EVALUATION OF LEGUME COVER CROPS INTERCROPPED WITH COFFEE

STEPHEN MUIA KISEVE

B.Sc. Agriculture (Hons), University of Nairobi

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENT FOR THE AWARD OF

MASTERS OF SCIENCE DEGREE IN AGRICULTURAL RESOURCES

MANAGEMENT

DEPARTMENT OF PLANT SCIENCE AND CROP PROTECTION

FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

2012

DECLARATION

I declare that this is my original work and has not been presented for an award of a degree in any other University

Stephen M. Kiseve_____________________________ Date ______________________

This thesis is submitted for examination with our approval as the University supervisors:

1. **Prof. Mary W. K. Mburu**

   Department of Plant Science and Crop Protection

   University of Nairobi

   Signature ______________________________ Date _______________________

2. **Prof. Charles K. K. Gachene**

   Department of Land Resource Management and Agricultural Technology

   University of Nairobi

   Signature ______________________________Date _______________________

3. **Dr. Jedidah M. Maina**

   Kenya Agricultural Research Institute

   Signature ___________________________Date ___________________________

DEDICATION

To The Lord God from whom all blessings come and for His grace by which I got the opportunity, resources and ability to study

To my dear parents Samson Kyumbi Kiseve and Bretta Munee who form the bed rock of my academic excellence through their motivation and good will

ACKNOWLEDGEMENT

I thank my supervisors Prof. M.W.K. Mburu (Department of Dryland Agriculture, South Eastern University College, constituent college of the University of Nairobi), Prof. C.K.K. Gachene (Department of Land Resource Management and Agricultural Technology, University of Nairobi) and Dr J.M. Maina of Kenya Agricultural Research Institute for the devotion, guidance and skillful advice during this study.

I am very grateful to the University of Nairobi technical staff who assisted me in field and laboratory work. I am indebted to the Public Service Commission of Kenya and Ministry of Agriculture for graciously according me study leave to pursue this programme. I am indebted to my collegues of the pioneering M.Sc. Agricultural Resource Management class who made my stay in Kabete memorable through academic discussions and shared fun. I acknowledge the District Agricultural Officer Siakago, Mr P. Nyaga and Gatundu District Agricultural Officer Mr A. Nyaga and Faith Kariuki for the assistance they accorded to me at my working stations.

Last but not least, I acknowledge my brothers Nahason Nyamasyo and Sam Kimanthi, sisters in Christ Dr. Martha Mueni Sila and Regina Mumbua Tende for their prayers and warm support during my study. God bless all who in one way or another contributed to my success.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

ACRONYMS

BNF	Biological Nitrogen Fixation
DAP	Days After Planting
DM	Dry Matter
GMLCC	Green Manure Legume Cover Crop
HI	Harvest Index
LCC	Legume Cover Crop
LRNP	Legume Research Network Project
LSD	Least Significant Difference
PAR	Photosynthetically Active Radiation
RUE	Radiation Use Efficiency
SMC	Soil Moisture Content
TDM	Total Dry Matter
WAP	Weeks After Planting

Abstract

A field experiment was conducted at the central highlands of Kenya at Kabete, University of Nairobi, during the March/ April 2005 long rains season. The objective of this study was to investigate the growth of 13 legume cover crops under coffee and their impacts on weeds. Yield of grain legumes and Soil moisture content under legumes was also assessed.

Average soil moisture content was significantly higher ($P < 0.05$) by 8 % at 11 WAP compared to 30 WAP and was also significantly higher by 15 % under mucuna compared to other legume at upper depths (< 50cm). All legumes had attained over 90 % PAR interception by 12 WAP except Neontonia and canavalia that attained the same at 16 WAP. Crotalaria accumulated the highest biomass (14,006kg/ha) and mucuna the lowest (1,004 kg/ha). Intercropped soyabean had the highest grain yield (894 kg/ha) among the assessed food legumes. Intercropping did not have significant effects on emergence and shoot vigor of legumes but on average it significantly ($P < 0.05$) decreased grain yield, biomass accumulation, litter fall by 59 %, 46 %, 42 % respectively. Total dry matter accumulation and cumulative PAR interception were positively and highly correlated. Silver leaf desmodium, crotalaria, mucuna were significantly ($P<0.05$) more effective in weed suppression compared to other legumes because they sustained high ground cover (> 90 %) overtime. Over all, the most outstanding legumes in terms of biomass accumulation, ground cover (PAR interception), and weed suppression were crotalaria, desmodium, dolichos and mucuna.

Results of this study indicate that the use of proper choice of legume cover crop species may provide a cost –effective alternative strategy for soil fertility improvement, soil moisture conservation and weed management in small holder coffee farms.

Key words: Coffee, legume cover crops, intercropping, weeds control.

CHAPTER 1

INTRODUCTION

1.1 History and global importance of coffee

Coffee is the most widely traded commodity in the world after petroleum with an annual turnover exceeding US$10 billion and a major contributor of even up to 80 percent of total foreign currency earnings in some African countries (Nair, 2010). In 2000/2001 it commanded a gross value of US$ 65billion (Coffee Board of Kenya, 2003a; International Coffee Organization, 2011) and accounted for exports worth US$ 15.4 billion in 2009/10 (International Coffee Organization, 2011). Coffee is produced in more than sixty tropical countries, providing a livelihood for twenty-five million farmers around the world (Waller *et al*., 2007). The two most commercially important coffee species grown are varieties of *Coffea canephora* (robusta) and *Coffea arabica* (arabica) with *Coffee arabica* being the most widespread species accounting for about 80 % of the world's coffee production (Coste and Cambrony, 1992; Coffee Research Institute, 2006).

The primary center of origin and genetic diversity of *Coffea arabica* is Ethiopia, which is recognized as its oldest exporter in the world (Coste and Cambrony, 1992; Waller *et al*., 2007). Coffee spread from Ethiopia and begun to be grown in other parts of the world such as Asia, Europe and India in early 1600s and later in the United States of America in 1668 (International Coffee Organization, 2011). It is now established in the economies and lifestyles of the main producing and trading nations. Coffee is cultivated for its popular beverage (coffee) obtained from the dried beans (Wilson, 1999). Currently coffee is cultivated in eighty countries within the tropics of

Cancer and Capricorn in South and Central America, the Caribbean, Africa and Asia. The largest producers of coffee are Brazil, Vietnam, Indonesia, Colombia, India, and Ethiopia in that order (Food and Agricultural Organization, 2010). Africa's contribution to the world's total coffee production was 27 % and 17 % between 1963 to 1980 and 1990 to 2004 respectively and 10.9 % in 2010 (Food and Agricultural Organization, 2012). The leading producers of coffee in Africa are Ethiopia, Uganda, Cote d' Ivoire, Madagasca, Cameroon, Kenya and Tanzania in that order (Food and Agricultural Organization, 2012). Kenya contributed 8.3, 8.5 and 4.6 % of Africa's total coffee in 1990, 2000 and 2010 respectively (Table 1).

Table 1 Coffee production between 1963 and 2010

Coffee (green) Production (1000) Mt)	1963	1970	1980	1990	2000	2010
World	4,152	3,850	4,837	6,072	7,550	836
Africa	997	1,295	1,161	1,255	1,185	908
Kenya	41	58	91	104	101	42
Kenya's % of Africa	4.1	4.5	7.8	8.3	8.5	4.6

Source: Food and Agricultural Organization, 2012

1.2 Importance of coffee in Kenya

Coffee was introduced as a cash crop in Kenya by the missionaries in 1898 and it has remained important in Kenya's economy to date (Coffee Board of Kenya, 2003b; Coffee Research Foundation, 2012a). The coffee sub sector is a major contributor to the Kenyan economy. In the 1980s, 2005 and 2011 coffee contributed about 40, 10 and 8 % of the total domestic foreign exchange earnings respectively. Coffee sales earned Kenya US $ 20 billion between 1987 and 2002 (Coffee Board of Kenya, 2003a) and 5.4 billion export sales in 2008 (Food and Agricultural Organization, 2010). It ranked fourth after tourism, tea and horticulture and contributed about KSh. 16 billion in 2009/10 (Ministry of Agriculture, 2011). Coffee incomes have been invested in the economy, mainly in the rural areas brining considerable rural development in terms of improvement of farm income, employment and food security. Over the years, coffee has contributed towards poverty alleviation especially among the small holders because it has a medium to high potential for agriculture growth and medium potential for poverty reduction. Today 250,000 Kenyans are employed in the coffee sector (Coffee Research Foundation, 2012a).

1.3 Coffee production systems in Kenya

The total area under coffee has steadily grown over the years from 1,215 hectares owned by 11, 864 licensed growers in 1952 to 170,000 hectares grown by about 700,000 smallholders and 3,217 estates in 2003 (Coffee Board of Kenya, 2001; Coffee Board of Kenya, 2003a) but has since reduced to 155,000 hectares in 2008 (Food and Agricultural Organization, 2012). The annual coffee production had been on a downward trend from an all time high of 128,700 mt in 1988 to 42,000 mt in 2010 (Food and Agricultural Organization, 2012). This decline was attributed to an escalating cost of production (especially fertilizer and other inputs), lack of affordable credit, adverse weather conditions, declining global coffee prices and poor corporate governance in coffee institutions (Coffee Board of Kenya, 2005; Ministry of agriculture, 2010).

Both large-scale commercial estates and small holder farmers currently grow coffee in Kenya and account for about 33 and 67 % of the total area under coffee and about 53 and 47 % of the actual total production respectively (Coffee Board of Kenya, 2003b). The commercial estates (> 25 hectares) typically maintain a monoculture system with high standard of management and achieve high yields and reasonable profitability. For many years many small-scale holders have been intercropping coffee with food crops to produce food for subsistence and income from the surplus produce (Wilson, 1999). Coffee yields in smallholder farms are very low compared to the estates. In 1993/94 cooperatives and estates registered average yields of 0. 34 tons/ ha and 1.01 tons/ ha that is nearly a 300 fold difference (Ministry of Agriculture and Livestock Development, 1997). The recent average production further reduced to 0.2 and 0.7 tons /ha of coffee for cooperatives and estates respectively (Coffee Board of Kenya, 2003b) and to 0.25 and 0.5 tons/ ha for cooperatives and estates respectively 2011 (Ministry of Agriculture, 2011).

The leading challenges that have contributed to decline in coffee industry performance in Kenya include high production, processing and transaction costs, lack of credit to finance farm activities, low and delayed coffee payments, competition for land between coffee and other high paying enterprises such as horticulture, floriculture, food crops and real estate development, restrictive world trade regulations, unpredictable coffee prices, unfavorable weather conditions, over dependence on old coffee trees, poor crop and post-harvest handling practices, poor soil fertility management, pests, diseases and weed infestations (Ministry of Agriculture and Livestock Development, 1997; Coffee Board of Kenya, 2003a; Coffee Board of Kenya, 2003b). For example when the International Coffee Agreement (ICA) collapsed in 1989 it lead to a decline in coffee prices that resulted to a 13 % drop in Kenya's production from over 100,000 tons of clean coffee in 1989/90 to 87,000 tones in 1990/91 (Kimemia, 1998).

Kenya's coffee is mainly grown in the highland districts of Kenya: Kiambu, Muranga, Nyeri, Thika, and Kirinyaga in CentralProvince; Meru North, Meru Central, Meru South, Embu, Machakos and Kitui in Eastern Province; Nakuru, West Pokot, Kajiado, Baringo, Kericho, Nandi, Laikipia, Transnzoia, UasinGishu, Keiyo, Marakwet and Kajiado in Rift Valley Province; Bungoma, Kakamega, and Busia in Western Province; Kisii, Siaya, Kisumu, and South Nyanza in Nyanza Province; and Taita in Coast Province. The high production zone is a triangle formed by Mt. Kenya, the Aberdare Range and Machakos Town essentially the Central and Eastern Provinces which account for about 70 per cent of Kenya's coffee production (Coste and Cambrony, 1992; Coffee Board of Kenya, 2001; Coffee Board of Kenya, 2010; Mureithi, 2008). Due to population pressure and demand for individual land ownership there has been an increase in sub-division of agricultural land, further reducing available coffee growing areas. Low coffee prices have pushed the small scale farmer from coffee growing to more profitable enterprises such as dairy and tea farming, which also flourishes very well at the higher altitudes, leaving coffee unattended. Due to slow payments and low returns coupled with lack of appropriate management practices, farmers do not have incentive to invest in better farm management practices in coffee and thus the decline in coffee productivity and quality.

The most important factors limiting coffee production in Kenya's smallholder farms are declining soil fertility, pest, disease and weed infestations, high costs of inputs (fertilizers, pesticides and labour) (Coffee Research Foundation, 2003) and low coffee prices (Coffee Board of Kenya, 2003b). Low coffee returns have reduced farmers' ability to effectively improve soil fertility through maintenance of soil conservation structures and application of recommended fertilizers rates and control weeds leading to further decline in coffee yields. Small scale farmers have now intercropped coffee with annual food legumes to maximize on land utilization for food production (Kimemia, 2003). Inappropriate intercrop systems have resulted to further destruction of soil conservation structures (terrace embankments) and increased soil erosion. These constraints should be addressed with the aim of guaranteeing greater production margins especially for small holder farmers who are more vulnerable to yield losses compared to large scale farmers.

To ensure improved productivity of coffee, the government has put in place strategies to improve coffee productivity that include creating an enabling legal and economic environment, improved research, extension and market services and effective land and water resource management and improved crop husbandry practices (Ministry of Agriculture, 1997; Ministry of Agriculture and Ministry of Livestock and Fisheries Development, 2004). High coffee yields can be achieved through high standards of husbandry including good soil fertility management practices, effective pest, disease and weed control (Wilson, 1999). Legume cover crops can potentially play an important role in reducing soil erosion, replenishing and maintaining soil fertility and weed control in coffee farms (Giller 2001).

1.4 Use of legume cover crops (LCC) as coffee intercrops

1.4.1 Potential advantages of using LCC as coffee intercrops

Growing of under-storey legumes has been widely practiced and found useful as cover crops with virtually all types of plantain crops such as coffee (Giller, 2001). Legumes that have been most successful cover crops in plantations are species that are excellent forage, pasture or green manure legumes and those that spread rapidly to provide complete soil cover between the established trees (Giller, 2001) resulting to various benefits and accompanying costs (Snapp *et al.*, 2005).

Like many other intercrops, legume intercrops are extensively used for soil fertility improvement through N fixation and organic matter accumulation (Gachene and Kimaru, 2003). Improvement in soil fertility translates to reduced fertilizer requirements and therefore savings on fertilizer inputs. A mixture of *Centrosema pubescens* and *Pueraria phaseoloides* was estimated to contribute 151 kg N ha^{-1} $year^{-1}$ in an oil plantation in Malaysia through atmospheric nitrogen (N_2) fixation (Giller, 2001). Vissoh *et al*, (1998) reported an annual saving of about 6.5 million kg of N-fertilizer valued at 1.85 million USD due to adoption of mucuna into Nigerian farming systems. The combined incorporation of green manures and 30 kg P_2O_5 ha^{-1} and 30 kg N ha^{-1} significantly increased maize yield compared to use of 30 kg P_2O_5 ha-1 and 30 kg N ha-1 or green manure alone (Kimidi, 2000) indicating an added advantage in fertility improvement when green manures are used.

Legume cover crops (LCCs) can be grown for control of soil erosion (Gachene and Haru, 1997) and moisture preservation (Abayomi, *et al*., 2001; Giller, 2001). They can also be used as live mulch (Muller and Kotschi, 1997; Food and Agricultural

Organization, 2000), a practice that is beneficial in sustaining moisture in the soil (Giller, 2001; Mburu *et al,* 2003) and moderation of soil temperatures (Muller and Kotschi, 1997). When slashed back, some perennial legumes re-grow under the next crop (Giller, 2001) thereby maintaining soil cover suitable for moisture retention across seasons.

Cover crops are important weed suppressors. Cover crops such *Calopogonium caeruleum* and *Desmodium ovalifolium* are suitable understorey crops because they are shade-tolerant and persist longer when established ensuring effective weed control for a long time (Abayomi, *et al*., 2001; Giller, 2001). Legumes have also been used for control of pests by providing suitable habitats for beneficial insects (Vissoh *et al,* 1998) or breaking disease and pest cycles thereby reducing the need for use of pesticides and fumigation (Snapp *et al.*, 2005) which are hazardous to man and the environment. For example *Canavalia* and *Mucuna* have been reported to have shown repellant and insecticidal properties (McIntyre, et al., 2001). Canavalia has been used by some communities to control moles (Gachene and Kimaru, 2003).

Benefits of growing cover crops in plantations include increased crop yields (Giller, 2001; Sullivan, 2003a). Rubber trees grown with legume cover crops gave much higher yields over the first 4 years compared to trees grown with grass or other none-legume covers (Giller, 2001). Better responses to fertilization have been observed in plantations with cover crops (Giller, 2001). Intercropping with LCCs result to lower crop production costs and general increase in land productivity through provision of food for humans and forage for livestock. A survey by Kabambe *et al.* (1998) showed that 100% of Malawian farmers growing *Mucuna* used it for food. Legumes such as

Lablab purpureus (dolichos) and *Glycine max* (soya beans) are used both as a food and forage plant (Bunch and Buckles, 1998; Gachene and Makau, 2000). Grain legume crop residues are more often than not used as dry-season fodder either for feeding to animals in stalls or by free grazing of animals to safe on fodder harvesting costs (Giller, 2001).

1.4.2 Potential disadvantages of using LCC as coffee intercrops

Use of cover crops has some disadvantages that largely relate to costs of production. The costs of adopting cover crops include increased direct production costs such as labour costs for establishment and incorporation of green manure legume cover crops; establishment costs can be ten times higher for leguminous crops than for grasses (Snapp *et al.,* 2005). Labour demand for turning a stand of mucuna into the soil on 1 ha of land can be as high as 60 man- days (Giller, 2001).

Intercropped cover crops, especially where appropriate crop combinations, spacing management are not observed, can use up stored soil water that might otherwise be used for the main crop (Giller, 2001). LCC can potentially reduce incomes if their use competes with other attractive (cash) crops and slow soil-warming (Snapp *et al.,* 2005) or if they contain toxic substances such as canavelin in *Canavalia ensiformis* (Jackbean) (Gachene and Kimaru, 2003) that may even hinder legume adoption by farmers.

Despite the known disadvantages, GMLCC and other LCC have been widely adopted in many parts of the world including Kenya (Bunch and Buckles, 1998; Giller, 2001; Gachene and Makau, 2000; Mureithi *et al.,* 2003). Adoption of cover crops by small-scale farmers depends on whether they are grown on land that has few opportunity costs; for example on land left fallow or under tree or commercial crops, whether their use saves or requires very little additional labour and their biomass provides benefits over and above improvements to soil fertility (Bunch and Buckles, 1998). Since land is scarce, the opportunity costs of establishing sole legumes on agricultural land can be high unless the land is otherwise left fallow (Bunch and Buckles, 1998) farmers use appropriate LCC intercrops systems.

In Kenya, some farmers have intensified crop production by intercropping coffee with food legumes such as common beans (*Phaseolus vulgaris*), maize (Z*ea mays*) and Irish potatoes (*Ipomea batatus*) (Coffee Research Foundation, 2003; Khisa, 2000 and Mureithi *et al.*, 2003) for food production and other legume cover crops for weed control (Mureithi *et al.*, 2003). Intercropping coffee with annual crops like beans (*Phaseolus vulgaris*), and cowpeas (*Vigna unguiculata*) does not significantly affect coffee in terms of tree growth, yield and quality during the first year of establishment Kimemia (2003).

Perennial tree crops affect coffee differently. Intercropping coffee with perennial crops such as pawpaw (C*arica papaya*), passion fruit (*Pasiflora edulis*), apples (*Malus pumila*), oranges (*Citrus sinensis*), avocadoes (*Persea americana*), loquats (*Eriobotrya japonica*) and macadamia (*Macadamia ternifolia*) did not reduce clean coffee yields or bean quality. Bananas (*Musa sapentium*) and guava (*Psidium guajava*) however significantly depressed coffee plant height and yield components but did not affect coffee quality significantly (Kimemia, 1998).

Screening of legume species under the Legume Research Network Project (LRNP) has been done and some “best-bets” identified (Mureithi *et al.*, 2003). These include crotalaria, jack bean, silver leaf desmodium and mucuna (Gachene and Wortmann, 2004; Mureithi *et al*., 2003). C*anavalia ensiformis (*jack bean) and *Mucuna pruriens* (velvet bean) are among the best species in terms of ability to nodulate under low soil moisture conditions, tolerance to moisture stress, soil conservation and providing good ground cover for effective weed control (Gachene and Makau, 2000; Saha *et al.*, 2000). *Vicia benghalensis* (purple vetch) and *Lablab purpureus* (lablab) showed good cover while *Mucuna pruriens* and *Lablab purpureus* were good in biomass production (Gachene and Makau, 2000). Since legume cover crops provide ground cover and accumulate high biomass over a short time, they have a potential to effectively control weeds and therefore contribute towards savings in weeding labour in coffee. Their ability to fix atmospheric N is an added advantage which can result to reduced N fertilizer requirements. The possibility of intercropping legumes with coffee is an opportunity for improvement of land productivity and hence poverty alleviation among the smallholder coffee farmers.

1.5 Problem statement and justification

Kenya’s coffee is predominantly grown under a monoculture system (Coffee Board of Kenya, 2003c) that is characterized by declining productivity (Food and Agricultural Organization, 2012), low payments and lack of credit to coffee farmers (Nyangito, 2001). The major coffee production constraints are high costs of fertilizers, pesticides and labour for pest, disease and weed control (Coffee Research Foundation, 2003; Coffee Board of Kenya, 2003a; Ministry of agriculture, 2010).

Studies in Kenya coffee show that 72 % of smallholder farmers hire labour for farm activities which include weeding, pest management and harvesting (Karanja, 2002). Weeds decrease coffee yield and quality by over 50% (Njoroge and Kimemia, 1990). Fertilizers constitute over 26 % of the coffee production costs which most small holder farmers cannot afford, subsequently, farmers use them sub-optimally resulting in low coffee yields and quality (Karanja, 2002). Low returns of (monoculture) coffee have reduced farmers' ability to effectively improve soil fertility through maintenance of soil conservation structures and application of recommended fertilizers and pesticide rates and hire labour for weed control leading to further decline in coffee yields (Coffee Board of Kenya, 2003a; Hassan *et al.*, 1998).

Low and unreliable coffee earnings have driven small holder farmers to intercrop coffee with food crops. Inappropriate intercrop practices have led to destruction of soil conservation structures (terrace embankments) and increased soil erosion. Adequate information on suitable coffee intercrops to address these problems is lacking and limited research has been carried out in Kenya on suitable legume cover crop intercrops with mature coffee (Kimemia, 2003). Studies by Legume Research Network Project (LRNP) showed that the potential of using legume cover crops for soil fertility improvement, weed and soil erosion control is enormous (Gachene and Makau, 2000). This study investigated the effects of legume cover crops under coffee on weeds. Recommendations for their use in coffee and further research were made based on the information generated.

1.6 Objectives

1.6.1 Broad objective

To investigate the growth of legume cover crops under coffee and their impact on weeds.

1.6.2 Specific objectives

1. To evaluate the growth of different legume cover crops under coffee
2. To determine the effects of the legume cover crops on weeds under coffee

1.7 Hypothesis

1. Coffee has no effects on intercropped legume cover crops
2. Legume cover crops have the potential of controlling weeds in coffee

CHAPTER 2

LITERATURE REVIEW

2.1 Environmental requirements of Coffee

2.1.1 Climatic and soil requirements

Natural stands of *Coffea arabica* are found on the high plateau of Ethiopia at altitude of 1300-1800 m above sea level with annual rainfall of about 1500-1800 mm and average temperature ranging between 15-25^{o}C (Wilson, 1999; Waller *et al*, 2007). Coffee is adaptable to a range of ecological conditions (Coste and Cambrony, 1992). It can be established at an altitude of 1400-2000 m above sea level. For optimal growth, the maximum day temperatures should not exceed 30^{o}C and minimum night temperature not below 15^{o}C and annual rainfall of not less than 1000 mm. It requires well- drained, slightly acidic fertile loam soils with a depth of at least 1.5m and pH ranging between 5.3-6.5 (Coffee Research Foundation, 2001; Elzebroek and Wind, 2008). Different varieties are adapted to different ecological zones, for example SL 28, K7 and SL 34 can only be grown in low to medium agro-ecological zones while RUIRU 11 (eleven) hybrid can be grown in all coffee growing areas in Kenya (Coffee Research Foundation, 2001).

