimental Botany 56: 435-47.

Weidner O., Muschler R., Goldbach H.E. and Burkhardt J. 2000. Influence of shade management on gas exchange and transpiration of coffee plants (*Coffea arabica L.*). Deutscher Tropentag 2000 in Hohenheim. Session: Impact of climate on crop production.

Willson, K.C. 1985. Mineral nutrition and fertilizer needs. In “Coffee: botany, biochemistry and production of beans and beverages (Ed. Clifford and Wilson). AVI Publishing Company. INC Westport, Connecticut. Pp 135-156.

Wintgens, J.N. 2004. The coffee plant. In: Coffee: growing, processing, sustainable production. J.N. Wintgens, V.C.H. Wiley, GmbH. Verlag and Co., KGaA (Eds). Weinheim, Germany. pp 3– 24.

Wormer, T. 1965. The effect of soil moisture, nitrogen fertilization and some meteorological factors on stomatal aperture of *Coffea arabica* L. Annals of Botany 29: 523 – 539.

Wrigley, G. 1988. Coffee. Tropical Agriculture Series Longman Scientific and Technical. John Willey and Sons, INC, New York 639pp.

Yadessa, A., Burkhardt, J., Denich, M., Gole, T.W., Bekele, B. and Goldhach, H. 2008. Effect of different indigenous shade trees on the quality of wild Arabica coffee in the Afromontane Rainforest of Ethiopia. Poster presented at the 22nd International Conference on Coffee Science (ASIC) held between 14-19 September 2008, Campinas, SP, Brazil.

Youkhana, A.H. and Idol T.W. 2010. Growth, yield and value of managed coffee agroecosystem in Hawaii. Pacific Agriculture and Natural Resources 2: 12-19.

APPENDICES

Appendix 1: Rainfall (mm) and temperature (°C) at Namwela

	Rainfall (mm)			Mean temperature (°C) (2010 – 2012)	
	2010	2011	2012	Maximum	Minimum
January	76.8	14.5	3.3	29.5	13.1
February	163.9	24.0	11.8	30.8	15.1
March	112.5	225.2	108.3	28.8	14.8
April	168.6	150.3	117.1	26.7	13.4
May	129.1	141.9	237.1	26.0	11.5
June	84.7	93.4	73.4	25.3	12.3
July	60.3	82.4	40.9	25.9	11.3
August	188.9	126.6	55	25.3	11.8
September	190.3	113	117.6	25.2	11.8
October	184.2	79.6	129.4	26.6	12.6
November	65.7	138.8	148.5	26.8	14.8
December	60.4	45.8	123.1	26.8	14.9
Total	1485.4	1235.5	1165.5		
Mean				27.0	13.1

Source: CRI Meteorological data, Namwela Meteorological Station

Appendix 2: Sensory evaluation procedure for beverage quality

Samples should first be visually inspected for roast color. This is marked on the sheet and may be used as a reference during the rating of specific flavor attributes. The sequence of rating each attribute is based on the flavor perception changes caused by decreasing temperature of the coffee as it cools:

Step 1 – Fragrance/Aroma

1. Within 15 minutes after samples have been ground, the dry fragrance of the samples should be evaluated by lifting the lid and sniffing the dry grounds.

2. After infusing with water, the crust is left unbroken for at least 3 minutes but not more than 5 minutes. Breaking of the crust is done by stirring 3 times, then allowing the foam to run down the back of the spoon while gently sniffing. The Fragrance/Aroma score is then marked on the basis of dry and wet evaluation.

Step 2 – Flavor, Aftertaste, Acidity, Body, and Balance

3. When the sample has cooled to 160º F (about 70º C), 8-10 minutes from infusion and evaluation of the liquor should begin. The liquor is aspirated into the mouth in such a way as to cover as much area as possible, especially the tongue and upper palate. Because the retro nasal vapors are at their maximum intensity at these elevated temperatures, Flavor and Aftertaste are rated at this point.