2.1.2 Coffee growth habit and agronomic requirements

Coffee is a perennial crop that can grow up to about 10m tall when mature. Its main stem is vertical (orthotropic) with lateral (plagiotropic) branches (Wilson, 1999; Winston *et al*., 2005) that bear evergreen leaves. The leaves intercept light for photosynthesis. The root system of mature coffee consists of a taproot growing to a depth of up to 1 m, axial roots that grow vertically downwards to a depth of 2.3 m and lateral roots forming a mat structure almost parallel to the soil surface (Coste and

Cambrony, 1992; Winston *et al*., 2005) with in the upper 30 cm of soil (Winston *et al*., 2005; Waller *et al* 2007). The root system is useful in nutrient and water uptake.

Coffee is widely spaced at 2.74 m x 2.74 m for the traditional varieties (K7, SL28 and SL34) or 2 m x 2 m for the compact varieties like RUIRU 11 (Coffee Research Foundation, 2001). Coffee requires weed free fields (Kimemia, 1998), effective soil conservation measures especially on sloppy ground (Khisa, 2000; Wilson, 1999) and adequate supply of nitrogen, phosphorus, calcium and magnesium (Coffee Research Foundation, 2001) for good establishment and production. The understanding of coffee agronomic requirements is important when considering intercropping coffee.

2.1.3 Weed, disease and insect pest management

Weed control or weed management is a term used to describe activities and modifications of measures or conditions in the cropping system with an intention of influencing or reducing weed populations (Hakansson, 2003). The three widely practiced methods of weed control in fruit and other perennial crops (including coffee) are mechanical, cultural and chemical application (Clay *et al.*, 1990; Coffee Research Foundation, 2003; Coffee Research Foundation, 2004). In Kenya, the use of integrated weed management (IWM), which is combination of the above methods, is recommended (Coffee Research Foundation, 2004; Nyabundi and Kimemia, 1998). Mechanical weed control involves manual or machine operated tools. Hand hoes are commonly used to remove perennial grasses such as *Digitaria abbisinica* (couch grass) and *Cynodon dactylon* (star grass) in small-scale farms. Weed slashing can be done to minimize water and nutrient uptake by weeds or when the soil is too wet to dig. Herbicides are used in large and small holder farms. The cost of using herbicides for weed control is generally high compared to cultural methods (Njoroge and Kimemia, 1990). Cultural methods like planting suitable legume cover crops can minimize weed control costs. Growing legume cover crops *in situ* is potentially cost-effective because they also serve as mulch (Muller and Kotsch, 1997). Application of mulch from plant materials grown *in situ* under coffee saves labour by 20 -40 % (Muller and Kotsch, 1997).

Insect pests and diseases are a major problem in coffee in Sub-Saharan Africa with estimated crop losses of 15 and 20 % respectively in Africa (Wilson, 1999). The most common coffee pests include leaf miners, mealy bugs and stem bores while the main coffee diseases are coffee leaf rust and coffee berry disease (Wilson, 1999; Waller *et al*, 2007). Pest and disease control are an integral part of coffee management in coffee farms and forms a significant part in production costs especially for small holder farmers (Wilson, 1999; Karanja, 2002) who do not benefit from economies of scale compared to large scale farms. Introduction of LCC in coffee may improve pest and disease management in coffee farms especially if the legumes used break disease and pest cycles (Snapp *et al.*, 2005). For example *Canavalia* and *Mucuna* have repellant and insecticidal properties (McIntyre, *et al*., 2001). Manipulation of cropping systems by use of LCC may offer an alternative integrated pest management approach in coffee farms.

2.1.4 Fertilizer requirements

Coffee exhausts the soil in which it is grown through extraction of soil nutrients and removal of harvested coffee beans (Winston *et al*., 2005). It takes 35 kg of nitrogen (N), 3 kg of phosphorus (P_2O_5) and 40 kg of potassium (K_2O) from the soil to produce 1 tonne of green coffee beans (Elzebroek and Wind, 2008). It is therefore necessary to replenish the nutrients in the coffee system to sustain coffee yields overtime. Nitrogen (N), potassium (K) and phosphorus (P) are among the major elements required in large quantities for nutrition of coffee (Coffee Research Foundation, 2012b). Nitrogen is important for vegetative growth, phosphorus for bean production and root development for nutrient uptake from the soil and potassium for berry development and ripening (Winston *et al.*, 2005; Coffee Research Foundation, 2012b).

In Brazil, the requirement for *Coffea arabica* is equivalent to 94.7 kg N, 14.4 kg P_2O_5 and 116.8 kg K_2O per hectare per year (Coste and Cambrony, 1992). In Kenya, it is recommended that NPK compound fertilizers should be shallowly incorporated into the soil (Coffee Research Foundation, 2004) at the rate of 50 -400 kg N /ha /year, 100 kg P_2O/ha/year and 100 kg K_2O /ha /year split into 3 -4 applications per year depending on the level of management and expected yields (Wilson, 1999). This is similar to 175 g N, 100 g P and 175 g K per tree per year (Elzebroek and Wind, 2008). Farmers in Kenya, especially small scale farmers, are however unable to implement these recommendations because of high costs of inorganic fertilizers coupled with lack of affordable credit to buy inputs (Hassan *et al.,* 1998; Coffee Board of Kenya 2003a). Farmers maintain soil fertility by use of farm yard manure which in many cases is inadequate (Mureithi *et al*., 2003) and its quality is usually low due to poor handling and poor quality feeds for livestock (Lekasi *et al*., 1998). The problem of soil fertility management is therefore a major challenge to coffee farmers. Incorporation of N-fixing legumes especially those that establish quickly

(Mureithi, *et al*., 2003) are preferred in coffee systems as an alternative source of soil nutrient supply for soil fertility improvement (Gachene and Kimaru, 2003).

2.2 Legume Cover Crops.

2.2.1 Legume cover crop establishment

A legume cover crop (LCC) is a legume primarily grown to prevent soil erosion, weed suppression through ground cover and for soil fertility improvement (Bunch and Buckles, 1998; Abayomi *et al*., 2001; Giller, 2001) through biological Nitrogen fixation (Sullivan, 2003a; Eninn *et al*., 2004; Chemining'wa *et al*, 2004). A legume cover crop can be incorporated into the soil as an organic fertilizer (Gachene and Kimaru, 2003) in which case it is regarded as green manure (Food and Agricultural Organization, 2000; Gilbert, 1998; Giller, 2001; Mureithi *et al*., 2003). The choice of growing a cover crop depends largely on the objectives of a farmer, whether to prevent soil erosion, as source of fertility, pest suppression, yield enhancement and suppression of root –not nematodes in cropping systems (Kimenju *et al*., 2007; Snapp *et al*., 2005). Establishment and performance of the chosen crop however depends on farmers' cultural practices such as the plant density, seed spacing and fertilizer applications (Giller, 2001).

The legumes' own characteristics also determine its growth and development; for example the germination of *Mucuna pruriens* can be difficult due to its hard seed coat but unlike *Canavalia ensiformis,* it establishes quickly due to its large seed and relative resistance to moisture stress at shoot emergence (Giller, 2001; Gitari *et al.*, 2000). Leguminous species such as *Crotalaria ochroleuca, Mucuna pruriens, Lablab purpureus, Glycine max, Vicia benghalensis* have good to excellent emergence and early plant vigour in 2 to 3 weeks after planting (Maobe *et al*., 2000a) while *Desmodium intortum* and *Neontonia wightii* are typically slow in establishment (Giller, 2001). *Neontonia wightii* can take 2 to 3 months to establish (Gitari *et al.*, 2000).

The performance of legumes overtime also differs from one legume to the other depending on prevailing environmental conditions (temperatures, light, soil fertility and moisture availability) that influence growth and development (Food and Agricultural Organization, 2000). *Mucuna pruriens* is adapted to low fertility soils with sandy to sandy-clay texture and a pH range of 5.0-7.0 and is susceptible to water logging and somewhat tolerant to drought (Vissoh *et al.*, 1998). Suitable temperatures for *Mucuna* range between 19 and 27^{o}C. *Canavalia* is well adapted to acidic and infertile soils and can grow in climates ranging from very wet to very arid (Giller, 2001). It does well at 0-1800 m a.s.l within an average temperature range between 14.4^{o}C –27.8^{o}C. Legumes should therefore be grown in conditions that favour their optimal growth so as to maximize their use.

2.2.2 Legume cover crop phenological development

The primary factor that determines plant phenological stages is temperature (Elmore, 2010), usually expressed in terms of thermal time (TT) or growing degree days (GDD) (^{o} C days) (Mburu, 1996; Sayid and Squaire, 2002; Elmore, 2010). Thermal time is described as the number of temperature degrees above a certain threshold base temperature, below which an organism does not grow or grows very slowly (Elmore, 2010; Stockle *et al.*, 2012). Thermal time varies from one crop to another and is accumulated throughout its growing season starting with planting until harvest such that a crop enters the next stage of development when the thermal time reaches the thermal time requirement for the respective stage (Stockle *et al.*, 2012; Wikipedia, 2012). For example the base temperature for common bean, lablab and soyabean is 8 (Mburu, 1996), 9.9 (Awadhwal *et al.*, 2001) and 10 ^{o} C (Elmore, 2010). Light, soil water content, nutrients, CO_2 and salinity may also influence crop phenology but to a lesser extent (Matthias, 2002; Howard *et al*., 2000; McMaster *et al*., 2002). Based on temperature, accumulated thermal time (TT) can be computed as follows; (Mburu, 1996)

$$TT_{DD} = \sum_{0}^{DAP} ((T_{max} - T_{min})/2) - T_b$$

Where DD is days after planting

T_{max} is daily maximum temperature (^{o} C)

T_{min} is daily minimum temperature (^{o} C) and

T_b is the base temperature

The minimum and maximum temperatures for most plants (crops) is usually 10 to 30 ^{o} C respectively because most plants do not grow outside that temperature range (Elmore, 2010; Wikipedia, 2012).

Legumes reach different phenological stages (time to emergence, anthesis, 50% flowering, 50% podding and physiological maturity) at different times (Stockle *et al.,* 2012). Experiments have shown that legumes reach flowering stage at varying periods in a growing season (Gitari, *et al*., 2000). Short lived annuals such as *Lablab*, *Crotalaria* , *Vicia*) and *Glycine max* (soya bean) reached on set of flowering at 84, 74, 66 and 66 DAP respectively while long lived legumes like *Mucuna* and *Desmodium uncinatum* reach on set of flowering at 102 and 103 DAP respectively

(Maobe *et al*., 2000a). Flowering in legumes coincides with the time when most root nodules are active for nitrogen fixation which contributes to soil fertility improvement (Giller, 2001; Liu *et al.,* 2011). However, legumes differ in the number of nodules at flowering. For example, *Vicia benghalensis,* soyabean, lablab had 100, 50 and 20 active nodules per plant respectively at 2-3 months after planting (flowering time), (Maobe *et al*., 2000a). Biological nitrogen fixation is a cost-effective means of nitrogen supply to the soil (Giller, 2001).

Different legumes have different growth characteristics. Some legume types are short and erect (e.g. soyabean and common bean), tall and erect (*Crotalaria ochroleuca*) while others are creeping or spreading (butter bean, Desmodium, *mucuna pruriens* and *lablab purpureus*). The creeping properties facilitate quick ground cover for weed suppression and soil erosion control. Annual legumes species are rapid in foliage establishment for ground cover (Gitari *et al.*, 2000). *Vicia benghalensis*, *Glycine max* and *Lablab* can achieve over 60% ground cover by 2 to 3 months after planting (Maobe *et al*., 2000a). Long-lived creeping perennials such as *Desmodium intortum* and *Neontonia* are able to achieve up to 100% ground cover within the first six months after planting (Giller, 2001; Gitari *et al.*, 2000). Fast legume establishment coupled with creeping characteristics ensure good ground cover which is important for soil erosion (Gitari *et al.*, 2000) and weed control (Vissoh *et al.*, 1998).

2.2.3 Legume biomass production

Plant biomass is the weight of living plant material contained above and below a unit of ground surface area at a given point in time (Roberts, *et al.*, 1995). Plant herbage (stem, leaves and reproductive parts) form the above ground biomass and the roots the below ground biomass (Roberts, *et al.,* 1995). Above ground biomass production is largely depended on intercepted radiation, transpiration and plant nitrogen uptake (Roberts, *et al.,* 1995). Each of these factors is capable of limiting growth. Estimation of biomass accumulation is necessary when growing legumes for either livestock feed or incorporation into the soil as green manure for fertility enhancement (Gitari *et al.,* 2000). The relationship between biomass accumulation and resource use is explained in section 2.4.2 of this study.

As legumes near maturity, senescence sets in resulting in litter fall (Gilbert, 1998; Ansari, and Chen, 2011). Senescence and litter fall occurs when the rate of respiration is greater than the rate of photosynthesis. The factors affecting leaf senescence include low light levels, water stress and self shedding characteristics of the legume (Gilbert, 1998; Ansari, and Chen, 2011). The amount of litter differs from one legume to another even under the same conditions; for example *Mucuna* leaf litter fall was double (3200 kg ha $^{-1}$) that of soybean (1560 kg ha $^{-1}$) in the same environment (Gilbert, 1998). Both leaf and stem litter contribute towards soil amelioration in various ways. *Mucuna* has a copious amount of N-rich litter that falls during the growth season. *Mucuna* rotations were found to contain 100 kg N ha $^{-1}$ in leaf and stem litter, which upon decomposing or incorporation into the soil becomes available for crop use (Gilbert, 1998). Other LCC that have high nitrogen content in their organic materials include desmodium (3.44 %), Jack bean (3.45 %), purple vetch (3.68 %), mucuna (3.56 %) and crotalaria (4.45 %) (Gachene and Kimaru, 2003). This shows that suitable LCC intercrops can be used to supply nutrients and organic matter through litter and leaf fall. Organic matter improves soil structure and water holding capacity, aeration and regulates soil temperature (Gachene and Kimaru, 2003).

2.2.4 Legume seed yield

The amount and duration of intercepted radiation and dry mater (DM) accumulation are directly linked to crop yield because DM is partitioned into the crops harvestable parts (pods, seeds) and the rest of the plant material (Akhter *et al*, 2009; Akinyele and Osekita, 2006). The relationship between seed yield, dry matter production and radiation interception is expressed by the equation below: (Simmonds *et al*, 1999).

$$Y_s = HI * e_s (\sum S_i * f)$$

Where: Y_s is seed yield (g m^{-2})

HI is harvest index

e_s is the ratio of dry matter to intercepted radiation (conversion efficiency g MJ^{-1}); SS_i is the cumulative total of intercepted radiation (MJ m^{-2}); S_i is the amount of radiation intercepted on day i and f is the fraction of incident radiation intercepted

From this equation, it is evident that radiation interception and dry matter accumulation are related and contribute to seed yield production. For grain crops, harvest index (HI) is the ratio of harvested grain to total shoot dry matter, and can be used as a measure of reproductive efficiency (Unkovich *et al.*, 2010). Factors that influence crop HI include the energy and protein content of seeds, extreme (either hot or cold) temperatures during crop reproductive development and crop husbandry especially delayed sowing, which shortens the length of the vegetative phase and increases HI (Unkovich *et al.*, 2010).

2.3 Coffee intercrop systems

2.3.1 Principles of intercropping

Intercropping is defined as a form of multiple cropping in which two or more crops are grown in row arrangements and simultaneously on the same piece of land (Palaniappan and Sivaraman, 2001) for at least part of the life of each species (Azam-Ali and Squire, 2001). When two or more crops are growing together, each must have adequate space to maximize cooperation and minimize competition between them. To accomplish this, spatial arrangement, plant density, maturity dates and plant architecture of the crops being grown need to be considered (Sullivan, 2003b). The most suitable special arrangement for intercropping in coffee is relay cropping (Njoroge, 1992). Relay cropping is planting a second crop into a standing crop at a time when the standing crop is at its reproductive stage but before harvesting (Sullivan, 2003b). To optimize plant density, the seeding rate of each crop in the mixture is adjusted below its full rate. Planting intercrops that feature staggered maturity dates or development periods takes advantage of variations in peak resource demands for nutrients, water, and sunlight Sullivan, 2003b). Having one crop mature before its companion crop lessens the competition between the two crops. Plant architecture is a commonly used strategy to allow one member of the mix to capture sunlight that would not otherwise be available to the others (Sullivan, 2003b). It is therefore more advantageous to intercrop plantation trees with shorter plant species because the understory plants capture light that is not intercepted by the taller species resulting in optimal light interception in the intercrop compared to the sole plantation crop (Giller 2001).

Advantages of intercropping have been widely documented (Giller 2001; Kimemia, 1998; Kimemia, 2003; Njoroge 1992; Vissoh *at al*., 1998; Sullivan, 2003a; Sullivan, 2003b). The documented advantages include increase in crop yields and farm income, intensified land use resulting to increased crop yield stability (Azam-Ali and Squire, 2001), reduction in labour requirements for weeding and land productivity per unit area (Kimemia, 1998; Maina, 1997; Sullivan, 2003b). Generally, these benefits are achieved through efficient use of limited resources (light, water and nutrients) leading to higher yields per unit area, income stability, more balanced distribution of labour requirements through the seasons (Njoroge, 1992). Intercrops may also reduce impacts of pests and diseases where pathogens may settle on non-host components of the intercrop (Azam-Ali and Squire, 2001).

Legumes cover crops suppress weed infestation and growth in intercrops resulting in less competition from weeds and thus contribute to yield advantages (Giller, 2001; Maina, 1997; Mureithi *et al,* 2003; Gachene and Makau, 2000). They also contribute to nutrient recycling in intercrop systems; the magnitude of nutrient recycling is determined by biomass production, nutrient contents and decomposition rate in the intercrop system (Lehmann *et al*., 2000). Legumes provide more N because they generally have high foliar N content ranging from 20 to 45 mg g^{-1} compared to non legumes (Lehmann *et al*., 2000). Intercrop systems that involve use of legumes also provide crop residue with low Carbon-Nitrogen C/N (10:1) compared to systems intercropped with cereals whose ratio is high (200:1) (Njihia, 2000). High C/N ratio materials decompose slower than low C/N ratio materials and there fore have a higher organic matter buildup than low C/N ratio materials (Njihia, 2000). Organic matter results in improved soil structure and reduction in nutrient leaching in intercrops.

Intercrops that enhance organic matter build up and soil cover are more beneficial because they help in maintenance of soil fertility and environmental protection (Giller, 2001; Bot and Benites, 2005).

Different intercrops combinations are widely practiced in various parts of the world. Perennial tree crops (including coffee) have been intercropped with annual food crops and leguminous species (Giller, 2001). Cereal food crops and legumes intercrops such as corn and soybean are found in Canada (Sullivan, 2003b) and relay – mucuna intercrops in west Africa (Vissoh *at al*., 1998). Intercrops of grasses such as Napier and forage legumes (e.g desmodium) are also widely practiced in sub-saharan Africa (Wandera *et al*., 2000). Coffee and maize have been intercropped with green manure cover crops such as canavalia and mucuna for soil fertility improvement in Uganda (Gachene and Wortmann, 2004) while cocoa and coffee have been intercropped with legume cover crops in Ghana (Giller, 2001). In Kenya, coffee has been intercropped with beans for food production (Njoroge, 1992).

2.3.2 Intercropping coffee with annual crops

In the past, coffee intercropping was not practiced in both large and small holder farms because of restrictive regulations by the Kenyan government (Nyangito, 2001). However in recent years, intercropping coffee with food crops has become increasingly necessary in small holder farms mainly for subsistence food production and income generation from produce surplus (Famaye, 2004).

Suitable coffee intercrop combinations with annual food crops have benefits which include reduction of soil erosion (Khisa, 2000) and provision of food for coffee farmers (Kimemia, 1998). Legume cover crops such as lablab (*Lablab purpureus*) can also be used for weed control and soil fertility and food (Mureithi *et al*., 2003). Coffee intercrops with food crops have been reported to result in net benefits. Coffee - food crop (potatoes, tomatoes and beans) intercrops were considered most ideal because the food crop yields were found to be higher than the corresponding pure stands. However maize affected coffee growth and yields adversely making its intercrop unprofitable (Njoroge, 1992).

Other studies in Kenya showed that intercropping coffee with annual food crops like dry beans (*Phaseolus vulgaris*), cowpeas (*Vigna unguiculata*), Irish potatoes (*Solanum tuberosum*), tomatoes (*Lycopersicon esculantum*) resulted in positive net returns even with increased coffee tree densities (Kimemia , 1998). Similarly, intercropping beans and garden peas in coffee planted at conventional and hedge row plantings had positive net returns. This shows that intercropping coffee with food crops can be advantageous especially when suitable agronomic practices such as crop spacing are observed. For example, short crops can be planted within the one (1) meter spacing between coffee rows without much competition with coffee and at least 60 cm from the coffee plants to avoid nutrient and water competition (Kimemia, 2003).

Annual legumes cover crops exhibit different responses in terms of dry matter accumulation, weed suppression and soil erosion control when intercropped with other crops. Sole mucuna produced 11 tons DM ha^{-1} (Mureithi *et al.*, 2003) and 3 tons ha^{-1} when intercropped with maize (Maobe *et al*., 2000b) while sole *Vicia benghalensis* (purple vetch) produced 2 tons DM ha^{-1} under similar environments.

Impacts of legume cover crops in controlling soil erosion have been recorded. Intercropping purple vetch (*Vicia benghalensis*) with maize reduced cumulative soil loss over an eight-month period by three fold compared to uncropped plots which had 7.1 t ha-1 cumulative soil loss (Gachene and Haru, 1997).

2.3.3 Intercropping coffee with perennial crops

Intercropping tree crops at establishment stages has been reported to be economically beneficial because the intercrops can utilize the light energy and other growth resources for production between the main trees before they closed their canopy (Njoroge, 1992). During the establishment phase of coffee, pawpaw (C*arica papaya*), passion fruit (*Pasiflora edulis*) and avocadoes (*Persea americana*) did not reduce clean coffee yields or bean quality. Bananas (*Musa sapentium*) and guava (*Psidium guajava*) significantly depressed coffee plant height and yield components but did not affect coffee quality significantly (Kimemia, 1998). The effects of intercrops on coffee may differ depending on whether they shade coffee or not. Coffee shaded by *Mimosa scrabella* yielded significantly less (1870 kg /ha) compared to unshaded coffee (2052 kg/ha) while *Grevillea robusta* and (*Macadamia ternifolia*) macadamia did not significantly affect the yield of clean coffee (Kimemia, 2003).

Intercropping coffee with perennial forage legume cover crops has different impacts on the intercrops. Kimemia (1998) intercropped coffee (Ruiru 11) with desmodium and recommended use of desmodium for weed suppression and moisture preservation but discouraged the use of desmodium as green manure in coffee because it has low rates of mineralization. Intercropping can reduce dry matter accumulation for legumes. For example the dry matter yield for sole D*esmodium uncinatum* (silver leaf desmodium) was depressed by over 85% from 10 t DM ha^{-1} to 2 t DM ha^{-1} due intercropping with napier in Embu (Wandera *et al*, 2000) .

Advantages of intercropping coffee with perennial legumes include continuous supply of livestock feed, prolonged weed suppression and moisture retention especially over dry seasons (Bunch, R. and Buckles, D. 1998; Giller, 2001). Challenges associated with intercropping perennial legumes generally include possible competition for light, water and nutrients (Giller, 2001; Ong *et al*., 1996; Palaniappan and Sivaraman, 2001) and yield reduction in the main crop (Giller, 2001; Kimemia, 1998).

Certain disadvantages of intercropping coffee with other crops have been reported. Intercropping generally hinders time-saving mechanized operations such as fertilizer and pesticide application and to some extent harvesting (Giller, 2001). It may result in resource (light and soil moisture) competition (Giller, 2001). For example, *Crotalaria* is an excellent green manure legume and an effective weed suppressor, but it may not be suitable for intercropping with established coffee because it grows tall (Gachene and Wortmann, 2004; Giller, 2001;), posing a challenge of competition for light through shading (Kroff, 1993a). It therefore needs to be cut back early to reduce light competition and to open up coffee farms for ease of harvesting (Maina *et al*., 2006). Trailing legumes require extra labour requirements to prevent the spreading cover crops from climbing over coffee bushes (Giller, 2001). It is recommended to train intercrop *Mucuna* and *Lablab* to prevent it from tangling coffee. Intercropping can also lead to reduction of the coffee grain yields (Kimemia, 2003).

2.3.4 Best- bet legume cover crop options

A good choice of a legume cover crop for intercropping in coffee systems is the one that is suited to the conditions favoring its growth and development and serve the purpose for which it is grown (Gachene and Wortmann, 2004). For coffee intercropping, the legume should be effective in weed suppression, soil erosion control and soil fertility improvement without making the intercrop system counterproductive (International Center for Tropical Agriculture, 2003; Gachene and Wortmann, 2004) (Table 2).

The most outstanding legume cover crops that can be suitable in coffee systems based on these attributes are *Mucuna pruriens*, *Canavalia ensiformis*, *Lablab purpureus* and *Desmodium unicinatum* (Maobe *et al*., 2000b; International Center for Tropical Agriculture, 2003; Mureithi *et al*., 2003; Gachene and Wortmann, 2004) (Table 2). Dual purpose annual cover crops like *Lablab purpureus* can be attractive to farmers who may want to intercrop them for food human consumption and forage provision for dairy cows (Gachene and Wortmann, 2004). Perennial cover crops like *Desmodium* and can be suitable for large scale farmers who are interested in fodder production (Giller, 2001).

Table 2 “Best bet” legume cover crops suitable for coffee intercrop systems

Best bet legume	Growth habit	Intercrop Recommendation	Use options
Canavalia ensiformis	Long lived annual, Erect canopy	Intercrop with newly planted coffee	Green manure
Lablab purpureus	Short lived annual, Spreading and climbing	Intercrop with newly planted coffee	Food, green manure, forage production and weed and soil erosion control
Mucuna pruriens	Long lived annual, Spreading and climbing	Intercrop with Established coffee	Green manure and Forage production, weed and soil erosion control

Source: Gachene and Wortmann, (2004).

2.4 Resource use in intercrops

2.4.1 Competition and complementarity in cropping systems

The basic principle underlying the concept of resource capture is that complementary or competitive interactions between species depend on their ability to capture and use the most limiting essential growth resources effectively (Ong *et al*, 1996). Capturing of the limiting resource (e.g. light, water or nutrients) depends on the number, surface, distribution and effectiveness of the individual elements within the canopy or root system of the species or mixture involved (Ong *et al.*, 1996). When resources are not limiting, densely planted monocultures usually provide the most efficient resource capture systems. However, where one (or more) resources is limiting, productivity may be improved by using species mixtures if the component species capture more of the available resources or use them more efficiently for growth. In such instances, mixtures may provide a greater yield than the combined yield of the corresponding sole crops. When the productivity of the mixture is superior to that of the sole-crop, yield advantages are realized and complementarily is said to have occurred. Competition is the reverse. Yield advantages are expressed in terms of Land equivalent ratio (LER). The Land Equivalent Ratio (LER) is the sum of the fractions of the intercropped yields divided by the sole-crop yield. LER is calculated using the equation: (Mazaheri, *et al.,* 2006; Morales-Rosales and Franc-Mora, 2009)

$$LER = \Sigma\ (Ypi/Ymi),$$

Where Yp is the yield of each crop or variety in the intercrop and Ym is the yield of each crop or variety in the sole crop or monoculture. For each crop (i) a ratio is calculated to determine the partial LER for that crop, the partial LERs are summed to give the total LER for the intercrop. A LER value of 1.0, indicates no difference in yield between the intercrop and the collection of monocultures. LER value greater than 1.0 indicates a yield advantage for intercrop. A LER of 1.2 for example, indicates that the area planted to monocultures would need to be 20% greater than the area planted to intercrop for the two species to produce the same combined yields.

2.4.2. Above ground resource use

Light is essential to all green plants because of its primary role in photosynthesis (Squire, 1990; Roberts *et al*., 1995). All kinds of radiant energy, including light, vary in several different ways, most important of which are irradiation (intensity), quality and duration. Under natural conditions, differences in irradiance have more significant effects upon growth of plants than differences in light quality (Roberts *et al*., 1995).

During crop growth incident solar radiation is converted to more useful forms of chemical potential energy located in the harvestable plant parts (Hall *et al*., 1993). This energy transformation is achieved through interception of incident solar radiation by the leaf canopy, conversion of the intercepted radiation energy (conveniently expressed in terms of plant dry matter), and partitioning of the dry matter produced between the harvested parts and the rest of the plant (Hall and Rao, 1994; Sayed and Squire, 2002). For any crop or stand of natural vegetation, the net biomass gain or net productivity (Y) is determined by the quantity of incident light (Si), the proportion of that light intercepted by green plant organs (f), the efficiency of photosynthetic conversion of the intercepted light into biomass (ε), and respiratory losses of biomass (R) (Hall and Rao, 1994). The relationship between plant productivity and these factors can be expressed as:

$$Y = (\varepsilon \sum (Si * f)) - R$$

These factors ultimately determine the efficiency with which intercepted photosynthetically active radiation (PAR) affects the conversion of CO_2 into crop dry matter (Hall and Rao, 1994). PAR is the solar radiation within the 400-700 nm band that is used in photosynthesis (Ehlers and Goss, 2003). There is a linear relationship between total dry-matter production and the quantity of radiant energy intercepted (Hall and Rao, 1994; Ehlers and Goss, 2003). The extent to which a canopy intercepts the available radiation depends on the leaf area index (LAI), leaf angle and canopy structure and architecture (Nobel, *et al*., 1995; Ehlers and Goss, 2003). LAI is the crop leaf area displayed per unit of soil surface area (Nobel, *et al*., 1995).

Canopy structure refers to the amount and organization of above ground plant material, including the size, shape and orientation of plant organs such as leaves, stems, flowers and fruits (Nobel, *et al.*, 1995). In canopies where leaves are nearly vertical (erectrophiles) light penetrates to the lower layers readily and so the foliar absorption coefficient (k) is often low, about 0.4 for many grasses. Canopies in which leaves are predominantly horizontal are termed planophile and allow less light to pass through (Nobel, *et al.*, 1995; Muthuri, 2004). Coffees' planophile canopy is expected to intercept considerable light leaving intercropped legumes with less light for photosynthetic activity.

Shading of understorey by taller plants results in lower leaf chlorophyll concentration per plant of the shadowed crop. Chlorophyll is a sensitive indicator of photosynthesis that reflects photosynthetic carbon assimilation capacity and low biomass production (Odeleye *et al.,* 2001). Plants grown in the open tend to have higher dry matter (DM) accumulation compared to those grown under reduced light intensity or in a competitive intercrop (Kroff, 1993a; Odeleye *et al.,* 2001). Although optimal light interception can be reached in sole crops compared to intercrops, efficiency in light utilization is usually higher in intercrops (Njoroge, 1992; Obuo *et al.*, 1997). Taller plants in an intercrop dominate light interception at the upper layer while shorter ones utilize the light transmitted to the ground that otherwise may be wasted in sole cropping.

2.4.3 Below ground resource use

The most important below ground resources for plant growth and development are soil water and nutrients. Water is a necessary constituent of all living plant cells and tissues and serves as a biochemical medium and solvent of nutrients and is involved in metabolic processes including photosynthesis (Hall *et al*., 1993). During the growth of a plant, water supply among other factors such as temperature and population density is key in determining leaf area and longevity (Bréda, 2008; Fang and Liang, 2008) and hence plant canopy development and biomass production.

Plants compete for soil water differently depending on the prevailing circumstances (Wallace, 1996). For example, plants growing in a mixture under a limited water situation will compete for soil water in particular and generally for light (Ong *et al.*, 1996; Wallace, 1996). Competition for water differs in principal from competition for light in that competition for light is a process of direct competition for resource capture, with an instantaneous nature (Ong *et al.*, 1996). If the light resource is not captured, it is lost because it is not stored in the system. Unlike light, water can be stored. The implication is that different plants grown in an intercrop can compete for water either directly or indirectly. Direct competition occurs when the life cycle of species in a mixture differs, for example, an early maturing species may not suffer water stress itself, but may subject the later maturing species to increased water stress by enhancing water loss earlier in the season (Kroff, 1993b).

To minimize competition for water, conservation measures that promote availability of moisture at the root zone and its surrounding areas creating conducive micro-environment are necessary. Conserved water leads to greater fertilizer use and efficiency, better nutrient uptake by plants (Snapp *et al*., 2005) and can enable perennial crops, including coffee, to survive dry spells across seasons, making it an important aspect in sustaining crop productivity. Soil moisture conservation in coffee can be achieved through *in situ* mulching which involves the use of legume cover crops as ‘live mulch’ and their litter as ‘dead mulch’ (Giller, 2001; Hussein *et al.,* 2000; Food and Agricultural Organization, 2000).

Increased shade from cover crops and their mulching effects reduce water runoff and evaporation from the soil which effectively raises water use efficiency (WUE). Water use efficiency is commonly defined as the amount of dry matter produced per unit water evaporated, from all surfaces, during a specific time (Nobel, *et al*., 1995; Squire, 1990). Some legumes have been shown to perform well interms of moisture conservation. *Mucuna pruriens* and *Canavalia ensiformis* are reported to be able to maintain soil moisture content of 46 and 72 % respectively during the early dry season in a semi arid zone due to good ground cover and continued biomass accumulation (Carsky and Ndikawa, 1998). In Ghana, *Mucuna pruriens* accumulated 13.8 t ha $^{-1}$ of dry mulch with a thickness of 12.6 cm after a fallow of two seasons in a bimodal rainfall season (Vissoh *et al.,* 1998). When intercropped with coffee, legumes should however be planted at least 50 cm away from the coffee plants to avoid water competition that can lead to reduced coffee yields (Kimemia, 1998).

2.5. Weeds

2.5.1 Introduction

A weed can be defined as ‘a plant out of place or growing where it is not wanted’ or growing without the grower’s intention or objective (Mortimer, 1990; Coffee Research Foundation, 2003; Hakansson, 2003). Weeds are also referred to as ‘volunteer’ crop plants (Hakansson, 2003). There are over 250,000 plant species in the world (Rao, 2000) of which about 8000 species of them behave as weeds and 250 of these are important for world agriculture (Memon *et al*., 2003). Weeds may be classified as annual, biennial or perennial depending on their origin, habitat, morphology and biological characteristics (Hakansson, 2003).

Annual weeds are those that come up from seed, flower, produce seed, and die in a year or less (Hakansson, 2003). Annual weeds (herbaceous and grasses) are easier to control because they are short lived and have shallow root systems (Coffee Research Foundation, 2003; Hakansson, 2003). Examples of annual weeds in coffee are *Amaranthus spp, Bidens pilosa ,Tagetes minuta and* (Coffee Research Foundation, 2003; Nyabundi and Kimemia, 1998). Biennial weeds complete their life cycle in two years. During their first year these weeds form an extensive root system below the ground and a cluster of leaves or rosette above the ground. Control of biennials is most effective in their regenerative phase before seed set during the first year (Hakanson, 2003). Perennial weeds live for three or more years and produce seeds and extensive root system which may include underground rhizomes, tubers, or bulbs (Hakansson, 2003) which sprout again when not fully uprooted or destroyed making them difficult to control (Coffee Research Foundation, 2003). Examples of perennial weeds in coffee are *Digitaria abbisinica* (Couch grass), *Commelina benghalensis* (Wondering Jew), *Cyperus rotundus* L.(Nut grass), *Cynondon dactylon* (Star grass) *Oxalis latifolia* (Wood sorrel), *Pennisetum clandestinum* (Kikuyu grass) (Coffee Research Foundation, 2003; Nyabundi and Kimemia, 1998)**.**

Weeds pose potential threat to crop production. Mortimer (1990) identified three categories of financial losses due to weeds in crop production systems; namely production inefficiency, commodity yield reduction and loss of commodity price. Commodity yield reduction is caused by reduced components of crop yield through competition; weed parasitism, pest and disease infestation where weeds act as alternate hosts. This is exacerbated by the fact that weeds are very prolific in multiplication and excessively competitive for soil moisture and nutrients (Clay *et al.*, 1990; Mortimer, 1990). Competition for nutrients by weeds can be seen in the amount of minerals they accumulate in their tissues. *Cyperus rotundus* is reported to accumulated 2.17 N, 0.26 P_2O_5 and 2.73 K_2O in its tissues and *Commelina benghalesis* accumulated 2.02 N, 1.46 P_2O_5 and 1.86 K_2O (Gupta 1998) indicating that they had drawn these nutrients, which would have otherwise been available for crop use from the soil.

Effects of weeds on coffee include water stress during dry spells, deficiencies of essential elements, reduction in yield and quality (Coffee Research Foundation, 2003). Yield losses due to these effects can be over 50% (Coffee Research Foundation, 2003). Production inefficiency is attributed to increased time and labour in weed control, crop damage in the application of weed control agents and interference with other management practices such as spraying, pruning and harvesting. Commodity price loss is caused by lowered produce quality through contamination and poor appearance (Mortimer, 1990).

2.5.2 Weed control methods

Weed control is defined as the activities and modifications of measures or conditions in the cropping system intended to reduce weed populations (Hakansson, 2003). One of the major challenges in weed control is reducing the amount of propagules (seed and or vegetative) in the soil or their regeneration after weeding (Hakansson, 2003; Kelton *et al*., 2011). Germination of weed seeds from the seed reserve in the soil depends on the availability of adequate moisture, adequate oxygen, a favorable temperature range and light (Rao, 2000). These factors plus availability of adequate nutrients, competition with other plants and applied weed control measures influence the germination and development of weed seedlings (Kropff, 1993b; Rao, 2000). Weeds have an adaptation mechanism to produce large numbers of seeds and other propagules that make them persist in the fields sustaining weed population from year to year (Clay *et al.*, 1990; Kelton *et al*., 2011). The cropping system, cultural practices and weed control methods adopted can determine weed seed population because they influence weed seeding and therefore their soil seed bank (Hakansson, 2003; Kelton *et al.,* 2011).

The choice of weed control method depends on its effectiveness and economic advantages associated with it (Traoré *et al.*, 2001). To attain efficient weed control, the choice of control methods needs to be based on objective assessment of weed effects and crop requirements, without neglecting the cost of the treatments available (Clay *et al.*, 1990). The most commonly practiced weed control methods include manual, mechanical cultivation and use of herbicides (Robinson, 1990) or integrated weed management (IWM). Integrated weed control involves the use of a range of weed control techniques embrasing physical, chemical and biological methods in an integrated manner without excessive reliance on any one method (Bayer Crop Science, 2009). The purpose of IWM is to reduce weed pressure and keep weeds below their economic thresholds while minimizing negative impacts on the environment (Coffee Research Foundation, 2003; Bayer Crop Science, 2009).

Manual weed control involves the use of handhoes such as the heavy blanded hoe (*Jembe*), *forked Jembe* and *Panga* which are most widely practiced by small-scale farmers for weed control in coffee among other crops (Coffee Research Foundation, 2003; Robinson, 1990). A major limitation of this method is that it is not very effective in dealing with weeds growing close to the crop and may result to physical injuries on coffee stems and lateral roots (Nyabundi and Kimemia, 1998). The weeding operations need to be repeated several times during the growing season, which is expensive. Mechanical weed control involves the use of tractor mounted implements such as rotary or tined cultivators in large coffee estates where the manual weeding would require a large labour force (Coffee Research Foundation, 2003).

Chemical control of weeds involves the use of herbicides. Herbicides can be defined as crop-protecting chemicals used to kill weeds (Lingenfelter and Hartwig, 2007). Herbicides provide a convenient, economical and effective way of managing weeds. Use of herbicides enhances minimum tillage leading to reduction in soil erosion, allows earlier planting dates and provides additional time to perform the other tasks because it is time saving (Lingenfelter and Hartwig, 2007) . Herbicides should however be used with caution because they are hazardous to man and the environment when used or disposed inappropriately. Their residues contaminate the environment especially when they infiltrate into ground water and water reservoirs like rivers and lakes (Food and Agricultural Organization, 2000). This adds to costs of government abatement programs against environmental pollution.

Herbicides can be classified into several ways based on their weed control spectrum (selective or nonselective), labeled crop usage, chemical families, mode of action and application timing/ method (Lingenfelter and Hartwig, 2007). For example based on mode of action and site of action herbicides are grouped according to contact and systemic herbicides. Contact herbicides kill only the plant parts contacted by the chemical, whereas systemic herbicides are absorbed by the roots or foliage and translocated throughout the plant. Herbicide activity can be either selective or nonselective. Selective herbicides are used to kill weeds without significant damage to desirable plants. Nonselective herbicides kill or injure all plants present if applied at an adequate rate. Use herbicides require skills because they are crop specific and have to be applied at recommended rates, times and methods. Use of herbicides has different effects on weed re-growth compared to mechanical methods. The effect of loosened soil due to hand weeding may encourage fresh germination of weeds (Traoré *et al.*, 2001). This is not expected with chemical control since there is no soil disturbance.

2.5.3 Suppression of weeds by legume cover crops

Compared to conventional farming which is characterized by high external inputs, organic farming and or use of organic amendments is cheaper and safer, making it an appropriate and sustainable option for farmers that have a low resource base. Organic farming and or organic amendments involve the use of biological resources that include legume cover crops (LCC) for weed control (Khisa, 2000). In Nigeria, legumes cover crops (especially *Mucuna spp*) have been used as ‘live mulch’ to maintain soil cover thus controlling both weeds and soil erosion (Giller, 2001). When slashed back after maturity, their residues prolong the duration for soil cover and weed control (Muller and Kotschi, 1997).

Key factors that facilitate effective weed suppression by LCCs include their ability to develop fast ground cover, their twining ability and allelopathic properties for some legumes (Vissoh *et al.*, 1998; Giller, 2001). These properties vary from species to species. *Lablab and* mucuna *are* suitable for weed control because of their high biomass production, good ground cover and twining ability (Giller, 2001; Mureithi *et al*, 2003). Mucuna can reach 100% ground cover in 60- 90 days after planting (Carsky and Ndikawa, 1998; Abayomi *et al*, 2001). *Canavalia* can reach flowering in 59 to 109 days and attain substantial ground cover there after. Compared to mucuna, *Canvalia* is not a good weed suppressor (Gachene and Kimaru, 2003) because it has an erect canopy and does not cover the ground quickly.

Mucuna has been used to rehabilitate fields formally abandoned because of degraded soils or excessive weed infestation (Peden, 1998). Studies in Benin show that mucuna reduced *Imperata* weed to less than 10% of its initial density on farmers' fields while spear grass density dropped from 270 shoots m^{-2} to 32 shoots m^{-2} and completely eliminated spear grass only after two to three consecutive mucuna crops (Vissoh *et al.*, 1998). Compared to other methods of controlling the *Imperata* weed, mucuna was the most effective mainly because of its substantial biomass production. Its foliage completely covers the soil and strangles all the weeds as it can climb as high as its support allows (Vissoh *et al.*, 1998). At the end of its life cycle mucuna leaves thick mulch free of weeds (Vissoh *et al.*, 1998). This has the benefit that little or no land preparation or weeding may be required in the subsequent season.

2.6. Research gaps

Legume cover crops have great potential in soil fertility improvement and weed control and provision of food and fodder in different cropping systems including plantation crops like coffee (Giller, 2001; Mureithi, *et al.*2003; Maina *et al.,* 2006). Intercropping coffee with legume cover crops in Kenya has not been widely practiced since intercropping coffee with other crops was prohibited by law (Coffee Act Cap 333) until it started recently (Kimemia, 1998; (Nyangito, 2001) indicating that few studies have addressed coffee intercropping. Some research involving coffee intercrops with legume cover crops has been done (Maina *et al.,* 2006) but there is still no exhaustive information on performance of these legumes under coffee.

In particular, more information on the performance of individual legumes in terms of their growth, use of both above (light) and below ground resources (water and nutrients) for biomass production and ground cover for weed suppression under coffee needs to be generated. Knowledge on performance of legumes under coffee can form a basis for recommending better husbandry practices for production of organic coffee that has an increasing demand in world coffee markets (Van der Vossen, 2005). Some legume cover crops such as lablab, soyabean and mucuna are potential sources of livestock feed and human feed (Mureithi, *et al.*2003; Bunch and Buckles. 1998). Their contribution to food and feed supply when intercropped with coffee requires investigation especially from the small holder point of view. In addition, the possibility of legume cover crops contributing to cash savings through reduced manual and mechanical weeding, inorganic fertilizer inputs and alternative food and feed provisions qualifies further investigations on use of these legumes in coffee systems.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental site

The study was conducted at the University of Nairobi Kabete Field Station, latitude 01^{o} 15’ S and longitude 36^{o}44’ E at altitude of 1940 m above sea level. It receives an average annual rainfall of 1006 mm (Karuku, 2011). The rainfall pattern is bimodal with the long rains in March to June and short rains in October to December. The mean annual temperature range is 13 ^{o}C -23^{o}C. Average humidity is 70%. The soils are humic nitosols, deep and well-drained with a pH_{water} of 6.5 (Karuku, 2011).

3.2 Experimental design

The experiment was conducted between March and October 2005. The legumes were sown as sole crop and intercropped with mature coffee (variety SL28) established in 1930 at a spacing of 2.74 m by 2.74 m. Eleven legume species were sown on 24th March 2005 in furrows at recommended spacing (Table 3) with 1 and 2 plants per hill for small and large seeded legumes respectively. The number of rows per plot varied from 4 to 8 for large and small seeded legumes, respectively.

The experiment design was randomized complete block design (RCBD) and replicated three times. Intercrop plots were 1.5 m wide and 5 m long, each surrounded by 6 coffee plants. Spacing between each plot was 2.74 m. The coffee plots that were intercropped with legumes measured 100 x 54 cm. A separate plot with sole legumes was established adjacent to the coffee- legume intercrop. Unweeded plots were maintained throughout the experiment in the sole and intercrop systems.

Table 3. Names and spacing of legume cover crops evaluated

	Scientific name	**Common name**	**Abbreviation**	**Spacing (cm)**	**Category**	**Duration months**
1	*Glycine max*	Soya bean variety 4	Sy4	50 x 5	Short duration annual	2.5 - 4
	Glycine max	Soya bean variety 17	Sy17	50 x 5	Short duration annual	2.5 - 4
2	*Phaseolus vulgaris*	Mwitemania bean	Be	50 x 5	Short duration annual	3 -3.5
3	*Phaseolus coccineus*	Butter bean	Bu	50 x 20	Short duration annual	3.5 - 5
4	*Crotalaria ochroleuca*	Tanzanian sunnhemp	Cr	30 x drill	Short duration annual	4 - 5
5	*Vicia benghalensis*	Purple vetch	Vi	30 x drill	Short duration annual	4 - 8
6	*Lablab purpureus*	Dolichos lablab (brown)	Do	60 x30	Medium duration annual	4 - 5
7	*Mucuna pruriens*	Velvet bean (mottled)	Mu (m)	60 x30	Medium duration annual	4 - 8
	Mucuna pruriens	Velvet bean (gray)	Mu (g)	60 x30	Medium duration annual	4 - 8
8	*Canavalia ensiformis*	Jack bean	Ca	50 x 50	Medium duration annual	4 -5
9	*Neontonia wightii*	Neontonia	Ne	30 x drill	Perennial	> 5
10	*Desmodium intortum*	Green leaf desmodium	GD	30 x drill	Perennial	> 5
11	*Desmodium uncinatum*	Silver leaf desmodium	SD	30 x drill	Perennial	> 5

Figure 1. Field layout of coffee – legume intercrop.

Block 1	Be	Ca	Mu (g)	GD	Bu	Mu (m)	Co	Vi	Sy4	SD	Ne	Cr	Sy17	Do
Block 2	Co	Mu (g)	GD	Mu (m)	Cr	Do	Be	Sy17	Ca	Sy4	Vi	SD	Ne	Bu
Block 3	Cr	Ne	Sy17	Mu(m)	Bu	Mu (g)	GD	Be	SD	Co	Sy4	Do	Vi	Ca

Key:

Be - Mwitemania bean

Bu - Butter bean

Ca – Canavalia

Co – Control (sole coffee)

Cr – Crotalaria

Do – Dolichos

GD - Green leaf desmodium

Mu (g) - Mucuna grey

Mu (m) - Mucuna mottled

Ne - Neontonia

SD - Silverleaf desmodium

Sy4 – Soyabean 4

Sy17 - Soyabean 17

Vi - Purple vetch

Note: The controls for sole and intercrop systems were uncropped plot (without legumes) and sole coffee respectively

3.3 Data collection and analysis

3.3.1 Legume growth, phenological development and biomass production

Legume growth and development was monitored. This included days to 50% emergence, anthesis, 50% flowering, 50% podding, seed set and physiological maturity. Canopy height was measured using a meter rule on seven randomly selected plants. Grain legumes were harvested, threshed and the grain weighed. The harvesting dates were between 30th May 2005 and 18th July 2005 depending on time to maturity.

Grain legume dry matter (DM) accumulation was determined at 4, 10 and 12 weeks after planting (WAP) while that of the perennial legumes extended to 10, 16, and 24 WAP. The fresh mass of three randomly selected plants was determined and a sub-sample dried at 105°C to constant mass to determine dry matter content. Litter was collected for canavalia, desmodium, mucuna, vicia, neontonia and crotalaria in a $0.25m^2$ quadrant placed randomly in the sole and intercropped legumes at 17th and 24th WAP. Litter for dolichos and butter bean was collected at 17 WAP. The litter was oven dried at 105°C to constant mass and weighed. Legume yield was determined from the entire plots of each food legumes. Total dry matter (TDM) accumulated by the food legumes (dolichos and butter bean) was determined at 17 WAP and at 24 WAP for non food legumes.