4. As the coffee continues to cool (160º F - 140º F; 70º C - 60º C), the Acidity, Body and Balance are rated next. Balance is the cupper's assessment of how well the Flavor, Aftertaste, Acidity, and Body fit together in a synergistic combination.

5. The cupper's preference for the different attributes is evaluated at several different temperatures (2 or 3 times) as the sample cools. To rate the sample on the 10-point scale, circle the appropriate tick-mark on the cupping form. If a change is made (if a sample gains or loses some of its perceived quality due to temperature changes), re-mark the horizontal scale and draw an arrow to indicate the direction of the score.

Step 3 – Sweetness, Uniformity, and Cleanliness

6. As the brew approaches room temperature (below 100º F; 37 º C) Sweetness, Uniformity, and Clean Cup are evaluated. For these attributes, the cupper makes a judgment on each individual cup, awarding 2 points per cup per attribute (10 points maximum score).

7. Evaluation of the liquor should cease when the sample reaches 70º F (21º C) and the Overall score is determined by the cupper and given to the sample as "Cupper's Points" based on ALL of the combined attributes.

Step 4 – Scoring

8. After evaluating the samples, all the scores are added as describe in the "Scoring" section below and the Final Score is written in the lower right hand box.

Appendix 3: Flavour attributes for coffee

Each of these attributes is described more fully as follows:

***Fragrance/Aroma**:* The aromatic aspects include Fragrance (defined as the smell of the ground coffee when still dry) and Aroma (the smell of the coffee when infused with hot water). One can evaluate this at three distinct steps in the cupping process: (1) sniffing the grounds placed into the cup before pouring water onto the coffee; (2) sniffing the aromas released while breaking the crust; and (3) sniffing the aromas released as the coffee steeps. Specific aromas can be noted under "qualities" and the intensity of the dry, break, and wet aroma aspects noted on the 5-point vertical scales. The score finally given should reflect the preference of all three aspects of a sample's Fragrance/Aroma.

***Flavor**:* Flavor represents the coffee's principal character, the "mid-range" notes, in between the first impressions given by the coffee's first aroma and acidity to its final aftertaste. It is a combined impression of all the gustatory (taste bud) sensations and retro nasal aromas that go from the mouth to nose. The score given for Flavor should account for the intensity, quality and complexity of its combined taste and aroma, experienced when the coffee is slurped into the mouth vigorously so as to involve the entire palate in the evaluation.

Aftertaste: Aftertaste is defined as the length of positive flavor (taste and aroma) qualities emanating from the back of the palate and remaining after the coffee is expectorated or swallowed. If the aftertaste were short or unpleasant, a lower score would be given.

***Acidity**:* Acidity is often described as "brightness" when favorable or "sour" when unfavorable. At its best, acidity contributes to a coffee's liveliness, sweetness, and fresh-fruit character and is almost immediately experienced and evaluated when the coffee is first slurped into the mouth. Acidity that is overly intense or dominating may be unpleasant, however, and excessive acidity may not be appropriate to the flavor profile of the sample. The final score marked on the horizontal tick-mark scale should reflect the panelist's preference for the Acidity relative to the expected flavor profile based on origin characteristics and/or other factors (degree of roast, intended use, etc.). Coffees expected to be high in Acidity, such as a Kenya coffee, or coffees expected to be low in Acidity, such as a Sumatra coffee, can receive equally high preference scores although their intensity rankings will be quite different.

***Body**:* The quality of Body is based upon the tactile feeling of the liquid in the mouth, especially as perceived between the tongue and roof of the mouth. Most samples with heavy Body may also receive a high score in terms of quality due to the presence of brew colloids. Some samples with lighter Body may also have a pleasant feeling in the mouth, however. Coffees expected to be high in Body, such as a Sumatra coffee, or coffees expected to be low in Body, such as a Mexican coffee, can receive equally high preference scores although their intensity rankings will be quite different.