3.3.2 Interception of photosynthetically active radiation (PAR)

The photosynthetically active radiation (PAR) intercepted by the canopy was measured using a sunfleck ceptometer (SF-80 Decagon, Pullman, Washington). The ceptometer was randomly placed perpendicular to the rows above and below each legume between 11.30 am and 1.30 pm (local time). Seven measurements were taken in each plot after every 2 weeks. Three ceptometer measurements were taken in the intercrop system; one above coffee canopy, another above the legume but below the coffee and the third one below the green area of the legume. The PAR intercepted was calculated by subtracting the ceptometer reading below the legume canopy from the ceptometer reading above the canopy.

$$\% \text{ PAR intercepted} = \{(PAR_a - PAR_b) / PAR_a\} * 100$$

Where: PAR_a = PAR above legume canopy and

PAR_b = PAR below legume canopy

3.3.3 Soil moisture

Soil water content (SMC) was determined gravimetrically at 0-25, 25-50, 50-75, and 75-100 cm in sole and intercropped legumes at 11 and 30 weeks after planting. The soil samples were obtained from these depths by use of a soil auger and oven dried separately at 105 °C for 24 hours. Soil moisture content was determined by subtracting the weight of oven dried soil sample from that of the fresh soil sample divided by weight of the dry soil sample.

$$\% \text{ SMC} = (S_w - S_d) / S_d \times 100$$

Where: S_w = Weight of wet soil

S_d = weight of dry soil

The soil moisture content was used to determine soil moisture conservation and extraction by sole and intercropped legumes

3.3.4 Weed density and biomass accumulation

Weed density was determined at 7 and 24 WAP by counting the individual weed species within a 0.25 m^2 quadrant. Weeds were cut and oven dried at 105°C to constant mass.

All data was analyzed using the Genstat statistical computer package (GenStat Release 7.2, Copyright 2002, Lawes Agricultural Trust (Rothamsted Experimental Station) and significant means separated using least significant difference (LSD) tested at 5% probability.

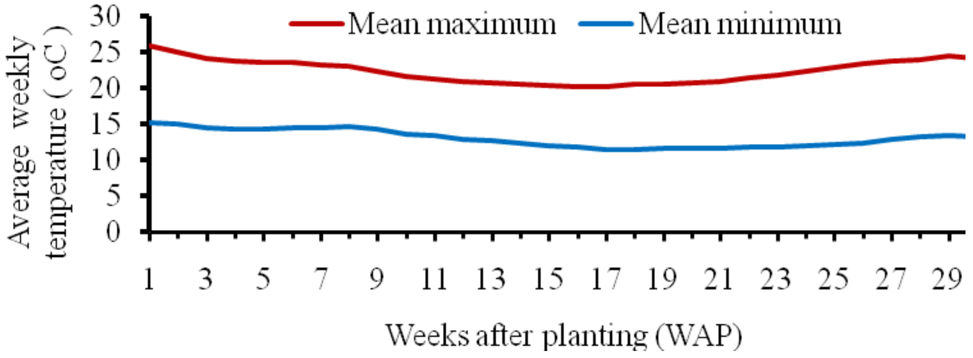
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Experimental site characteristics

4.1.1 Rainfall and temperature

Rainfall (mm) and mean maximum and minimum temperature (^{o} C) were obtained from a meteorological station from the farm over a period of nine months. Mean maximum temperature varied from 20.1 to 25.8 ^{o} C. Mean minimum temperatures during the growing period ranged between 14.4 to 15.1 ^{o} C (Figure 2a). The total amount of rainfall received during the experiment period of 30 weeks was 894.8 mm. A total 830.3mm (93 %) was received during the first 14 WAP with a peak of 154 mm at 9 WAP. Weekly rainfall remained below 25 mm between 15 to 30 WAP (Figure 2b).



(b) Total weekly rainfall (mm)

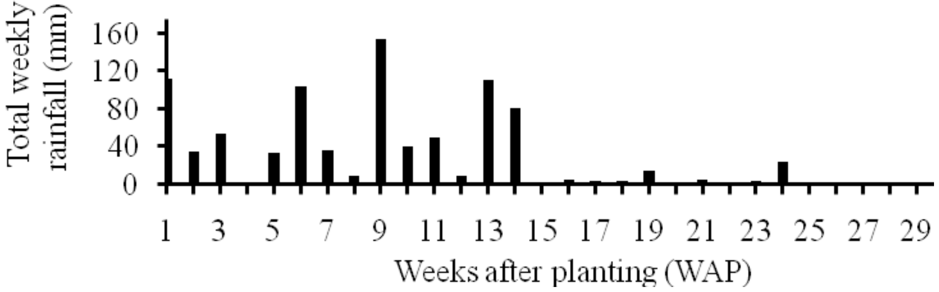


Figure 2. (a) Average weekly mean maximum and mean minimum temperature (^{o} C) distribution and (b) total weekly rainfall (mm) at the Kabete Field Station farm.

All the legumes were sown on the same day to allow their growth at same temperature and rainfall regimes.

4.1.2 Soil moisture content

Soil moisture content was measured in plots of sole and intercropped mucuna, desmodium, Neontonia and crotalaria at 11 and 30 WAP (Figure 3). Average soil moisture content was significantly higher by 8 % at 11 WAP compared to 30 WAP due to input from rainfall during the first 14 WAP. At 11 WAP the soil moisture content was comparable in all treatments and at all depths but differences were apparent by 30 WAP (Figure 3). This was attributed to low rainfall between 15 to 30 WAP, direct soil water evaporation and plant uptake contributed to decline in soil moisture (Figure 3). Soil water content variation was more apparent under sole legumes compared to those intercropped with coffee between 11 and 30 WAP.

Differences in soil moisture content among legumes and between sole coffee and coffee – legume intercrops indicated variations in legume ground cover (life and dead mulch) and extend of soil moisture conservation or extraction. For example, high soil water content under mucuna may be attributed to its maintained high ground cover (> 90 %) and its comparatively high seasonal litter fall between 11 and 30 WAP. Both live and dead mulch of mucuna, desmodium, C*anavalia ensiformis* and Neontonia may have reduced direct evaporative water loss from the soil. This resulted in high soil moisture in plots long after rains subsided between 15 to 30 WAP enabling these legumes to survive soil moisture stress over this period. The difference in the amount of litter among the legumes may have influenced water loss through evaporation. Intercropped Mucuna had the highest amount of litter (748 kg/ha) compared to

Neontonia (115 kg/ha) and the soil water content higher (31 %) at upper soil depths compared to that of Neontonia (25 %) at the same depth indicating that more litter mulch resulted in greater soil moisture conservation. Soil water change was influenced by direct evaporative loss (controlled by litter) and also uptake by roots (McIntyre *et al.*, 2001)

Soil water content in sole coffee plots was higher by 26 % compared to that in the uncropped plots at 25 cm soil depth. This was indicative that coffee shading probably reduced temperatures and reduced wind speed, leading to reduced soil water evaporation hence the higher soil moisture content at that depth, but was comparable at 50 cm at at 30 WAP (Figure 3). It was however significantly lower in the coffee-legume intercrop plots compared to that in sole coffee and varied among the intercropped legumes. Average soil moisture content in plots with sole and intercrop legumes was generally lower in the upper (< 50cm) compared to the lower depth (75 and 100cm) but was apparent among individual legume species at all depths at 30 WAP. This may be attributed to high water extraction rate due to high concentration of both legumes and coffee roots at this depth. The greatest coffee feeder and lateral root concentration is in the first 20 and 30 -45 cm respectively (Coffee Research Institute, 2006).

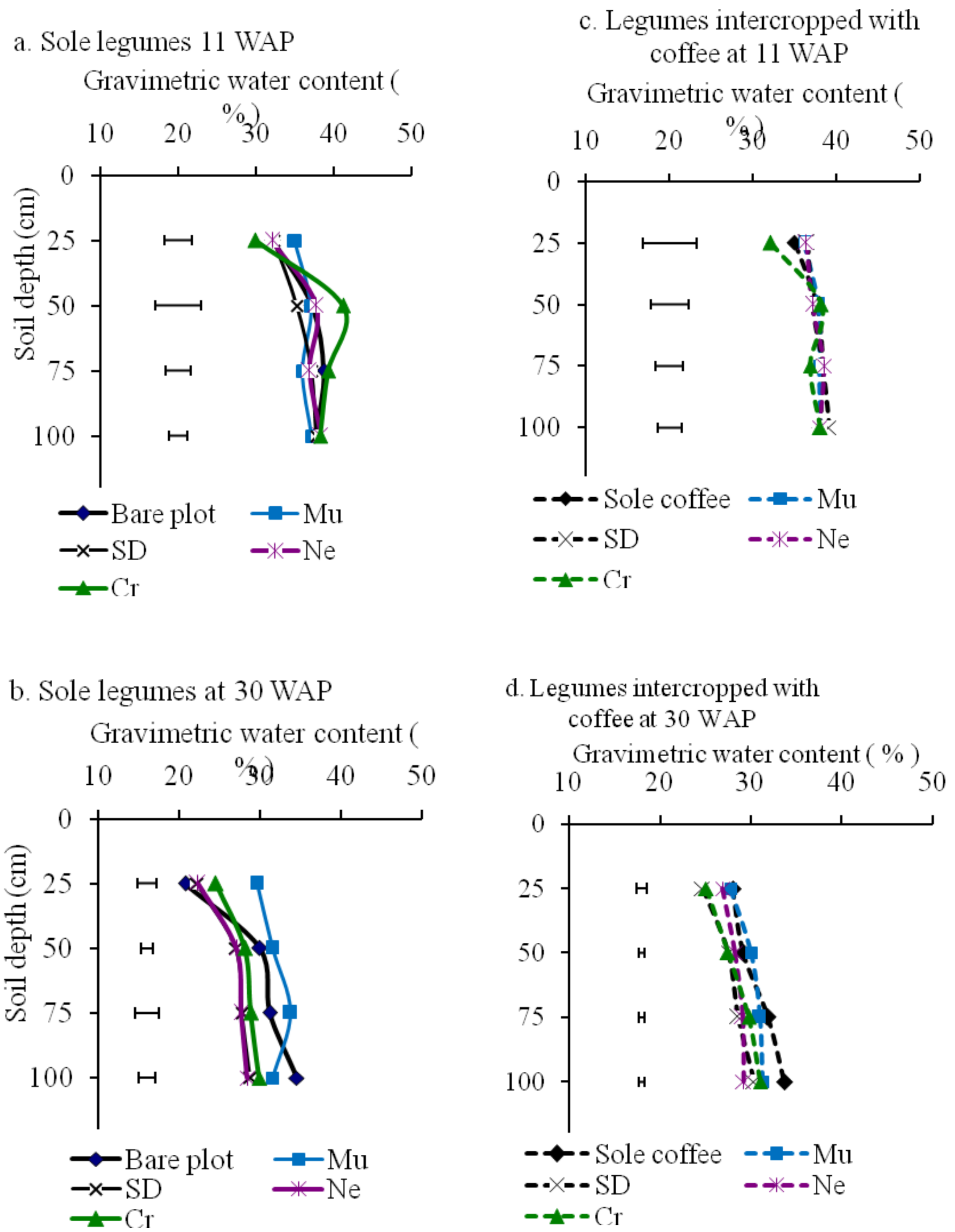


Figure 3. Soil water content in coffee plots undersown with legumes and sole cropped legumes at 11 and 30 weeks after planting. Mu, SD, Ne and Cr represents Mucuna, Silver leaf desmodium, Neontonia Crotalaria and respectively. Uncropped plot and sole coffee are controls of sole and intercrop systems respectively. Least significant difference (LSD) bars shown.

Average soil moisture content in plots under mucuna was significantly higher than silver leaf desmodium and Neontonia by 15 % at upper soil depths (<50 cm) and by 10 % at lower depths (> 75 cm) at 30 WAP. Mucuna, silver leaf desmodium, crotalaria and Neontonia had low soil moisture content below 50 cm indicating that their roots may have reached and taken up water at this depth at 30 WAP (Figure 3). Mucuna and crotalaria have the ability to extend roots into the subsoil (65 cm) and take up residual soil moisture leading to decreased soil moisture overtime at that depth (Gachene *et al.,* 2000). Understanding the differences in root depth between coffee and intercropped legumes is important because it may provide an avenue for selecting the most complementary legumes for intercropping with coffee that minimize competition for water and nutrients and therefore increase productivity in coffee farms. Overall, soil water content was highest in plots planted with mucuna followed by crotalaria, silverleaf desmodium and Neontonia and varied with depth among these legumes. This showed that the legumes differed in soil moisture conservation and extraction.

4.2 Physiological basis of legume phenological characteristics

4.2.1 Legume establishment

Legume establishment and growth was good due to favorable weather conditions but varied among the legume species. Intercropping did not significantly affect time to emergence, 50 % flowering and podding significantly (Table 4). Small seeded legumes (desmodium, crotalaria and Neontonia) germinated better than medium (Mwitemania and soya bean) and large seeded legumes (mucuna, canavalia, and Butter bean) (Table 4) probably because they comparatively require less moisture to germinate (Njarui *et al.*, 2003). Generally all the legumes had regular to high shoot vigor (Table 4).

High shoot vigor and rate of seedling growth observed in the medium and large seeded legumes compared to small seeded legumes was probably due to availability of adequate food reserves (assimilates) in the large seeds (Gunaga, 2008). Seedling vigor was also attributed to legume genotypic characteristics such as seed size (Hojjat, 2011) Canavalias' fast establishment within 4 WAP was comparable to observations made by Gitari *et al.*, (2000) where canavalia established faster than the other legumes.

4.2.2 Legume phenological duration

Phenological duration (time to emergence, anthesis, 50 % flowering, 50 % podding and physiological maturity) generally varied significantly between legume species and not between cropping system (Table 4). Soyabean emerged earliest (6.3 DAP) among food legumes and desmodium among non food legumes (14 DAP). Neontonia emerged last (20.5 DAP).

Table 4. Early seedling vigor and duration of phenological stages of legumes

Legume	Early seedling vigor	Time to 50 % (in Days)				
		Emergence	Anthesis	Flowering	Podding	Physiological maturity
Mwitemania bean	4.0	12.7	37.3	39.8	48.2	92.7
Butter bean	4.0	12.5	35	40.3	47.8	96
Soyabean4	4.0	6.3	69.8	74	78.1	101.8
Soyabean17	4.0	6.2	75.5	78.8	80.7	89
Dolichos	3.7	8.8	80.3	98.3	114.3	156
Mucuna (grey)	3.7	15.5	99	105	111	-
Mucuna (mottled)	3.5	15.8	101.5	109.2	114	-
Crotalaria	3.7	11.7	97.7	113.5	129	-
Vicia benghalensis	3.3	15.0	152	159.7	168.5	-
Silver leaf desmodium	3.7	15.3	75.5	-	-	-
Green leaf desmodium	3	14.8	-	-	-	-
Canavalia	3.7	13.0	-	-	-	-
Neontinia	3.2	20.5	-	-	-	-
Fpr	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
L.S.D	1.82	0.49	1.367	1.4	1.572	2.971
CV %	12.1	11.6	1.4	1.3	1.4	2.3

Shoot vigor: scale 1, 2, 3, 4 and 5 represents very bad, low, regular, high and excellent respectively.

Differences in the length of phenological stages of legumes at the vegetative stage (emergence to 50 % flowering) and reproductive stage (50 % flowering to physiological maturity) may be attributed to differences in thermal duration in degree days (Mburu, 1996; Elmore, 2010). The vegetative stage of common beans, soya beans, Dolichos and was 424^{o} C, 629 ^{o} C and 708^{o} C days accumulated over 37, 70, and 80 days, respectively, while the reproductive stages were 974^{o} C, 838^{o} C and 1190^{o} C days accumulated over 93, 102 and 156 days respectively (Table 5). This was similar to Soya bean and Dolichos that took to 72 (Wanjekeche *et al.*, 2004) and 117 DAP (Abayoni *et al.*, 2001) to flower, respectively. Legume flowering time and seed filling stages are important because they coincide with the peak of biological nitrogen fixation which is important for soil fertility improvement (Ennin *et al.*, 2004; Liu *et al.,* 2011).

The earliest maturing (89 - 102 days) were annual grain legumes (Soya beans, mwitemania and butter bean) compared to medium maturing legumes such as Dolichos (116 days). The reproductive stage marks the seed production time for grain crops (Nordby, 2004). Physiological maturity of perennial legumes could not be established because the experiment was terminated (210 DAP) before these legumes reached seeding. Perennial legumes (Neontonia and *Desmodiums*) were considered as late maturing based on their perennial nature. The results showed that thermal time influenced legumes phenological stages. Knowledge of phenological stages such as flowering (peak time for BNF activity) is important especially when legumes are grown for soil fertility improvement. Similarly, timing physiological maturity is important when grain legumes for food.

Table 5. Relationship between food legume phenological stages and accumulated thermal time ^{o}C days since zero days after planting to physiological maturity

Phenological stage	**Accumulated thermal time (^{o}C days)**		
	Bean (T_b =8)*	Dolichos (T_b = 9.9)$^{\$}$	Soyabean (T_b= 10)$^{\#}$
Emergence	147	95	63
Anthesis	424	708	629
50 % flowering	457	829	658
50 % podding	544	927	687
Physiological maturity	974	1190	838

T_b is base temperature (^{o} C): Source; *(Mburu, 1996), $^{\$}$(Awadhwal *et al.*, 2001) and $^{\#}$ (Elmore, 2010)

4.2.3 Legume growth

The canopy height of the erect and determinate legumes (bean, soyabean and crotalaria) increased overtime in both sole and intercropped systems and varied significantly among legume types but not among cropping systems within species (Figure 4). Bean canopy height increased significantly at 4 and 6 WAP but not thereafter. Sole and intercropped mwitemania canopy reached maximum height of 60 cm at 10 WAP respectively while intercropped soyabean 4, soyabean 17 and crotalaria had maximum canopy of 49, 64 and 108 cm respectively at 14 WAP (Figure 4).

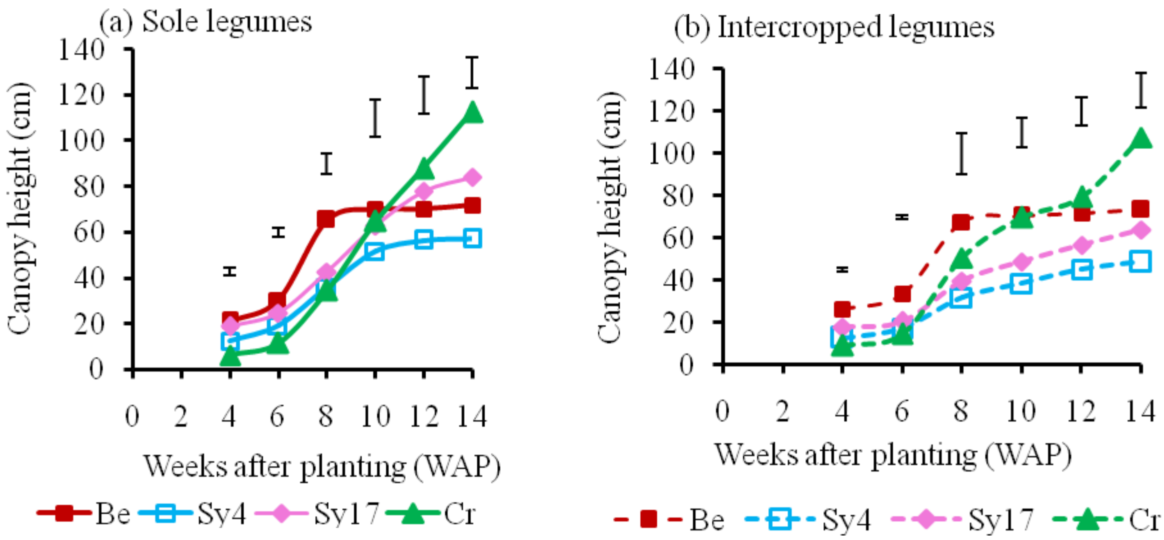


Figure 4. Canopy height of determinate legumes: Sy4, Sy17, Be and Cr represents soyabean4, soyabean17, bean and crotalaria respectively. Least significant difference (LSD) bars shown.

The height of canopy of Mucuna, butter bean, , *Lablab purpureus, Neontonia wightii* (climbing and creeping legumes), *Desmodium uncinatum, Desmodium intortum Vicia benghalensis (creeping)* and *Canavalia ensiformis* (erect) was not measured but from intercepted PAR observations (Figures 4 a and 4 b), these legumes had established considerable canopy at 14 WAP (Plate 1). Crotalaria established a high canopy quickly posing a light competition challenge making it suitable for intercropping with coffee if grown when coffee is not ready for picking or if it is slashed back to provide mulch. The climbing legumes (such as mucuna) were trained not to entangle the coffee canopy. Plant (canopy) height is a major resource use factor when determining intercrop suitability.

(a) (b)

(c) (d)

Plate 1: Intercropped legumes with over 90 % canopy cover at 14WAP: (a) Dolichos (an annual food legume), (b) Desmodium (perennial non food legume), (c) Mucuna (creeping annual legume) and (d) Crotalaria (erect annual legume)

4.3 Physiological basis for legume biomass accumulation

4.3.1 Canopy PAR interception overtime

Canopy photosynthetically active radiation (PAR) interception differed significantly within legume species and among sole and intercropped legumes. Coffee canopy intercepted approximately 41 % of the incident PAR largely due to its planophile canopy leaving 59 % of the total incident PAR was available to the intercropped legumes. Consequently, canopy PAR interception by sole legumes was significantly higher than in the coffee – legume intercrop throughout the growing season (Figure 5 a and 5 b). Differences in PAR interception may be attributed to variations in legume duration and growth habits (erect or spreading). Legumes with high ground cover (crotalaria and silver leaf desmodium) intercepted more PAR compared to those with low ground cover (canavalia and Neontonia). Intercepted PAR in all the legumes increased with time and either leveled off or decreased where leaf abscission occurred.

All legumes had attained over 90 % PAR by 12 WAP except Neontonia and canavalia (both comparable) that attained the same at 16 WAP (Figure 5 a and 5 b). Short duration food legumes established faster and reached peak % PAR interception earlier than medium duration annual and perennial legumes. The PAR interception for short duration annual legumes (bean, soyabean, crotalaria and *Vicia*) increased linearly during the vegetative phase (within 8 WAP) and declined at the reproductive after 10 WAP (Figure 5 a). The rate of PAR interception by bean and soyabean decreased at 10 and 12 WAP respectively possibly due to reduced ground cover associated with end of the vegetative phase (leaf production), beginning of the reproductive phase (pod formation) and subsequent leaf senescence at physiological maturity (Ansari and Chen, 2011).

Mwitemania bean and soyabean reached peak radiation interception (65 % and 82 % PAR) earliest at 8WAP and 10 WAP respectively among annual food legumes (Figure 5 a). Peak interception for intercropped mwitemania bean and soyabean 17 was 65 % and 82% PAR respectively. Intercepted PAR for soya bean 4 and soyabean 17 were not significantly different so only soyabean 17 is shown in Figure 5 a. Similarly PAR interception of Dolichos and butterbean was comparable and reached peak PAR interception latest (90 % PAR) at 14 WAP and maintained the highest % PAR interception even after 16 WAP (Figure 5 a) among the food legumes.

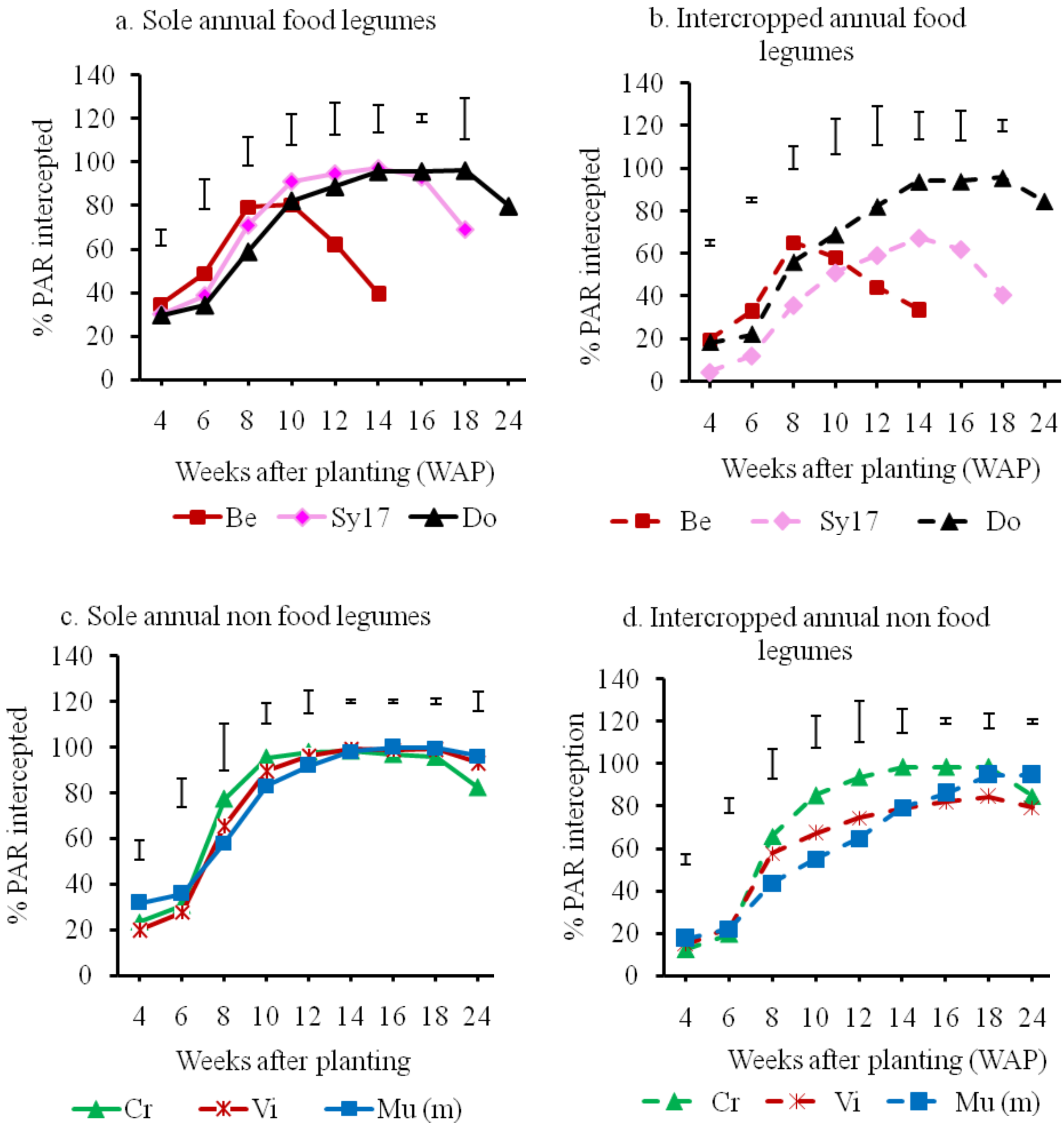


Figure 5 a. Canopy photosynthetically active radiation (PAR) interception by sole and intercropped annual food and non food legumes; Be, Sy17 and Do represents Mwitemania bean, Soya bean 17 and Dolichos respectively. Cr, Vi and Mu (m) represents Crotalaria, *Vicia benghalensis* and Mucuna (mottled) respectively. Least significant difference (LSD) bars shown.

Crotalaria intercepted higher PAR compared to *Vicia benghalensis* and mucuna (Figure 5 a). The rate of PAR interception of crotalaria, increased rapidly between 6

WAP and 12 WAP and generally slowed thereafter when the legumes reached maximum PAR interception (Figure 5 a).

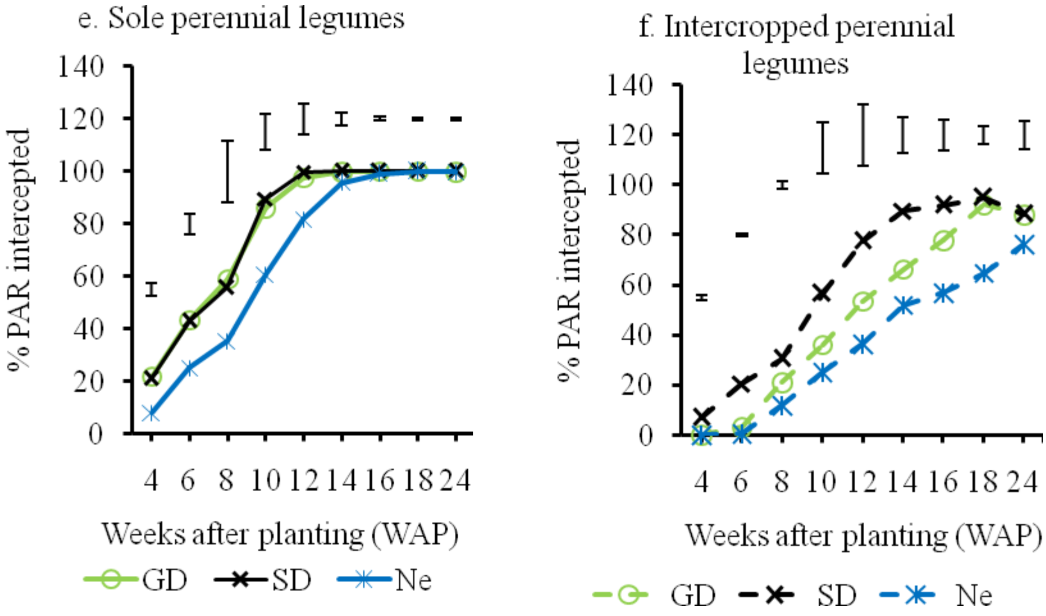


Figure 5 b. Canopy photosynthetically active radiation (PAR) interception by sole and intercropped perennial legumes; GD, SD and Ne represent Green leaf desmodium, Silver leaf desmodium and Neontonia respectively. Least significant difference (LSD) bars shown.

The sole silver and green leaf desmodium intercepted comparable PAR throughout the growing season. Intercropping reduced PAR interception of green leaf desmodium and *Neontonia wightii* compared to silver leaf desmodium throughout the growing season (Figure 5 b). The rate of PAR interception of these legumes increased gradually between 4 WAP and 12 WAP and slowed thereafter. Sole *Neontonia wightii* and green leaf desmodium intercepted over 60 % and 86 % PAR by 10 WAP, respectively while in the intercrop they intercepted 36 % and 25%, respectively at that time. Over all, Crotalaria, silver leaf desmodium, *Vicia benghalensis* and mucuna maintained highest % PAR interception overtime compared to other legumes while *Neontonia wightii* intercepted the least PAR comparatively.

4.3.2 Legume dry matter accumulation overtime

The amount of dry matter (biomass) accumulated increased over time and differed among the legumes and cropping systems (Figure 6). Differences in total dry matter (TDM) accumulation among legumes may be attributed to variations in (mainly) the amount and time of PAR intercepted by legumes. Amount of PAR intercepted was determined by legumes' growth habits and crop management (sole-cropping and intercropping). Legumes that grew fast (mwitemania, soyabean and crotalaria) and those that had spreading growth habit (butter bean, *Vicia*, desmodium) attained fast ground cover hence high PAR interception (Figure 5a and 5b). This possibly led to the observed early dry matter accumulation by these legumes (Figure 6).

Mwitemania bean accumulated the highest biomass in both sole and intercrop systems at 10 WAP, while Dolichos had the lowest at that time. Among the non food legumes *Vicia* and crotalaria (short duration annuals) accumulated DM faster than Neontonia and desmodium (perennials). The dry matter accumulated by perennial spreading forage legumes (desmodium, mucuna, Neontonia) was comparable at 10 WAP in both the sole and intercrop but differenced significantly between 12 and 16 WAP when rate of dry matter accumulation was highest, then declined gradually thereafter (Figure 6).

Intercropping significantly decreased amount of DM accumulated in all legumes. This was probably due to reduced incident PAR due to coffee shading that led to slowed leaf photosynthetic activity in intercropped legumes, hence depressed dry matter accumulation in these legumes compared to sole legumes. Intercropping reduced the dry matter accumulated by *Vicia* and Neontonia by 83 % and 78 %, respectively and in both silver leaf desmodium and mucuna by 69 % at 17 WAP. Overall, Crotalaria accumulated significantly higher DM than all the other legumes in both sole and intercrop throughout the experiment period (Figure 6).

Perennial (long term duration) legumes (Neontonia, desmodium) may have accumulated low DM early in the season (8WAP) (Figure 6) because they intercepted less light at that time (Figure 5 b). These legumes however, increased tremendously in leaf ground cover (over 80 %) with time due to their spreading growth habit and durable nature leading to high and prolonged PAR interception period (Figure 5 b). This resulted in high final TDM accumulation at 24 WAP. This fast increase in DM accumulation by spreading legumes was also reported by Anthofer and Kroschel (2005). Canavalias' slow rate of establishment and erect growth habit probably contributed to low PAR interception hence slowed DM accumulation.

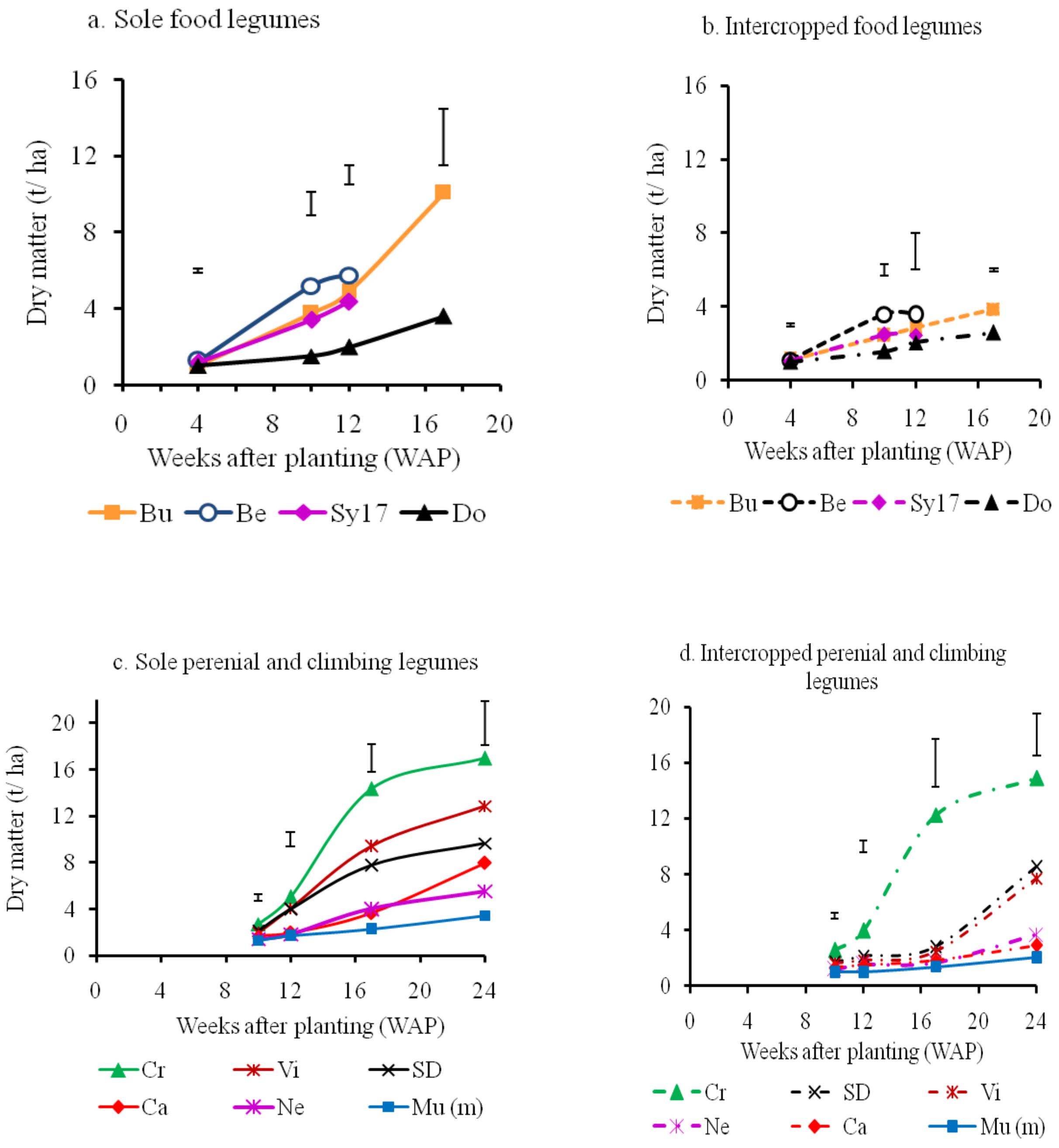


Figure 6. Biomass accumulation (t/ha) of (a) sole and (b) intercropped food legumes; Bu, Be, Sy17 and Do represents Butter bean, Mwitemania bean, Soya bean 17 and Dolichos respectively. Sole (c) and intercropped (d) perennial and climbing legumes; Ca, Mu (m), Vi, and Ne, SD and Cr represents Canavalia, Mucuna (mottled), *Vicia*, Neontonia, Silverleaf desmodium and Crotalaria respectively. Least significant difference (LSD) bars shown.

Intercropped silver leaf desmodium accumulated high dry matter overtime possibly because it was resistant to coffee shading (Kanton and Dennett, 2004) since sole and intercropped silver leaf desmodium peak PAR interception and accumulated TDM were comparable (Tables 7 and 16). Crotalarias' height corresponded with high biomass accumulation compared to other legumes. This implied that even when intercropped, it captured more radiation energy due to its heght, thereby making it a better use of incident radiation in the intercrop comparatively (Kanton and Dennett, 2004). Differences in soil moisture content (Figure 3) among sole and intercropped legumes may also have affected TDM accumulation. Lower soil moisture content and low accumulated DM in the intercrop compared to that in sole system (Figure 3) indicated that the intercropped legumes may have experienced competition for water and possibly nutrients (Famaye, 2004), leading to less legume biomass accumulation by these legumes.

These results showed that radiation capture and effective legume dry matter accumulation among legumes and between sole and intercrop systems was mainly influenced by amount of incident radiation, leaf area index (canopy ground cover) and leaf area (photosynthetic) area duration. Both canopy cover and duration are depended on the growth habits (morphology) and phenology of a plant (Kanton and Dennett, 2004). The amount of foliage in the plant canopy is commonly quantified by leaf area index (LAI) (Breda, 2008) which is an important measure of the primary sites of energy and mass exchange in plants upon which canopy interception, evapotranspiration, and gross photosynthesis take place (Fang and Liang, 2008). LAI determines net primary production, water and nutrient use, and carbon balance in plants and consequently dry matter accumulation (Breda, 2008).

4.3.2 Seasonal litter fall

The total amount of litter collected by the end of the season differed significantly among legumes and between the sole and intercrop systems. Silver leaf desmodium had the lowest seasonal litter among the legumes probably because it is a perennial legume and its leaves have a long life span than the annual legumes. It thereby retained much of its foliage. Mucuna was better in mulch (litter) supply compared to other legumes (Table 6), probably because of its genetic self shedding characteristics. This suggested mucuna would be a competitive option for soil fertility improvement in coffee farms because its high amount of litter provided mulch on the soil and this may have preserved soil moisture, provided soil organic matter and suppressed weeds.

On average, the litter in intercropped legumes was lower by 42 % compared to that in sole legumes (Tables 6 and 7). This difference may be attributed to slowed leaf senescence probably due delayed leaf physiological maturity associated with low PAR interception in the intercrop. Intercropping significantly reduced the litter of mucuna, Dolichos and butter bean but did not significantly affect litter from the other legumes. Cessation of leaf photosynthetic activity in mucuna and physiological maturity in Dolichos and Butter bean was likely the main reason for leaf senescence leading to high litter fall in these legumes. The litter from sole and intercropped crotalaria, desmodium, *Vicia* and Neontonia was comparable but significantly lower than from canavalia. The amount of litter from Dolichos was significantly higher than that from butter bean in both sole and intercrop (Table 7).

4.3.3 Legume Seasonal litter and total dry matter (TDM) accumulation

Total dry matter (TDM) accumulation differed significantly among legume species and between sole and intercropped systems. Among the food legumes butter bean had the highest biomass followed by mwitemania bean (Table 6). Crotalaria accumulated the highest TDM followed by silverleaf desmodium, *Vicia benghalensis* and green leaf desmodium among non food legumes (Table 7). Overall, crotalaria accumulated the highest TDM. Intercropping significantly reduced TDM of canavalia, green leaf desmodium, mucuna and *Vicia benghalensis* but had no significant effect on crotalaria, Neontonia and silver leaf desmodium (Table 7). On average, intercropping reduced TDM production of butter bean and Dolichos by 78 % and 55 %, respectively but had insignificant effect on TDM of soyabean and mwitemania bean. Silver leaf desmodium had the lowest TDM reduction compared to other legumes (Table 7).

Legumes with high seasonal litter fall had comparatively low TDM accumulation. Mucuna had the highest seasonal litter fall in both cropping systems but had the lowest TDM accumulation compared to other non food legumes (Table 7). Among the food legumes, sole Butter bean had significantly higher TDM than Dolichos but had significantly lower seasonal litter fall compared to that of Dolichos in both systems (Table 6). Relative TDM yield varied among the legumes species. Soyabean and butter bean had the highest and lowest relative TDM respectively, among food legumes (Table 6). Silverleaf desmodium and crotalaria had higher relative TDM yield compared to mucuna among non food legumes (Table 7). Litter fall to TDM ratio differed significantly among legumes. On average mucuna and crotalaria had the highest and lowest litter fall to TDM ratio respectively (Table 7).

Table 6. Seasonal litter fall, total dry matter (TDM), relative TDM yield and % TDM reduction for food legumes

Food legumes	**Seasonal litter fall (kg/ha)**		**TDM (kg/ha)**		**Relative litter yield**		**Relative TDM yield**	**% TDM reduction**
	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop		
Soyabean4	-	-	2525	1720	-	-	0.68	32
Butter bean	588	274	10675	2331	6	12	0.22	78
Mwitemania bean	-	-	4228	2586	-	-	0.61	39
Dolichos	1158	635	3785	1685	31	38	0.45	55
Soyabean17	-	-	2422	1477	-	-	0.61	39
Fpr	0.007	0.113	0.043	0.260				
LSD	205	572.1	6349.8	1787.6				
CV %	6.7	35.8	25	25.3				

Note: - HI for soya beans and mwitemania bean was calculated using legume final biomass only because seasonal litter fall for these legumes was not collected.

- Relative litter yield is the proportion of litter to TDM calculated as follows; (Litter fall / TDM) x 100

- Relative TDM yield is the ratio of the TDM of intercropped legumes to the TDM of sole legumes

Table 7. Seasonal litter fall, total dry matter (TDM), relative TDM yield and % TDM reduction of non food legumes

Non food legumes	**Seasonal litter fall (kg/ha)**		**TDM (kg/ha)**		**Relative litter Yield (%)**		**Relative TDM yield**	**% TDM reduction**
	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop		
Mucuna (mottled)	1063	433	3524	1004	30	43	0.28	72
Mucuna (grey)	883	530	4558	1537	17	35	0.34	66
Neontinia	146	115	4703	2788	3	4	0.59	41
Canavalia	512	366	7490	2297	7	16	0.31	69
Silver leaf desmodium	105	128	7782	7699	1	2	0.99	1
Vicia benghalensis	121	128	11979	6820	1	2	0.57	43
Green leaf desmodium	210	126	13485	5090	1	3	0.38	62
Crotalaria	201	136	16173	14006	1	1	0.87	13
Fpr	<0.001	<0.001	<0.001	<0.001				
LSD	193	85.6	3762.8	2817				
CV %	27.2	19.9	24.7	31.2				

Note: - Relative litter yield is the proportion of litter to TDM calculated as follows; (Litter fall / TDM) x 100

- Relative TDM yield is the ratio of the TDM of intercropped legumes to the TDM of sole legumes

4.3.3 Correlation between cumulative PAR intercepted and TDM accumulation

Generally, the accumulated TDM was linearly positive and highly correlated to the cumulative intercepted PAR, but differed in level of correlation among the legumes (Figures 7, 8 and 9). For example, the high regression slop (gradient) observed in intercropped mwitemania beans (1.357) compared to that of Dolichos (0.336) (Figure 7) indicated that any given increase in cumulative PAR corresponded with a greater increase in the amount of TDM accumulated in former compared to the latter. Correlation coefficient (*r*) (derived from the corresponding R^2 values) was 0.996 0.991, 0.987, 0.957 and 0.713 for soyabean bean, crotalaria, Dolichos and mucuna respectively) (Figures 7, 8 and 9). High *r* values indicated that legume dry matter production was highly associated with the photosynthetically active radiation (PAR) intercepted (Akhter *et al*., 2009). PAR interception depended on legume canopy ground cover and duration (Tesfaye *et al*., 2006; Kanton and Dennett, 2004 and Mureithi *et al*., 2003). Correlation coefficient (*r*) was on average 0.979 and 0.885 in sole and intercropped system respectively (Figures 7, 8 and 9) indicating that intercepted PAR was not as strongly correlated to TDM accumulation in the intercrop legumes as in the sole legumes.

Butter bean and soyabean had intercepted 270 and 240 MJ m^{-2} at 10 WAP compared to Dolichos (205 MJ m^{-2}) at the same time (Figure 7). The cumulative (total) intercepted PAR for intercropped crotalaria was higher (656 MJ m^{-2}) compared to that for mucuna (553 MJ m^{-2}) at 24 WAP. Crotalaria probably intercepted high PAR because of its high ground cover (Figure 5a) leading to high DM accumulation (Figure 6).

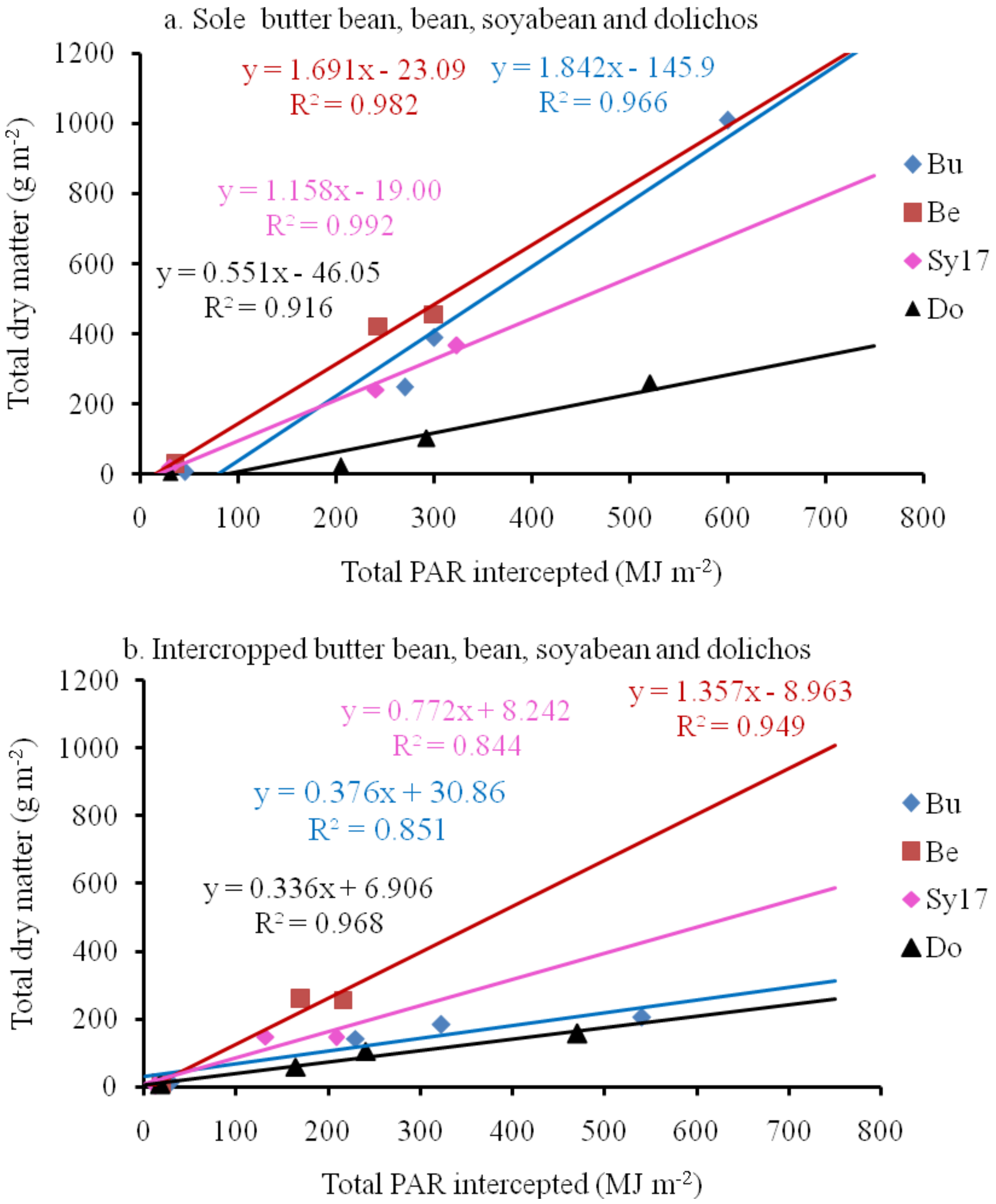
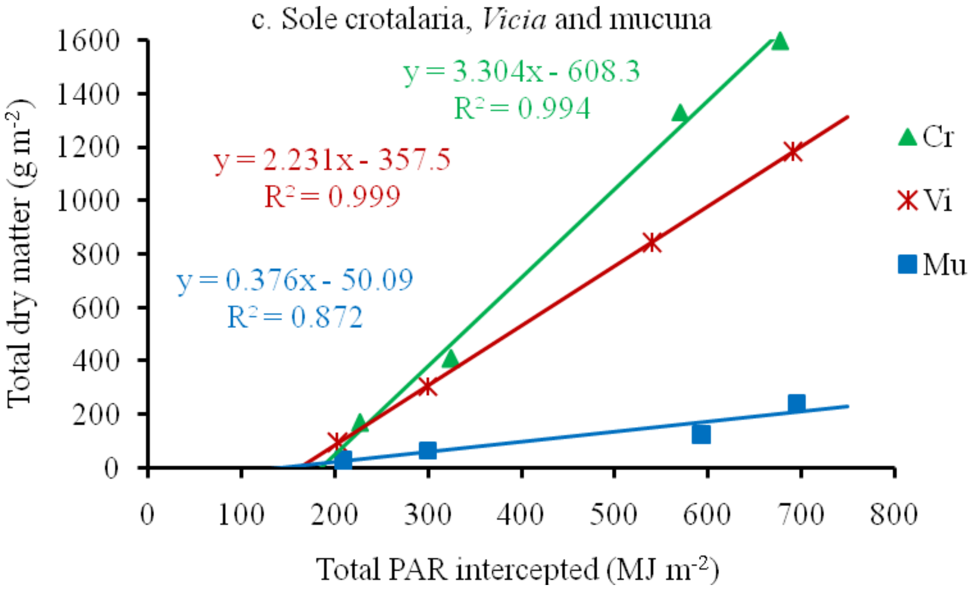


Figure 7. Correlation between dry matter and intercepted PAR of (a) sole and (b) intercrop annual food legumes: Be, Sy17, Bu, Do, represent bean Mwitemania, soyabean 17, Butter bean and Dolichos respectively.