***Balance**:* How all the various aspects of Flavor, Aftertaste, Acidity and Body of the sample work together and complement or contrast to each other is Balance. If the sample is lacking in certain aroma or taste attributes or if some attributes are overpowering, the Balance score would be reduced.

***Sweetness**:* Sweetness refers to a pleasing fullness of flavor as well as any obvious sweetness and its perception is the result of the presence of certain carbohydrates. The opposite of sweetness in this context is sour, astringency or "green" flavors. This quality may not be directly perceived as in sucrose-laden products such as soft drinks, but will affect other flavor attributes. 2 points are awarded for each cup displaying this attribute for a maximum score of 10 points.

***Clean Cup**:* Clean Cup refers to a lack of interfering negative impressions from first ingestion to final aftertaste, a "transparency" of cup. In evaluating this attribute, notice the total flavor experience from the time of the initial ingestion to final swallowing or expectoration. Any noncoffee like tastes or aromas will disqualify an individual cup. 2 points are awarded for each cup displaying the attribute of Clean Cup.

Uniformity*:* Uniformity refers to consistency of flavor of the different cups of the sample tasted. If the cups taste different, the rating of this aspect would not be as high. 2 points are awarded for each cup displaying this attribute, with a maximum of 10 points if all 5 cups are the same.

Overall*:* The "overall" scoring aspect is meant to reflect the holistically integrated rating of the sample as perceived by the individual panelist. A sample with many highly pleasant aspects, but not quite "measuring up" would receive a lower rating. A coffee that met expectations as to its character and reflected particular origin flavor qualities would receive a high score. An exemplary example of preferred characteristics not fully reflected in the individual score of the individual attributes might receive an even higher score. This is the step where the panelists make their personal appraisal.

The quality of specific flavor attributes is analyzed, and then drawing on the cupper's previous experience, samples are rated on a numeric scale. The scores between samples can then be compared. Coffees that receive higher scores should be noticeably better than coffees that receive lower scores. The Cupping Form provides (Appendix 4) a means of recording 11 important flavour attributes for coffee: Fragrance/Aroma, Flavor, Aftertaste, Acidity, Body, Balance, Uniformity, Clean Cup, Sweetness, Defects, and Overall. The specific flavor attributes are positive scores of quality reflecting a judgment rating of the cupper; the defects are negative scores denoting unpleasant flavor sensations; the Overall score is based on the flavor experience of the individual cupper as a personal appraisal. These are rated on a 10-point scale representing levels of quality increments between numeric values from 1 to 10.

The Cupping Form provides a means of recording 11 important flavour attributes for coffee: Fragrance/Aroma, Flavor, Aftertaste, Acidity, Body, Balance, Uniformity, Clean Cup, Sweetness, Defects, and Overall. The specific flavor attributes are positive scores of quality reflecting a judgment rating of the cupper; the defects are negative scores denoting unpleasant flavor sensations; the Overall score is based on the flavor experience of the individual cupper as a personal appraisal. These are rated on a 10-point scale representing levels of quality increments between numeric values from 1 to 10. These levels are: Quality Scale

Scale	Acidity	Mouth feel (Body)	Preference
1	Very Flat	Very Thin	Very Poor
2	Flat	Thin	Poor
3	Very Soft	Very Light	Acceptable
4	Soft	Light	Fair
5	Slightly Sharp	Slightly Full	Average
6	Sharp	Full	Good
7	Very Sharp	Very Full	Very Good
8	Slightly Bright	Slightly Heavy	Fine
9	Bright	Heavy	Excellent
10	Very Bright	Very Heavy	Outstanding

Individual Component Scores

On some of the positive attributes, there are two tick-mark scales. The *vertical* (up and down) scales are used to rank the *intensity* of the listed sensory component and are marked for the evaluator's record. The *horizontal* (left to right) scales are used to rate the panelist's *preference* of the particular component based upon their perception of the sample and experiential understanding of quality. The attribute score is recorded in the appropriate box on the cupping form.