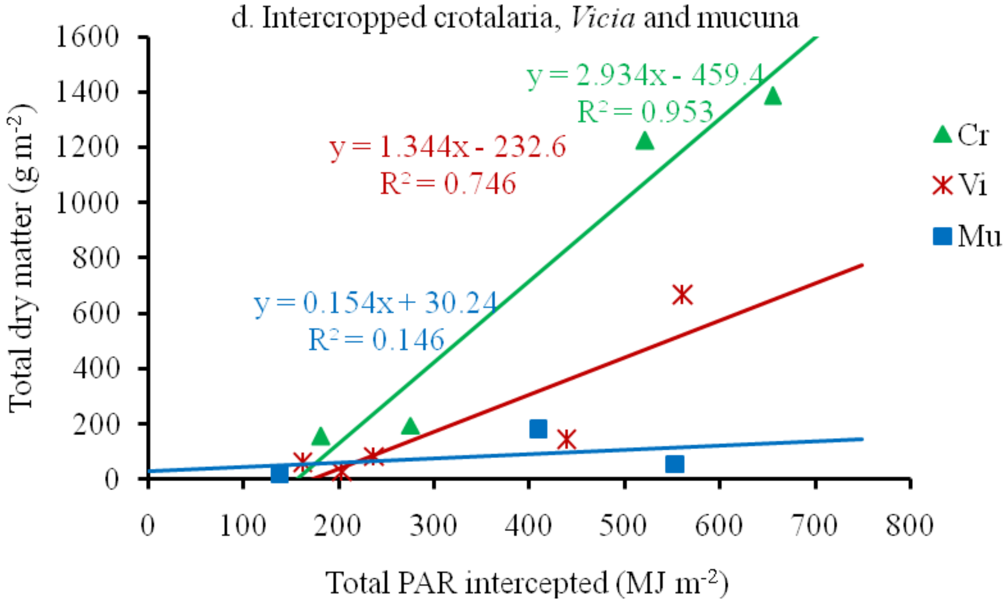
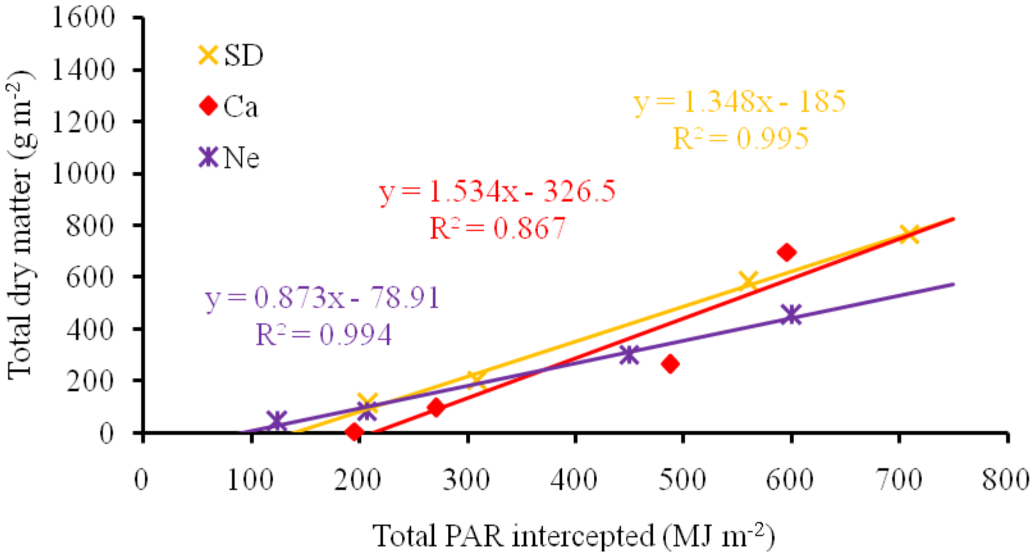


Figure 8. Correlation between total dry matter and intercepted PAR of (c) sole and (d) intercrop non food annual legumes: Cr, Vi, Mu represent crotalaria, *Vicia* and mucuna respectively.

e. sole silverleaf desmodium, canavalia and Neontonia



f. Intercropped silverleafd desmodium, canavalia and Neontonia

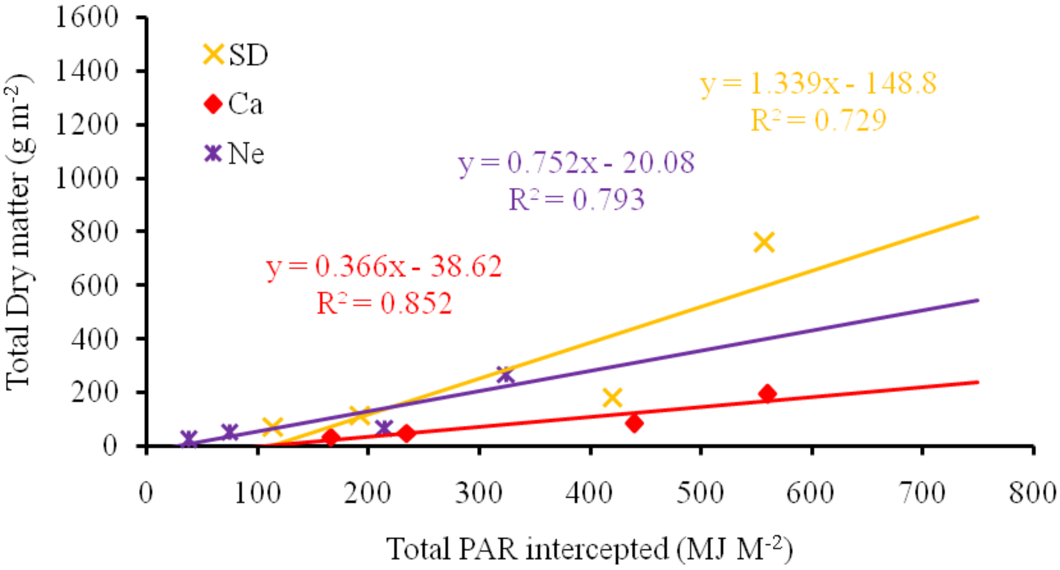


Figure 9. Correlation between total dry matter and intercepted PAR of (e) sole and (f) intercrop perennial and climbing legumes: SD, Ne and Ca represent, Silver leaf desmodium, Neontonia and canavalia respectively.

Crotalaria had a higher RUE (2.934 g DM MJ^{-1}) compared to mucuna (0.154 DM MJ^{-1}) suggesting that crotalaria comparatively converted more of the intercepted radiation for dry matter production. Crotalaria was ranked higher than mucuna based on these observations. However, though crotalaria is characteristically good in early ground cover development, its height and erect growth (Abayomi, 2001) may pose a light competition challenge against coffee.

4.5.4 Seed yield and harvest index

Butter bean, Dolichos and mwitemania bean and soyabeans grains were harvested at 17, 12 and 10 WAP respectively because their grains reached physiological maturity at these different times (Table 4). Mwitemania and soya bean are determinate and matured early and uniformly within one week period. Dolichos and Butter bean are semi determinate hence matured unevenly over a month. Seed yield (kg/ ha), 100 seed mass, number of pods per plant and number of seeds per pod differed significantly among the legumes. Mwitemania bean and soyabean17 had the highest seed yield in the sole and intercrop systems respectively and soya bean 4 the lowest yield in both systems (Table 8). Differences in amount and duration of intercepted radiation led to variations in accumulated dry matter; hence differences in seed yield among legumes and between sole and intercropped legumes (Kanton and and Dennett, 2004; Tesfaye *et al.,* 2006).

Intercropping significantly depressed seed yield and number of pods per plant in all food legumes but had no significant effects on number of seeds per pod and 100 seed mass. Seed yield reduction due to intercropping was highest in Soya bean 4 followed by that of butter bean and mwitemania bean (Table 8). Intercropping significantly reduced number of pods per plant in butter bean, soyabean 17, Dolichos and soyabean 4 by 56 %, 31 %, 27 % and 13 %, respectively (Table 8). Reduced photosynthetic activity due to less PAR reaching intercropped legumes led to low dry matter accumulation and radiation use efficiency (RUE) hence reduced intercrop yields (Table 9). Radiation use efficiency is the ratio between biomass accumulation and radiation interception during a considered time interval (Stockle and Kemanian, 2009). It is estimated as the slope of the linear regression between cumulative biomass and cumulative intercepted radiation for a given period of time (Figure 7). A RUE of 1.4 g MJ^{-1} for C3 plant species (dry beans, soyabean) has been reported (Stockle and Kemanian, 2009). Butter bean and Dolichos had comparable PAR interception but TDM for the former was comparatively higher than the latter because Butter bean had higher light use efficiency. Low Mwitemania yields in the intercrop system (593 kg ha^{-1}) in this experiment were comparable to an average of 701 kg ha^{-1} per season observed under a similar coffee intercrop (Kimemia, 1998). Reduced seed yield of Dolichos and soya bean by 59 and 42 % respectively corresponded with 55 and 32 % DM reduction due to intercropping for the respective legumes implying that DM accumulation and grain yield in food legumes are related (Tesfaye *et al.,* 2006).

Harvest index (HI) differed significantly among food legumes and between sole and intercrop systems. On average soya bean17 had the highest HI while butter bean had the lowest in both sole and intercrop systems (Table 8). HI of soyabean 4 and mwitemania were comparable in both the sole and intercrop but significantly reduced by 78 % and 52 %, respectively, due to intercropping. Intercropping did not affect HI of butter bean and

Dolichos. Differences in HI among Butter bean, Mwitemania, soya bean and Dolichos were attributed to differences in grain yields and biomass accumulation among these legumes (Table 8).

Table 8. Yield components of sole and intercropped food legumes

Legume	**Number of pods per plant**		**Number of seeds per pod**		**100 seed mass (g)**		**Seed Yield kg/ ha**		**Harvest Index (HI)**	
	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop
Soya 4	43.9	38.0	2.7	2.7	10.1	8.8	1224	781	0.48	0.45
Soya 17	36.8	25.5	3.0	2.7	15.6	16.9	1634	894	0.67	0.61
Dolichos	31.4	23.0	3.6	3.8	24.3	25.6	1842	753	0.49	0.45
Butter bean	13.4	5.9	3.0	2.7	99.9	103.8	1857	314	0.17	0.13
Mwitemania bean	*	*	*	*	36.5	38.8	2202	593	0.52	0.23
Fpr	0.002	<0.001	0.007	0.023	<0.001	<0.001	<0.008	<0.001	0.022	<0.001
LSD 5 %	11.81	4.438	0.699	0.965	9.51	5.578	357.2	124.8	0.272	0.154
CV %	21.4	11.0	11.3	16.1	13.5	7.6	11.1	12.1	30.5	26.3

NB: HI for Mwitemania bean, soyabean4 and 17 was calculated using legume final biomass. Litter fall for these legumes was not collected. * Data not collected

Table 9. Seed yield, harvest index (HI) and radiation use efficiency (RUE) of intercepted of sole and intercropped food legumes

Legume	**Seed Yield (kg/ ha)**		**TDM (kg/ha)**		**Harvest Index (HI)**		**Total PAR intercepted (MJ m^{-2})**		**Radiation use efficiency (RUE*) (g DM MJ^{-1})**	
	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop	Sole crop	Intercrop
Soya 4	1224	781	2525	1720	0.48	0.45	326	163	1.190	0.811
Soya 17	1634	894	2422	1477	0.67	0.61	333	209	1.158	0.772
Dolichos	1842	753	3785	1685	0.49	0.45	520	470	0.551	0.336
Butter bean	1857	314	10675	2331	0.17	0.13	600	540	1.842	0.376
Mwitemania bean	2202	593	4228	2586	0.52	0.23	300	216	1.691	1.357
Fpr	<0.008	<0.001	0.043	0.260	0.022	<0.001	-	-	-	-
LSD 5 %	357.2	124.8	6349.8	1787.6	0.272	0.154	-	-	-	-
CV %	11.1	12.1	25	25.3	30.5	26.3	-	-	-	-

Note: RUE* values are derived from the linear regression equation between legume total dry matter and cumulative intercepted PAR

(Stockle *et al*., 2009), (Figures 7, 8 and 9)

High HI in soyabean 17 (with erect growth habit) may be attributed to its high grain yield in relation to TDM accumulation indicating that much of the plant assimilate was translated into reproductive organs (seed resource) compared to the HI of Butter bean (spreading growth habit and extensive vegetative parts) that comparatively accumulated higher TDM in relation to its grain yield hence its low HI. The maturity and growth habit of component crops in an intercrop determine the productivity of each of the crops (Adeniyan and Ayoola, 2006). High grain yield of sole Mwitemania and Butter bean corresponded with high TDM accumulation indicating a direct correlation between TDM accumulation and grain yield. On average about 64 %, 48 %, 47 %, 38 % and 15 % of the total dry matter produced was allocated to seed in soyabean 17, soyabean 4, Dolichos, bean and Butter bean respectively, at the end of the growing season (Table 10). This showed that TDM partitioning into seed deferred among legumes, suggesting that careful consideration should be made on the impact of intercropping on the legume grain yield especially if the objective of intercropping includes grain production for food.

Table 10. TDM partitioning to seed yield

	Proportion of seed yield to TDM (%)		
Legume	Sole legumes	Intercropped legumes	Average
Soyabean17	67.5	60.5	64
Soyabean4	48.0	45.0	46.5
Dolichos	48.7	44.7	47
Bean	52.1	22.9	38
Butter bean	17.4	13.5	15

These findings confirm that radiation capture and use efficiency in intercrops is critical in plant dry matter accumulation and yield. Suitability of grain legume species selected for coffee intercrops should therefore be based on their ability to quickly develop and sustain a large (photosynthetic) leaf area (in terms of LAI) that can intercept and convert radiation into dry matter efficiently, and partition the dry matter into seed yield **(**Tesfaye *et al.,* 2006). This may be achieved by careful consideration of radiation use efficiency (RUE) and the morphological characteristics of the legumes to be intercropped with coffee.

4.6 Impact of legume canopy on weed density and biomass

4.6.1 Weed density and growth habits

Weed density (number of weeds per unit area) and biomass were measured at 7 and 24 WAP. The controls for the sole and intercrop systems were uncropped plot (without legumes) and sole coffee respectively (both unweeded). Eleven different weed species were identified in both sole and intercrop systems (Table 11). The most common five weed species were *Oxalis latifolia, Galinsoga parviflora, Bidens pilosa, Cyperus rotudus* and *Commelina benghalensis* (Table 11). Notably *Conyza bonariensis* (fleabane) appeared later in the season (24 WAP) but was comparably among the least common weeds. Weed density differed significantly among plots sown with different legume species and in the sole and coffee- legume intercrop overtime. Variations in individual weed density overtime may largely be attributed to differences in weed growth habits, legume cover and duration and influence of the cropping system (sole or intercrop) as discussed in sections 4.6.2 to 4.6.3. Average weed population in uncropped and sole coffee plots decreased by 16 % and 52 %, respectively, between 7 and 24 WAP while the average weed density in sole and intercropped legume plots decreased by 65 % and 85 %, respectively, over the same time. This general decrease may be attributed to death of some of the weeds (especially short leaved legumes) after completing their life cycle and restricted germination of fresh weeds due to low soil moisture between 15 and 30 WAP (Figure 1).

Table 11. Weed species found in both sole and intercrop system

No.	**Botanical name**	**Common name**	**Growth habit**
1	*Oxalis latifolia*	Wood sorrel	Annual and perennial broad leaved
2	*Galinsoga parviflora*	Gallant soldier	Annual broad leaved
3	*Bidens pilosa*	Black jack	Annual broad leaved
4	*Commelina benghalensis*	Wandering Jew	Annual and perennial broad leaved
5	*Setaria verticillata*	Love grass	Annual grass
6	*Cyperus rotudus*	Nut grass	Perennial sedge
7	*Conyza bonariensis*	fleabane	Annual broad leaved
8	*Oxygonium sinuatum*	Double thorn	Annual broad leaved
9	*Sonchus oleraceus*	Sow thistle	Annual broad leaved
10	*Amaranthus spp*	Pigweed	Annual broad leaved
11	*Cynodon dactylon*	Star grass	Annual grass

On average, weed density of annual weeds was lower compared to that of perennial weeds between 7 and 24 WAP. For example, *Galinsoga parviflora* and *Bidens pilosa* (both annual and herbaceous) were easily suppressed compared to *Cyperus rotundus*, *Commelina benghalensis* and *Oxalis latifolia* (all perennial) among the five most common weeds at 7 and 24 WAP (Tables 12 - 15). Annual and herbaceous weeds are easier to control because it is easier to break their short life cycle and therefore prevent further seed production (Damalas, 2008) which is their primary method of propagation (Rao, 2000). The perennial weeds had unique growth habits and /or morphology (Coffee Research Foundation, 2003) that made them survive suppressive effects by the legumes, making them difficulty to control. In particular *Commelina benghalensis* is succulent and it thrived in even during the dry season between 15 and 24 WAP (Figure 2). *Cyperus rotundus* was difficult to control through suppression probably because it multiplied very quickly during wet weather before legumes established large ground cover. Its tubers which remain dormant under the soil (Coffee Research Foundation, 2003) rejuvenated into new shots later in the season (24 WAP) prolonging its survival. *Oxalis latifolia* may have escaped legume suppression by surviving using its underground bulbs (Coffee Research Foundation, 2003).

Legumes significantly differed in suppression of the five most common weeds. Compared to other legumes, and soyabeans (among food legumes) and crotalaria, silver leaf desmodium, mucuna (mottled), *Vicia benghalensis* (all non food legumes) suppressed weeds the most (Tables 14 and 15) at 7 and 24 WAP. The number of *Galinsoga parviflora* weeds in plots with crotalaria, soya bean 4, *V.* benghalensis, silverleaf desmodium and mucuna was comparable and reduced by over 90 % between 7 and 24 WAP (Table 14 and 15). The numbers of *Bidens pilosa* declined by over 90 % between 7 and 24 WAP in plots with crotalaria, mucuna and silver leaf desmodium. Plots with *V. benghalensis* and soyabean had less *Bidens pilosa* numbers at 7 WAP compared to those at 24 WAP. On average crotalaria, *V. benghalensis* and

Neontonia poorly suppressed *Commelina benghalensis* at 7 WAP compared to other legumes (Table 14). Legume properties that may have contributed to the differences in weed suppression (section 4.6.2)

Table 12. Density of five most common weeds in food legumes plots at 7 WAP

	Weed density (numbers per m^2) at 7 WAP									
Treatment	***Bidens pilosa***		***Oxalis latifolia***		***Cyperus rotundus***		***Galinsoga parviflora***		***Commelina benghalensis***	
	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop
Control	6.7	117.3	48	180	20	70.7	53.3	220	7	12
Food legumes										
Soyabean17	1.33	45.3	66.7	12	6.7	42.7	1.3	5.3	1.33	16
Soyabean4	0	28	40	43.3	5.3	24	5.3	1.3	0	12
Dolichos	0.0	9.3	65.3	30.7	6.7	102.7	1.3	14.7	1.33	16
Mwitemania bean	0.0	10.7	40	24	1.3	74.7	16	10.7	1.33	14.7
Butter bean	0.0	16	72	30.7	0.0	72	8	25.3	0.00	5.3
Fpr	0.061	<0.001	0.713	0.003	0.023	0.311	0.007	<0.001	0.770	0.952
LSD	4.79	29.1	59.2	69.8	10.7	73.8	25.1	68.7	3.25	27.9
CV %	197.5	42.3	58.8	69.6	88.3	62.9	97.1	72	268.3	121.1

Note: The controls for sole and intercrop systems was uncropped plot (without legumes) and sole coffee respectively

Table 13. Density of five most common weeds in food legumes plots at 24 WAP

Weed density (numbers per m^2) at 24 WAP

Treatment	***Bidens pilosa***		***Oxalis latifolia***		***Cyperus rotundus***		***Galinsoga parviflora***		***Commelina benghalensis***	
	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop
Control	28	14.7	17	10	3.3	4	25	13	14.3	14.7
Food legumes										
Soyabean17	4	4.7	2.7	4	0	0	6.7	1.3	0	2.7
Soyabean4	0	0	0	0	0	0	0	0	0	0
Dolichos	2	2.7	2.7	14.7	0	0	3.3	8	2.7	2.7
Mwitemania bean	0	1.3	4.7	0	0	0	6	0	1.3	0
Butter bean	1.3	1.3	1.3	2	0	0	4.7	0	0	2.7
Fpr	<0.001	0.002	0.012	0.003	<0.001	0.066	<0.001	<0.001	<0.001	0.006
LSD	6.89	5.55	8.45	6.66	0.92	2.97	7.48	5.21	3.57	3.021
CV %	64.3	74.1	98.3	71.6	82.7	244.9	54	76.9	64.3	97.9

Table 14. Density of five most common weeds in non food legumes plots at 7 WAP

	Weed density (numbers per m^2) at 7 WAP									
Treatment	***Bidens pilosa***		***Oxalis latifolia***		***Cyperus rotundus***		***Galinsoga parviflora***		***Commelina benghalensis***	
	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop
Control	6.7	117.3	48	180	20	70.7	53.3	257	0	12
Non food legumes										
Vicia benghalensis	0	25.3	30.7	20	5.3	65	8	7	0	25.3
Mucuna (grey)	26.7	18.7	65.3	47	5.3	59	6.7	47	0	4
Mucuna (mottled)	0	84	54.7	111	2.7	99	4	63	0	5.3
Canavalia	0	26.7	48	52	1.3	91	14.7	92	0	10.7
Green leaf desmodium	6.7	73.3	38.7	197	0	60	36	84	0	20
Silver leaf desmodium	16	69.3	12	153	6.7	104	6.7	124	103.3	10.7
Crotalaria	2.7	20	86.7	49	4	71	0	8	0	10.7
Neontinia	1.3	93.3	70.7	47	5.3	4	6.7	275	0	13.3
Fpr	0.466	0.019	0.138	0.057	0.156	0.623	0.004	0.024	0.473	0.581
LSD	27.18	60.31	49.02	126.6	13.05	106.6	24.38	165.5	1.332	21.79
CV %	235.6	59.4	56.1	76.9	133.9	84.9	93.2	90	519.6	101.1

Table 15. Density of five most common weeds in non food legumes plots at 24 WAP

	Weed density (numbers per m^{2}) at 24 WAP									
Treatment	***Bidens pilosa***		***Oxalis latifolia***		***Cyperus rotundus***		***Galinsoga parviflora***		***Commelina benghalensis***	
	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop	Sole crop	Inter crop
Control	28	14.7	17	10	3.3	4	25	13	14.3	14.7
Non food legumes										
Vicia benghalensis	0	2.7	0	5.3	0	2.7	0	5.3	0	4
Mucuna (grey)	0	9.3	1.3	9.7	1.3	0	2.7	7.7	0	2.7
Mucuna (mottled)	0	1.3	0	6.7	0	1.3	2.7	9.3	0	0
Canavalia	2.7	12	10	24.7	0	2.7	4	15.3	0	11.3
Green leaf desmodium	0	6.7	0	44	0	0	0.3	5.3	0	2.7
Silver leaf desmodium	0	1.7	0	1.3	0	0	0	0.3	0	0
Crotalaria	28	1.3	0	0	0	0	0	0	0	1.3
Neontinia	0	4	0	29.7	0	0	4	5.3	0	4
Fpr	<0.001	0.040	<0.001	0.005	0.002	0.254	<0.001	0.011	<0.001	0.005
LSD	3.948	9.04	6.381	21.16	1.452	3.885	5.71	7.907	2.146	7.144
CV %	66.9	87.6	117.1	83.8	161.8	189.4	76.8	27.2	71.2	91.3

4.6.2 Legume growth habits and weeds density

There were significantly fewer weeds in annual legume plots compared to perennial legume plots at 7 WAP. Marked differences in weed suppression between annual and perennial legumes may be attributed to differences in the legumes duration and phenological (growth) characteristics. Legumes with fast ground cover establishment (crotalaria and *Vicia*) and spreading growth habits such as desmodium and *Vicia benghalensis* smothered the weeds at a faster rate and were therefore more effective in reducing weed densities (Table 15) early in the season (7 WAP). This was observed

under silver leaf desmodium, crotalaria, mucuna and canavalia where on average, weed numbers reduced by 99 %, 93 %, 89 % and 67 % respectively between 7 and 24 WAP were the lowest at 24 WAP (Table 14).

Plots under soya bean, crotalaria and *Vicia benghalensis* had the lowest weed densities at 7 WAP among short duration annual legumes (Table 13) while mucuna (mottled) and silver leaf desmodium plots had lowest weed densities among medium to long duration at the same time (Table 15). This indicated that these annual legumes were best in weed suppression early in the season (7WAP) due to early ground cover. The medium to long duration legumes (mucuna, desmodium and Neontonia) were poor weed suppressors due to slow establishment at early stages of growth and subsequent poor ground canopy cover (Figure 5b) at that time. However, these legumes (with spreading growth habits) were more effective in weed control later in the season (24 WAP) (Table 15) due to sustained high ground cover (99 %) overtime (Sparks, 2004). Desmodium is slow to establish and not effective in weed control at early stages of development but is very effective later when it has dense ground cover (Gachene and Kimaru, 2003). This indicated that the short duration legumes would be best in weed suppression shortly after onset of rains when many weeds sprout while the long duration would be effective past the rainy season ensuring prolonged weed control. In addition, there were other legume attributes that may enhance weed suppression. For example mucuna was effective in weed suppression probably because of its twining abilities in addition to good ground cover. Legumes are known to smother weeds through shading and twinning properties (Udensi *et al.,* 2005). Udensi *et al,* (2005) demonstrated that mucuna canopy suppressed spear grass weed biomass by 90 % in 5 months.

4.6.3 Cropping system and weeds density

There were significantly more weeds in coffee-legume intercrop plots compared to those of sole legume at 7 and 24 WAP (Tables 12 - 14). This was attributed to low legume ground cover in the intercrop that allowed much of the PAR (59 %) reaching legumes in the intercrop to be transmitted through their canopy (Table 16). Weeds utilized the transmitted radiation for fresh and sustained weed growth hence increased weed numbers and biomass accumulation (Udensi *et al.,* 2005). Intercropped canavalia was not effective in suppressing weeds (Table 19) probably due to low ground cover. Since it was also widely spaced (Table 3), it generally intercepted less light implying that a lot of PAR was transmitted and therefore available for weeds growth (Table 16).

Table 16. % PAR at peak legume interception in coffee-legume intercrop

% PAR	Coffee only	Butter bean	Dolichos	Mwitemania	Soyabeans	Canavalia	Crotalaria	Desmodium	Mucuna	Neontonia	*Vicia*
7 WAP											
Below coffee	59										
Above legume	-	55	68	55	51	56	69	65	65	56	60
Below legume	-	23	44	35	61	45	35	70	57	88	42
24 WAP											
Below coffee	59										
Above legume	-	55	62	*	*	57	62	65	63	56	60
Below legume	-	58	5	*	*	23	15	10	5	24	21

* Mwitemania bean Soya beans 4 and 17 had already been harvested

The positive relationship between poor legume canopy cover and poor weed control was also reported by Gachene and Kimaru (2003) who observed that canavalia did not suppress weeds effectively even at 6 months (24 WAP) primarily because of its low canopy cover, implying that canavalia may not be suitable for weed control in coffee systems.

Besides the radiation transmitted through the legumes, other factors that may have influenced weed suppression were litter and soil moisture levels. Legume litter on the soil service may have obstructed (intercepted) the PAR transmitted through legumes from reaching weeds hence preventing their germination and or growth. High legume litter corresponded with low weed numbers implying that litter enhanced weed suppression.

It is also possible that higher soil moisture levels in the upper soil horizon (< 25 cm) (Table 17), which is also the major seed and root zone for most weeds (Peralta *et al.,* 2011), may have contributed to high weed numbers at 24 WAP. The soil under intercrops had higher soil moisture content at 0 - 25 cm soil depth compared to the sole crops (Table 16). This corresponded with higher weed numbers in the former compared to the latter (Tables 18 and 19), implying that higher soil moisture (Kelton *et al*., 2011) may have comparatively favoured weed growth in the intercrop.

Table 17. Soil water content at 25 cm depth at 11 and 30 WAP

	11 WAP		**30 WAP**	
	Sole crop	**Intercrop**	**Sole crop**	**Intercrop**
Control (unweeded sole coffee plot)	32.17	35.0	20.78	28.02
Mucuna	34.92	36.15	29.60	27.75
Silverleaf desmodium	32.28	36.48	22.1	24.71
Neontonia	32.1	36.4	22.28	26.91
Crotalaria	29.99	32.13	24.48	25.08
Fpr	0.187	0.062	<0.001	0.001
LSD 5 %	4.03	3.19	2.847	1.326
CV %	6.6	4.8	6.3	2.7

These results showed that the radiation transmitted through legume canopy and soil moisture content were the main factors influencing high weed numbers and dry matter accumulation. This also confirmed that there is a direct relationship between light reaching weeds and weed density and dry matter accumulation. Differences in weed and legumes growth habits may have contributed to variations in levels of weed suppression. Legume ground cover and litter mulch prevented weed growth and multiplication hence weed suppression. Legumes that developed high ground cover and produced a lot of litter were good weed suppressors.

4.6.4 Collective weed density and biomass accumulation

Weed biomass differed significantly among legume species and between sole and intercropped legumes overtime (Tables 13 and 14). Differences in weed numbers and biomass were both influenced by the amount of PAR transmitted through the legumes because this is the light energy they used for their growth (Table 15). Weed biomass in the uncropped and sole coffee (both unweeded) plots was significantly higher by 86 % and 84 % respectively, compared to that of weeds in plots with legumes implying that legume canopy intercepted light leaving less PAR available to weeds for DM accumulation. For example weed biomass in plots with sole Mwitemania bean, Dolichos, soyabean 17 and soya bean 4 was lower than their respective coffee-intercropped stand by 79 %, 60 %, and 48 % and 41 % respectively at 7 WAP (Table 13). Poor ground cover in coffee- Butter bean and canavalia intercrop permitted high radiation (58 % and 23 % PAR respectively) (Table 14 and 15) to reach weeds leading to high weed biomass accumulation. This contrasted with the low weed biomass was observed in Silver leaf desmodium and mucuna plots where the legumes transmitted less radiation (10 % and 5 % PAR respectively) (Table 14), leading to low weed biomass accumulation.

The average weed biomass in plots with non food legumes increased by 84 % and 67 % in sole and intercropped systems respectively between 7 and 24 WAP but varied significantly among legumes over the same time. Weed biomass in intercrop plots of crotalaria, silver leaf desmodium, mucuna and *canavalia* decreased by 96 %, 57 %, 56 % and 51 % respectively compared to unweeded coffee between 7 and 24 WAP (Table 14). Increase of weed biomass over time indicated that PAR transmitted through the legumes continued to be absorbed by weeds leading to dry matter accumulation by the weeds overtime.

Table 18. Weed density and biomass accumulated at 7 weeks after planting in food legume plots

Treatment	**Weed density (numbers /m^2)**				**Weed biomass (kg/ha)**			
	7 WAP		**24 WAP**		**7 WAP**		**24 WAP**	
	Sole crop	**Intercrop**	**Sole crop**	**Intercrop**	**Sole crop**	**Intercrop**	**Sole crop**	**Intercrop**
Control (weedy plot)	217.3	776	-	-	291.7	543.3	-	-
Food legumes								
Soyabean17	85.3	131	-	-	41.3	78.7	-	-
Soyabean4	53.3	139	-	-	49.3	82.7	-	-
Dolichos	82.7	183	-	-	40.0	100.0	-	-
Mwitemania bean	61.3	141	-	-	21.3	102.7	-	-
Fpr	<0.001	<0.001	-	-	<0.001	<0.001	-	-
LSD 5 %	53.49	135.2	-	-	48.61	62.67	-	-
% CV	30.2	28.8	-	-	32.9	21.4	-	-

NB: Weed density and biomass included all weed species. Weed data was not collected in food legume plots at 24 WAP.

Table 19. Weed density and biomass accumulated at 7 and 24 weeks after planting in sole and intercropped coffee legume systems

Treatment	**Weed density (numbers /m^2)**				**Weed biomass (kg/ha)**			
	7 WAP		**24 WAP**		**7 WAP**		**24 WAP**	
	Sole crop	**Intercrop**	**Sole crop**	**Intercrop**	**Sole crop**	**Intercrop**	**Sole crop**	**Intercrop**
Control (weedy plot)	217.3	776	183.0	370.7	291.7	543.3	1791	1635
Non food legumes								
Vicia benghalensis	73.3	167	0	30.7	129	105	0	59
Mucuna (grey)	121.3	184	10.7	42.7	372	127	428	262
Mucuna (mottled)	68.0	436	8.0	36.0	135	183	145	78
Canavalia	93.3	324	26.7	122.7	105	243	153	501
Green leaf desmodium	121.3	493	0	82.7	372	248	0	144
Silver leaf desmodium	65.3	511	0	4.7	155	257	0	120
Crotalaria	114.7	173	5.3	12	89	279	20	12
Neontinia	109.3	519	10.7	52	184	352	335	238
Fpr	0.12	0.002	<0.001	<0.001	0.163	0.26	<0.001	<0.001
LSD 5 %	71.93	256.5	21.11	29.73	212.0	223	559.3	314.4
% CV	38.0	37.2	44.9	31.3	68.8	49.6	101.2	53.6

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Crotalaria, mucuna, silver leaf desmodium ranked best in terms of ground cover development, total dry matter accumulation and weed suppression. Mucuna had the highest litter.

Legume PAR interception (both depended on legume growth characteristics) was the main factor contributing to variations in legume dry matter accumulation and weed suppression. Intercepted PAR (canopy cover) and total dry matter (TDM) accumulation were linearly and positively correlated and differed significantly among legumes and between the sole and intercrop systems. Intercropping significantly reduced the TDM accumulation, legume litter and seed yield.

Annual legumes (crotalaria, *Visia benghalensis* and soyabeans) were good in short term weed control during rainy season while , medium to long duration legumes (silver leaf desmodium and mucuna) were found suitable for prolonged weed control in coffee. Soyabeans were preferable for seed production compared to the investigated food legumes.

Soyabeans excelled in seed yield production because of its high resource use efficiency that led to a significant amount of its TMD was allocated for seed production. Dolichos was second best based on seed yield. Butter bean and mwitemania bean were poorest in seed yield.

Crotalaria, desmodium and vicia benghalensis had fast ground cover development and were therefore more effective in weed suppression early in the season. Mucuna and neontonia established slowly but had high and sustained ground cover later in the season, ensuring prolonged weed control under these legumes (Table 17).

Despite crotalarias' good traits (quick canopy development, high biomass accumulation and effective weed suppression) its height would make it unsuitable for intercropping with coffee unless it is slashed back to provide mulch under coffee or it is established when the coffee is not ready for picking. Although mucuna grew and accumulated dry matter slowly it was effective in weed suppression later in the season and had high litter that would provide nutrients for coffee. Mucuna however would require training by cutting off its tips to control trailing of coffee.

Silver leaf desmodium produced high biomass, effectively suppressed weeds but has the potential to compete for water with coffee. Proper management of silver leaf desmodium especially allowing it to grow when rainfall is high and cutting it back and using its high biomass as mulch in the dry season would enhance weed control and minimize water competition in the coffee intercrop. Silver leaf desmodium is also good forage for livestock.

Vicia benghalensis developed fast in ground cover development but was good in ground cover duration, dry matter accumulation and weed suppression. This implies that intercropping coffee with *Vicia* may reduce the need for conventional weed control from onset of rains up to the early weeks after planting, after which other weed methods should be applied. Neontonia persisted for long under coffee even during the dry seasons but poorly conserved soil moisture. Neontonia was not effective in weed control and soil moisture conservation. Further studies would be necessary to investigate the suitability of intercropping coffee with Neontonia.

In summary, the results of this study suggest that the choice of legume cover crops species for intercropping in coffee systems may be based on their ability to development a fast, high and sustained ground cover (life and /or dead mulch) for soil moisture conservation and weed suppression and also their ability to accumulate high dry matter for possible soil fertility improvement through provision of organic matter and seed yield for food legumes. The choice of such legumes however needs to be put into consideration due to the possibilities of above and below ground resource competition so as to minimize competition and optimize resource use in the coffee- legume intercrops. It is therefore very necessary to further examine the potential of using legume cover crops as a cost effective means of improving soil fertility and weed control hence increased land productivity among small holder coffee farms.

5.2 Recommendations

The following recommendations can be suggested from this study;

Legumes that accumulate high biomass and ground cover for weed control, with minimal competition for soil moisture and light, should be given priority when considering in coffee – legume cover crop intercrops (Table 17).

In this study the impact of the legumes on coffee growth and yields was not evaluated. A study to evaluate the impact of intercropped legumes on coffee is recommended.

Since intercropping can result in maximization of resource capture and use as well as resource competition, an evaluation on the most appropriate planting densities of the legume cover crops under established coffee was recommended. Intercropping coffee with legumes may also alter microclimate in the intercrop. This change may create an environment either conducive for buildup or even suppression of certain pests and diseases. The effects of such changes should be investigated and the cost effectiveness of using legume cover crops as integrated pest management strategy in coffee explored.

REFERENCES

Abayomi, Y.A., Fadayomi O., Babatola, J.O. and Tian G. 2001. Evaluation of Selected Legume Cover Crops for Biomass Production, Dry Season Survival and Soil Fertility Improvement in a Moist Savanna in Nigeria. *African Crop Science Journal*, 9: 615-627

Adeniyan, O.N. and Ayoola, O.T. 2006. Growth and Yield Performance of Some Improved Soybean Varieties as Influenced by Intercropping with Maize and Cassava in Contrasting Locations in South Nigeria. *African Journal of Biotechlogy,* 5:1886 – 1889.

Akhter, N., Rahman, M.M., Hasanuzzaman, M. and Nahar, K. 2009. Dry Matter Partitioning in Garden Pea (Pisum sativum L.) As Influenced by Different Light Levels. *Academic Journal of Plant Sciences* IDOSI Publications. 2: 233 – 236.

Akinyele, B.O. and Osekita O.S. 2006. Correlation and Path Coefficient Anlysis os Seed Yield Attributes in Okra (Abelmoschus esculentus (L.) Moench). *African Journal of Biotechnology. Academic Journals.* 5: 1330 – 1336.

Ansari, M. I. and Chen, S.C.G. 2011. Leaf Senescence - An Overview. *International Journal of Recent Trends in Science and Technology,* 1: 110 – 114.

Anthofer, J. and Kroschel, J. 2005. Above-ground biomass, nutrients, and persistence of an early and a late maturing Mucuna variety in the Forest–Savannah Transitional Zone of Ghana. *Agriculture, Ecosystems and Environment, Fallow management in the Tropics*. Elsevier Journals. 110: 59 -77

Awadhwal, N.K., Gowda, C.L.L., Chauhan, Y.S., Pande, S., Flower, D.L., Haware, M.P., Rego, T.J., Saxena, N.P. Shanower, T.G. and Johansen, C. 2001. Establishment of Legumes Following Rice - A Review. Natural Resource Management Program, Report No. 2. Patancheru 502 324, Andhar Pradesh, India: International Crops Research Institute for The Semi- Arid Tropics. pp 49

Azam-Ali S.N and Squire G.R. 2001. Principles of Tropical Agronomy, pp 107. CAB International, Wallingford, UK

Bayer Crop Science, 2009. Integrated Weed Management; Tools, Guidelines and Strategies for Integrated Weed Management. Second Edition, P 4. Available at www.bayercropscience.com

Bunch, R. and Buckles, D. 1998. Epilogue: Achieving Sustainability in The Use of Cover Crops, In: Buckles, D., Eteka A., Osiname O., Galiba M., Galino N. (eds) *Cover Crops in West Africa: Contributing to Sustainable Agriculture*. International Development Research Centre (IDRC). 15: 46-49.

Bot , A. and Benites J. 2005. The importance of soil organic matter. Key to drought-resistant soil and sustained food and production. Food and Agricultural Organization, Soils Bulletin 80

Bréda, N.J.J. 2008. Leaf Area Index. *Encyclopedia of Ecology.* Academic Press, pp 2148-2154. *www.sciencedirect.com.*

Carsky, J.R. and Ndikawa, R. 1998. Identification of Cover Crops for The Semi-arid Savanna Zone of West Africa, In: Buckles, D., Eteka A., Osiname O., Galiba M., Galino N. (eds) *Cover Crops in West Africa: Contributing to Sustainable Agriculture*. International Development Research Centre (IDRC). 13: 39-45

Chemining'wa, G.N., Muthomi, J.W., and Odudho, E.O. 2004. Effect of Rhizobia Innoculation and Ures Application on Nodulation and Dry Matter accumulation of Green Manure Legumes at Katumani and Kabete Sites, Kenya. *Legume Research Net Work Project Newsletter. Issue No. 11*

Clay, D.V., Lawson, H.M. and Greenfield, A.J. 1990. Weed control in Fruit and Other Perennial Crops, *In:* Hance, R.J. and Holly, K. (eds). *Weed Control Handbook: Principles.* Eighth Edition. Blackwell Scientific Publications, London, pp 367

Coffee Board of Kenya, 2001. Sessional Paper No 2 of 2001 on Liberalization and Restructuring of the Coffee Industry. Kixto Enterprises, Nairobi

Coffee Board of Kenya, 2003a. Coffee Industry Highlights. Kixto Enterprises, Nairobi

Coffee Board of Kenya, 2003b. Position Paper on the Status of the Kenyan Coffee Industry. Kixto Enterprises, Nairobi

Coffee Board of Kenya, 2003c. Coffee Industry Agenda after Reforms: Towards Sustainable Coffee Quality and Incomes. Kixto Enterprises, Nairobi

Coffee Board of Kenya, 2005. Critical Issues on Coffee Industry. Kixto Enterprises, Nairobi

Coffee Board of Kenya, 2010. Kenya Coffee; Coffee Growing Areas

Coffee Research Foundation, 2001. Coffee Establishment. Technical Circular No. 501.

Coffee Research Foundation, 2003. Weed Control in Coffee. Technical Circular No. 502.

Coffee Research Foundation, 2004. Coffee and Weather. Coffee Research Foundation Bulletin October- December 2004, 5: No.19.

Coffee Research Foundation, 2012a. History of Kenyan Coffee, Coffee Research Foundation, Kenya. *www.crf.co.ke*

Coffee Research Foundation, 2012b. Coffee Nutrition. Technical circular No. 203. Coffee Research Foundation, Kenya. *www.crf.co.ke*

Coffee Research Institute, 2006. Arabica and Robusta Coffee Plant. *www.coffeereserach.org*

Coste, R. and Cambrony, H. 1992. Coffee. The plant and the Product. Macmillan, London. pp 328

Damalas, C.A. 2008. Distribution, biology, and agricultural importance of *Galinsoga parviflora* (Asteraceae). *Weed Biology and Management.* Volume 8, Issue 3, pp 147–153, Wiley online library.

Ehlers, W and Goss M. 2003. Water Dynamics in Plant Production. CAB International, Wallingford, UK. pp. 95-123

Elmore, R.W., 2010. Crop Growth, Production and Management, Agronomy 212. Iowa State University. *www.agron.iastate.edu/courses*

Elzebroek, A.J.G and Wind K., 2008. Guide to Cultivated Plants. CAB International, Wallingford, UK. pp. 1

Ennin, S.A., Dapaa, H.K. and Abaidoo, R.C. 2004. Nitrogen Credits from Cowpea, Soyabean, Groundnuts and Mucuna to Maize in Rotation. *West Africa Journal of Applied Ecology*, 6: 65 - 74

Famaye, A.O. 2004. Effect of intercropping Coffee with Food Crops. *Journal of agricultural Research and Development.* 3. 27 -35. Faculty of Agriculture, University of Ilorin

Fang, H. and Liang, S. 2008. Leaf Area Index Models. *Encyclopedia of Ecology*. Academic Press. pp 2139 - 2148

Food and Agricultural Organization, 2000. Manual on Integrated Soil Management and Conservation Practices. FAO Land and Water Bulletin 8. Food and Agricultural Organization, Rome. *www.fao.org.*

Food and Agricultural Organization, 2010. FAOSTAT. Food and Agricultural Organization, Rome. *www.fao.org.*

Food and Agricultural Organization, 2012. FAOSTAT. Food and Agricultural Organization, Rome. *www.fao.org.*

Gachene , C.K.K. and Haru, R. 1997. Controlling Seasonal Soil Loss Using Purple Vetch (*Vicia benghalensis*). *African Crop Science Conference Proceedings*. 3: 369 -373

Gachene , C.K.K., Makau, M. and Haru, R. 2000. Soil Moisture Extraction by Different Legume Cover Crops. In: Mureithi, J.G., Mwendia, C.W., Muyekho, F.N., Onyango, M.A. and Maobe, S.N. (eds) *Participatory Technology Development by Smallholder Management and Legume Research Network Project. Special Publication of Soil Management and Legume Research Network Projects.* (LRNP/ KARI). pp. 133- 143

Gachene, C. K. K. and Makau, M. 2000. Screening Legume Cover Crops for Dry –land Season Survival in a Semi Arid Environment of Kenya, In: Mureithi, J.G., Mwendia, C.W., Muyekho, F.N., Onyango, M.A. and Maobe, S.N. (eds) *Participatory Technology Development by Smallholder Management and Legume Research Network Project. Special Publication of Soil Management and Legume Research Network Projects. (LRNP/ KARI).* pp. 77-86

Gachene, C. K. K. and Kimaru G. 2003. Soil Fertility and Land Productivity: A Guide For Extension Workers in The Eastern Africa Region. Technical handbook No 30. *Kenya Agricultural Research Institute*

Gachene, C. K. K. and Wortmann C.S. 2004. Green Manure/Cover Crop Technology in Eastern and Central Uganda: Development and Dissemination. In: Eilitta, M., Mureithi, J.G. and Derpsh, R. (eds). *Green Manure/Cover Crop Systems of Smallholder Farmers. Experiences from Tropical and Subtropical Regions. Kluwer Academic Publishers, Netherlands.* pp.*219-236*

Gilbert, R.A. 1998. Undersowing Green Manures for Soil Fertility Enhancement in the Maize-Based Cropping Systems of Malawi. In: Waddington, S.R., Murwira, H.K., Kumwenda, J.D.T., Hikwa, D. and Tagwira, F. (eds). *Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe. . Proceedings of the Soil Fertility Network Results and planning workshop, 7-11 July 1997, Mutare,* Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe. pp. 73-80

Giller, K.E. 2001. Nitrogen Fixation in the Tropical Cropping Systems, Second edition. CAB International, Wallingford, UK, pp 169-185, 222- 135

Gitari, J.N., E.A. Dyck and P. Maina. 2000. Legume Screening For Soil Fertility Improvement In The Coastal Lowlands Of Kenya, In: Mureithi J.G. *et al (*eds) *Participatory Technology Development by Smallholder Management and Legume Research Network Project (LRNP)*. KARI, Nairobi.