Final Scoring

The Final Score is calculated by first summing the individual scores given for each of the primary attributes in the box marked "Total Score." Defects are then subtracted from the "Total Score" to arrive at a "Final Score." The Final Score is recorded in the lower right hand box.

The following Scoring Key has proven to be a meaningful way to describe the range of coffee quality for the Final Score: -

Total Score	**Specialty Description**	**Classification**
90-100	Outstanding	Specialty Rare
85-89.99	Excellent	Specialty Origin
80-84.99	Very Good	Specialty
< 80.0	Below Specialty Quality	Below Specialty

Source: SCAA Roasting and cupping protocol,

https://onyxcoffee.wordpress.com/2009/10/01/scaa-roasting-and-cupping-protocol/

Appendix 4: Cupping form

Specialty Coffee Association of America Cupping Form

SPECIALTY COFFEE ASSOCIATION OF AMERICA

Name: ______________________

Date: __________ Table: __________ Session: __________

Classification:

6.00 - Good	7.00 - Very Good	8.00 - Excellent	9.00 - Outstanding
6.25	7.25	8.25	9.25
6.50	7.50	8.50	9.50
6.75	7.75	8.75	9.75

Sample #

Roast level

Fragance/Aroma — *Total:* — 6 7 8 9 10 — Dry, Quality:, Crust:

Flavor — *Total:* — 6 7 8 9 10

Aftertaste — *Total:* — 6 7 8 9 10

Acidity: — *Total:* — 6 7 8 9 10 — Intensity: High, Low

Body — *Total:* — 6 7 8 9 10 — Intensity: High, Low

Uniformity — *Total:* — □ □ □ □ □

Balance — *Total:* — 6 7 8 9 10

Clean Cup: — *Total:* — □ □ □ □ □

Sweetness — *Total:* — □ □ □ □ □

Overall — *Total:* — 6 7 8 9 10

Total Score

Defects (subtract) — Taint=2, Fault=4 — # of cups □ X Intensity □ = □

Notes:

Final Score

Sample #

Roast level

Fragance/Aroma — *Total:* — 6 7 8 9 10 — Dry, Quality:, Crust:

Flavor — *Total:* — 6 7 8 9 10

Aftertaste — *Total:* — 6 7 8 9 10

Acidity: — *Total:* — 6 7 8 9 10 — Intensity: High, Low

Body — *Total:* — 6 7 8 9 10 — Intensity: High, Low

Uniformity — *Total:* — □ □ □ □ □

Balance — *Total:* — 6 7 8 9 10

Clean Cup: — *Total:* — □ □ □ □ □

Sweetness — *Total:* — □ □ □ □ □

Overall — *Total:* — 6 7 8 9 10

Total Score

Defects (subtract) — Taint=2, Fault=4 — # of cups □ X Intensity □ = □

Notes:

Final Score

Sample #

Roast level

Fragance/Aroma — *Total:* — 6 7 8 9 10 — Dry, Quality:, Crust:

Flavor — *Total:* — 6 7 8 9 10

Aftertaste — *Total:* — 6 7 8 9 10

Acidity: — *Total:* — 6 7 8 9 10 — Intensity: High, Low

Body — *Total:* — 6 7 8 9 10 — Intensity: High, Low

Uniformity — *Total:* — □ □ □ □ □

Balance — *Total:* — 6 7 8 9 10

Clean Cup: — *Total:* — □ □ □ □ □

Sweetness — *Total:* — □ □ □ □ □

Overall — *Total:* — 6 7 8 9 10

Total Score

Defects (subtract) — Taint=2, Fault=4 — # of cups □ X Intensity □ = □

Notes:

Final Score

Source: Specialty Coffee Association of America (SCAA)