Gunaga R.P., Daddabasava and Vasudeva R., 2008. Influence of Seed Size on Germination and Seed Growth in *Mammea suriga*. Karnataka Journal of Agricultural Sciences, 24: 415-416 (2011)

Gupta, O.P., 1998. Modern Weed Management: With special reference to Agriculture in The Tropics and Sub-tropics. Agribotanica

Hakansson, S. 2003. Weeds and weed management on Arable Land: An Ecological Approach. CAB international, Wallingford, UK pp. 3-20

Hall, D.O., Scurlock, J.M.O., Bolhar-Nordenkampf, H.R., Leegood, R.C. and Long, S.P. 1993. Photosynthesis and Production in a Changing Environment. A Field and Laboratory Manual. Springer; First edition pp 59

Hall, D.O and Rao, K.K. 1994. Photosythesis. (Studies in Biology). Cambridge University Press. Fifth edition pp100

Hassan, R.M., Muriithi, F.M. and Kamau, G. 1998. Determinants of fertilizer use Gap Between Farmers' Maize yields and Potential Yields in Kenya. In: *Hassan, R.M. (Ed.). Maize Technology Development and Transfer: A GIS Application for Research Planning in Kenya.* CAB International, Wallingford, UK. pp 137-161

Hojjat, S.S. 2011. Effects of Seed Size on Germination and Seedling growth of Some Lentil Genotypes (*Lens culinaris* Medik). International journal of Agriculture and Crop Sciences. 3: 1-5

Howard, M Rowson and Helena Gomez MacPherson. 2000. Explanation of Plant Development, In Irrigated Wheat. Food and Agricultural Organization, 2000, Section 6

Hussein, M. A., Asmud, B. Are-Halvo, A., Trygve, B. and Hail, G. 2000. The Effect Of Plant Population And Water Conservation Methods On Grain Yield Of Early Maturing Maize Varieties in The Moisture –Stress Areas of Southern Ethiopia. *African Crop Science Journal*. 8: 159-170

International Center for Tropical Agriculture, 2003. Highlights, CIAT in Africa. Farmers' evaluations and innovations with legume cover crops. No.6. *In:* www.ciat.cgir.org

International Coffee Organization, 2011. The Story of Coffee. www.ico.org

Kabambe, V.H., R.P. Ganunga, and J.D.T. Kumwenda. 1998. *Mucuna* Management in an Intercrop with Maize in Southern Malawi: Preliminary Survey Results. In: *Annual report for the Cereals Commodity Group for 1997/98.* Ministry of Agriculture and Irrigation. Lilongwe, Malawi. pp. 187-189.

Kanton, R.A.L. and Dennett, M.D. 2004. Radiation Capture and Use as Affected by Morphologically Contrasting Maize/ Pea in Sole and Intercropping. West African Journal of Applied Ecology, Vol 13.

Karanja, A. M. and Wageningen, U. 2002. Liberalisation and Smallholder Agricultural Development: A Case Study of Coffee Farms in Central Kenya, pp 203. Wageningen, The Netherlands. Wageningen University

Karuku G. N. 2011. Effects of Crop Residue Management Practices on Soil Moisture Conservation and Validation of CROPWAT Model for Predicting Water Use Requirements for Tomato Crop in Kabete, Kenya. PhD. Thesis, University of Nairobi.

Kelton , J.A., Andrew J. Price, A.J., Santen, E., Balkcom, S.K., Arriaga, F.J. and Shaw, J.N. 2011. Weed seed bank density and composition in a tillage and landscape variability study. International Journal of the Faculty of Agriculture and Biology, Communications in Biometry and Crop Science. Warsaw University of Life Sciences, Poland. 6: 21–30

Khisa, W. P. 2000. Soil loss and Nutrient losses Due To Erosion in a Maize-Legume based Cropping System in Gatanga (Kenya). *Msc Thesis, Soil Science Dept. University of Nairobi.*

Kimemia, J.K. 1998. Studies on Green Manure Application and Intercropping in *Coffee arabica* Production. PhD Thesis, University of Nairobi.

Kimemia, J.K 2003. Principles and Practices of Intercropping in Coffee.

Kimenju, J.W., Kagundu, A.M., Nderitu,J.H., Omuolo, F.M. and Mutua, G.K. 2007. Use of Green Manure Plants in Cropping Systems to Suppress Root-Knot Nematodes. *African Crop Science Conference Proceedings*. *African Crop Science Society.* Vol. 8. pp. 1083-1085.

Kimidi, M., Gitahi F., Osore, P., Cheruiyot, D., Okumu, M., and Baraza, G. 2000. Effect of Maize and Beans in Matunda Farm, Transzoia district, North Rift Kenya. In Mureithi J.G. *et al (*eds) *Participatory Technology Development by Smallholders in Kenya. Special Publication of Soil Management and Legume Research Network Projects.* KARI, Nairobi. pp. 63-75.

Kroff, M.J. 1993a. Mechanisms of Competition for Light, In: Kroff, M.J. and Van Laar, H.H. (eds) *Modeling Crop- Weed Interactions*. CAB International, Wallingford, UK pp.33-62

Kroff, M. J. 1993b. Mechanisms of Competition for Water, In: Kroff M.J. and Van Laar H.H. (eds) *Modeling Crop- Weed Interactions*. CAB International, Wallingford, UK pp. 63-75

Lehmann,J., J.P. da Silva Jr., L. Trujillo and K. Uguen, 2000. Legume Cover Crops and Nutrient Cycling in Tropical Fruit Tree Production. *Acta Horticulturae* 531: 65-72

Lekasi, J.K., Tanner, J.C., Kimani, S.K. and Harris, P.J.C. 1998. Manure Management in the Kenya Highlands: Practices and Potential. High Potential Production System Portifolio for the Natural Resources Systems Program, Renewable Natural Resources Knowledge Strategy. Department for International Development. A Publication of the Henry Doubleday Research Association, UK. pp 35

Lingenfelter, D.D. and Hartwig, N.L. 2007. Introduction to Weeds and Herbicides. College of Agricultural Sciences, Agricultural Research and Extension, Pennsylvania State, U.S.A. www.cas.psu.edu. UC175.

Liu, Y. Wu, L., Baddeley, J.A. and Watson, C.A. 2011. Models of Biological Nitrogen Fixation of Legumes. In: Lichtfouse E. *et al (*eds) *Sustainable agriculture Vol 2*. Springer Science –EDP Science. pp 883-905

Maina J. M. 1997. The Effect of Intercropping on Weeds and Weed Management in Maize Growing in Kenya. PhD Thesis, University Of Reading, United Kingdom

Maina, J.M., Mburu, M.W.K., Mureithi, J.G., Gachene, C.K.K., Mburu, J.N. and Kimemia, J.K. 2006. Evaluation of Legumes as cover Crops for Soil and Weed

Management in Smallholder Coffee Cropping Systems in Central Kenya. In: *Legume Research Network Project Newsletter. Issue No. 12,* pp 4.

Maobe, S.N., Dyck, E. and Rondicho, A.R. 2000a. Legume Screening For Soil Fertility Improvement In A High Potential Area In South West Kenya. In: Mureithi J.G. *et al (*eds) *Participatory Technology Development by Smallholders in Kenya. Special Publication of Soil Management and Legume Research Network Projects.* KARI, Nairobi. pp.. 63-75.

Maobe, S.N., Mbugua, D.M., Mkwaro, Ondicho A.R. and Dyck, E. 2000b. Researching with Farmers on Green Manure Technology in a High Potential area in South West Kenya. In: Mureithi J.G. *et al (*eds) *Participatory Technology Development by Smallholders in Kenya. Special Publication of Soil Management and Legume Research Network Projects.* KARI, Nairobi. pp. 109-119

Matthias L., 2002 . Thermal time, Solar Radiation and Plant Development. pp 128. International Conference on AIDS and STIs in Africa (ICASA).

Mazaheri, D., Ahad, M and Meysam, O. 2006. Assessing the Land Equivalent Ratio (LER) of Two Corn [*Zea Mays* L.] Varieties Intercropping at Various Nitrogen Levels in Karaj, Iran. Journal of Central European Agriculture. 7: 359-364

Mburu, M.W.K., 1996. The Effects of Irrigation, Fertilizer Nitrogen and Planting Density on Bean (*Phaseolus vulgaris*) Yield under Different Weather Conditions. PhD Thesis, University Of Reading, United Kingdom

Mburu, M.W.K., Mureithi, J.G., and Gachene, C.K.K. 2003. Effects of Mucuna Planting Density and Time on Water and Light Use in a Maize- Legume Intercrop System

McIntyre, B.D., Gold, C.S., Kashaija, I.N. Ssali, H., Night, G., and Bwamiki, D.P. 2001. Effects of Legume Intercrops on Soil-borne Pests, Biomass, Nutrients and Soil Water in Banana. Biol Fertil Soils (2001) 34: pp 342- 348

McMaster, C.S., Ascough II, H.C., Edmunds, D.A., Andles, A.A., Wagner, L. and Fox, F. 2002. Multi-Crop Plant Growth Modeling for Agricultural Models and Decision Support System.

Memon, R.A., Bhatti, G.R and Khalid, S. 2003. Weed Diversity of Wheat Crop in Kharpur District, Sindh. *In: Pakistan Journal of Weed Science*. Res. 9: 99-103

Ministry of Agriculture and Livestock Development, 1997. Coffee Sector Strategic Study (Final Report- June 1997). Ministry of agriculture, Kenya.

Ministry of Agriculture and Ministry of Livestock and Fisheries Development. 2004. Strategy for Revitalizing Agriculture, 2004- 2014. Ministry of agriculture, Kenya.

Ministry of Agriculture, 2010. Economic review of agriculture. Ministry of agriculture, Kenya.

Ministry of Agriculture, 2011. The Agriculture outlook, January- June 2011. Ministry of agriculture, Kenya. pp 32.

Morales-Rosales, E.J. and Franc-Mora, O. 2009. Biomass, Yield and Land Equivalent Ratio of *Helionthus annus* L. in Sole Crop and Intercropped with *Phaseolus Vulgaris* L. in High Valleys of Mexico. Tropical and Subtropical Agro-ecosystems 10: 431-439

Mortimer, A.M. 1990. The Biology of Weeds, In: Hance, R.J. and Holly, K. (eds) *Weed Control Handbook: Principles.* Eighth edition. Blackwell Scientific Publications, London, pp1.

Muller-Samann, K.M. and Kotschi, J. 1997. Sustaining Growth: Soil Fertility Management in Tropical Smallholdings. In: *IFOAM Training Manual on Organic Agriculture in the Tropics*, pp 87. International Federation of Organic Agriculture Movements, Bonn, Germany

Mureithi, J.G., Gachene, C.K.K. and Wamuogo, J.W. 2003. Legume Cover crops Research in Kenya: Experiences of the Legume Research Network Project. Highlights of Phase 1 Research Activities (1994-2000). KARI Technical Note Series No. 12, February 2003.

Mureithi, L.P. 2008. Coffee in Kenya: Some Challenges for decent work. International Labour Office, Geneva. Working Paper No 260

Muthuri, C.W. 2004. Impact of Agro forestry on Crop Performance and Water Resources in Semi- arid Central Kenya. PhD Thesis, JomoKenyatta University of Agriculture and Technology

Nair, K.P. 2010. Coffee. The Agronomy and Economy of Important Crops of The Developing World. Elservier, London, pp181 -208. www.sciencedirect.com

Njarui, D.M.G., Bahnish, L.M., O'Hagan, B. and So, B. 2003. Emergence of Forage Legume Seedlings Influenced by Water Potential and Soil Strength. East African Agricultural and Forestry Journal. 2003. 69: 29-38

Njihia, C.M. 2000. Performance of Mixed Cropping In The Yala Swamp, Kenya, In: *Soil Science Society of East Africa (SSSEA), Proceedings of the 15th Annual General Meeting Sportsman's Arms Hotel, Nanyuki, Kenya. August 19th – 23rd, 1996.*

Njoroge, J.M. and Kimemia, J.K. 1990. A Comparison of Different Weed Control Methods in Kenya, Kenya Coffee 55: 863. Coffee Research Foundation, Kenya

Njoroge, J.M. 1992. Studies on Fertilization, Plant Density, Pruning, Replacement Methods of Established Coffee and Intercropping Food Crops With Coffee Arabica L. Cv. Ruiru. *PhD Thesis University Of Nairobi, Kenya*.

Nobel, P.S., Forseth, I.N. and Long S. P. 1995. Canopy structure and light interception In: Hall, *et al.* (eds). Photosynthesis and Production in a Changing Environment, A Field and Laboratory Manual

Nordby, D. 2004. Pocket Guide to Crop Development: Illustrated Growth Timelines for Corn, Sorghum, Soyabean and Wheat. University of Illinois, U.SA, C1389. pp 1-5.

Nyabundi, K.W. and Kimemia, J.K. 1998. Difficult Weed in Kenya Coffee. Kenya Coffee 63: 2747-2751

Nyangito, H.O., 2001. Policy and Legal Framework for the Coffee Subsector and the Impact of Liberalization in Kenya. *Kenya Institute of Public Policy Research and Analysis. KIPPRA Policy Paper No. 2, January 2001.*

Obuo, J.E., Adipala, E., and Osiru, D.S.O. 1997. Effect of Weeding Frequency on The Cost-Benefit Ratio and Yield Advantage of Cowpea / Sorghum Intercropping, In: Adipala, E., Tenywa, J.S., and Ogenga-Latigo, M.W. (eds) *African Crop Science Conference Proceedings, Pretoria, 13-17 January 1997.* 3: 865-869.

Odeleye, F.O., Togun, A.O. and Tayo, T.O. 2001. The Effect of Light Intensity on The Growth, Development and Yield of Soybean in South West Nigeria. *African Crop Science Journal*, Vol. 9 No.3, pp.577- 590.

Ong, C.K., Black, C.R., Marshal, F.M. and Corlett, J.E. 1996. Principles of Resource Capture and Utilization of Light and Water, In: Ong, C.K. and Huxley P. (eds) *Tree-Crop Interactions: A Physiological Approach.* CAB International, Wallingford, UK pp. 73-185.

Palaniappan, S.P. and Sivaraman, K. 2001. Cropping in the Tropics, Principles and Management, Second Edition, pp. 209. New Age International (p) Ltd publishers

Peden, D. 1998. Introduction, In Buckles, D., Eteka A., Osiname O., Galiba, M., Galino, N. (eds) *Cover Crops in West Africa: Contributing to Sustainable Agriculture*. Document1. International Development Research Centre (IDRC).

Peralta R.C., Candia, P.S. and Hinojosa, E.A. 2011. Characterization of The Weed Seed Bank in Zero and Conventional Tillage Central Chile. Chilean Journal of Agricultural Research. 71: 140-147

Rao, V.S. 2000. Principles of Weed Science. Oxford and IBH Publishing Co. pp 7, 411, 447.

Roberts, M. J., Long, S. P., Trezen, L.L. and Beadle, C.L. 1995. Measurements of Plant Biomass and Net Primary Production of Herbaceous Vegetation In: Hall, *et al.* (eds). Photosynthesis and Production in a Changing Environment, A Field and Laboratory Manual. pp. 465-477. Chapman and Hall

Robinson, T.H. 1990. The Methodology of Application, In: Hance, R.J. and Holly, K. (eds). *Weed Control Handbook: Principles.* 350pp. Eighth Edition, Blackwell Scientific Publications, London.

Saha, H.M., Njunie, M.N. and Tsanje, N.M. 2000. Legume Screening for Soil fertility Management in the Coastal Lowlands of Kenya, In: Mureithi J.G. *et al (*eds) *Participatory Technology Development by Smallholder Management and Legume Research Network Project (LRNP)*. KARI, Nairobi.

Sayed N.A. and Squire G.R. 2002. Principles of Tropical Agronomy. CAB International, Wallingford, UK pp 22

Simmonds, L.P., Mburu, M.W.K. and Pilbeam, C.J., 1999. Bean Growth and Yield Response to Nitrogen, Fretilizer and Planting Density Under Temperate and Tropical Conditions. *East African Agriculture and Forest Journal* (1999) 65 (1), 21 837

Snapp, S.S., Swinton, S.M., Labarata, R., Mutch D., Black, J.R., Leep, R., Nyiraneza, J., and O'Neil, K., 2005. Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. *Agronomy journal*, VOL. 97, January- February 2005. pp 322-332

Sparks, D.L. 2004. *Advances in Agronomy*, Vol. 82. Academic Press, Elsevier Inc, USA. pp 484

Squire, G.R., 1990. The Physiology of Tropical Crop Production. CAB International, Wallingford, UK, pp 236.

Stockle, C. and Kemanian, A. 2009. Crop Radiation Capture and Use Efficiency: A Frame Work for Crop Growth Analysis. In: Sandras *et al* (eds) *Crop Physiology: Applications for Genetic Improvement and Agronomy.* Academic Press. P 145

Stockle, C., Nelson, R. and Kemanian, A. 2012. Crop Simulation: Phenology. *In:* CropSyst Manual. Washington State University. pp 1-2

Sullivan, P. 2003a. Overview of Cover Crops and Green Manures. Fundamentals of Sustainable Agriculture. National Center for Appropriate Technology (NCAT), U.S. *At* www.attr.ncat.org. pp 1-16

Sullivan, P. 2003b. Intercropping Principles and Production Practices. Agronomy systems Guide. National Center for Appropriate Technology (NCAT), U.S. www.attra.ncat.org. pp 1-12

Tesfaye, K., Walker, S. and Tsubo, M. 2006. Radiation interception and radiation use efficiency of three grain legumes under water deficit conditions in a semi-arid environment. *European Journal of Agronomy*. Elsevier 25: 60 - 70

Traoré, H., Hess, D.E., Hoffmann, G., Son, G. A. and Salle, G. 2001. Use of hand-weeding and Herbicides to control *Striga Hermontheca* in Burkina Faso, In: *African Crop Science Journal*, 9: 645-653.

Udensi, U.E., Chikoye, D., and Ogunyemi, S. 2005. Effect of Level and Source of Shade on the Biomass of Speargrass in Nigeria. *African Crop Science Journal*, 13: 153-162

Unkovich, M., Baldock, J. and Forbes, M. 2010. Variability in Harvest Index of Grain Crops and Potential Significance for Carbon Accounting: Examples from Australian Agriculture. *Advances in Agronomy*. Elsevier, 105:173 -219

Van der Vossen, H.A.M. 2005. A Critical Analysis of The Agronomy and Economic Suitability of Organic Coffee Production. Cambridge University Press, United Kingdom. Experimental Agriculture, 41: 449-473

Vissoh, P., Manyong, V. M., Carsky, J.R., Osei- Bonsu, P. and Galiba, M. 1998. Experiences with Mucuna in West Africa. In Buckles, D., Eteka A., Osiname O., Galiba M., Galino N. (eds) *Cover Crops in West Africa: Contributing to Sustainable Agriculture*. Ottawa, Canada. International Development Research Centre (IDRC). Document 5: pp 1-32

Wallace, J.S., 1996. The Water Balance of Mixed Tree-Crop Systems. In: Tree-crop interactions: a physiological approach. Ong, C.K. and Huxley, P. (Eds). pp. 189-233. Centre for Agriculture and Biosciences International (CABI) and the

International Centre for Research in Agro-Forestry (ICRAF). Wallingford, UK and Nairobi

Waller, J.M., Bigger, M., and Hillocks R.J.2007. Coffee Pests, Diseases and Their Management. CAB International, Wallingford, UK pp 1- 17

Wandera, J. L., Munyekho, F. N., Mbugua, D. M. and Kiruiro, E. M. 2000. Effects Of Intercropping Herbaciouslegumes and Napier On Frage Dry Matter Production In The High rainfall Highlands Of Kenya, In: Mureithi J.G. *et al (*eds) *Participatory Technology Development by Smallholders in Kenya. Special Publication of Soil Management and Legume Research Network Projects.* Kenya Agricultural Research Institute, Nairobi, pp. 101-107.

Wanjekeche , E., Mureithi J.G., Gachene, C.K.K and Wakasa, V. 2004. Screening of promiscuous soybean varieties in the North Rift Valley of Kenya. *Legume Research Network Project Newsletter*. Issue No. 11. Kenya Agricultural Research Institute, Nairobi, pp 5

Wikipedia, 2012. Growing Degree Day. At: *http://en.wikipendia.org*

Wilson, K.C. 1999. Coffee, Cocoa and Tea. Centre for Agriculture and Biosciences International (CABI), Wallingford, UK pp 15-97

Winston, E., Laak, L.O., Marsh, T., Lempke, H., Aung, O., Nyunt, T. and Chapman, K. 2005. Arabica coffee manual for Myanmar. In. *www.fao.org*. Food and Agricultural Organization, Regional Office for Asia and the Pacific, Bangkok, Thailand.

Appendix 1. Analysis of variance table showing MSS of Legume emergence vigor (EV), time to emergence (TE), anthesis (TA), 50 % flowering (TF), 50 % podding (TP) and physiological maturity (PM) in sole and intercrop systems

		Mean sum of sums (MSS)					
		Days after planting (DAP)					
Source of variation	DF	EV	TE	TA	TF	TP	PM
Replication	2	0.8590	0.667	1.271	4.396	0.271	9.300
Production system (Sole / intercrop)	1	0.0513	10.782	93.521	44.083	27.00	313.633
Error 1	2	0.1667	0.974	0.021	4.646	2.312	3.233
Legume species	12	0.6346**	96.959**	8500.3**	9601.4**	10411.29**	4617.13**
Interaction (Production system x legume)	12	0.1346	22.088	38.33	16.08	5.571	5.080
Error 2	48	0.1795	2.459	1.336	1.402	1.768	5.892
Total	77						

** Significant at ≤ 1% NB: Analysis for time to anthesis, 50 % flowering and 50 % podding did not include desmodium, canavalia and neontonia. Only food legumes were included in analysis for time to physiological maturity.

Appendix 2. Analysis of variance table showing MSS of canopy height (cm) for mwitemania bean, soya bean 4 and soya bean 17 overtime in sole and intercrop systems

		Mean sum of sums (MSS)					
		Weeks after planting (WAP)					
Source of variation	DF	4	6	8	10	12	14
Replication	2	4.028	8.324	61.10	145.08	50.54	165.05
Production system (Sole / intercrop)	1	9.798	18.625	12.50	366.48	476.58	373.19
Error 1	2	1.270	4.319	38.64	86.49	38.29	55.89
Legume species	2	185.271*	355.522*	1786.58*	948.58*	503.33**	842.06**
Interaction (Production system x legume)	2	16.606	31.255	4.06	94.85	198.25	172.12
Error 2	8	3.067	4.534	43.85	55.28	58.83	97.84
Total	17						

* Significant at ≤ 5%   ** Significant at ≤ 1%

Appendix 3. Analysis of variance table showing MSS of % PAR interception for annual food legumes (butter bean, mwitemania bean, soya bean 4, soya bean 17 and dolichos) overtime in sole and intercrop systems

		Mean sum of sums (MSS) Weeks after planting (WAP)								
Source of variation	DF	4	6	8	10	12	14	16	18	24
Replication	2	42.91	137.75	626.5	442.39	158.41	88.25	55.42	255.5	93.2
Production system (Sole / intercrop)	1	2399.68	2703.89	2075.2	4199.18	1854.96	580.36	1434.69	1261.5	243
Error 1	2	1.66	16.45	192.8	108.19	139.53	237.65	29.07	108.9	262.8
Legume species	4	305.89 **	508.9 *	827.6 *	314.89 *	1679.42 **	4464.98 **	299.82 **	1877.4 **	2408.3 *
Interaction (Production system x legume)	4	49.46	54.61	350.3	295.37	230.76	254.38	212.98	234.9	1728
Error 2	16	40.59	79.37	143.9	96.17	82.24	42.55	25.95	142.5	141.2
Total	29									

* Significant at ≤ 5%, ** significant at ≤ 1% NB: Final % PAR interception for mwitemania and soya beans was done at 14 and 18 WAP respectively.

Appendix 4. Analysis of variance table showing MSS of % PAR interception for non food annual legumes (canavalia, crotalaria, *Vicia benghalensis*, mucuna (grey) and mucuna (mottled) overtime in sole and intercrop systems

		Mean sum of sums (MSS)								
		Weeks after planting (WAP)								
Source of variation	DF	4	6	8	10	12	14	16	18	24
Replication	2	3.95	11.83	1.8	242.32	174.03	5.42	4.341	14.53	27.23
Production system (Sole / intercrop)	1	1355.56	1243.44	809.4	2623.24	2616.51	937.55	1012.68	213.33	48.13
Error 1	2	16.29	12.57	71	358.18	391.09	495	4.54	6.93	34.23
Legume species	4	104.66*	81.01	462.5*	777.73**	290.34*	218.18**	162.71**	128.92**	875.62**
Interaction (Production system x legume)	4	64.10	57.73	43.5	231.26	103.89	113.57	92.04	80.75	362.55
Error 2	16	15.22	36.28	120	98.06	78.55	16.68	5.22	16.98	37.36
Total	29									

* Significant at ≤ 5%, ** significant at ≤ 1%

Appendix 5. Analysis of variance table showing MSS of % PAR interception for perennial legumes (silver leaf desmodium, green leaf desmodium and neontonia) overtime in sole and intercrop systems

		Mean sum of sums (MSS)								
		Weeks after planting (WAP)								
Source of variation	DF	4	6	8	10	12	14	16	18	24
Replication	2	0.00	0.19	15.4	262.9	285.2	226.67	138.18	74.39	366.89
Production system (Sole / intercrop)	1	954.84	3716.94	3381.4	7006.5	6155.7	3784.5	5509.35	1136.06	1012.5
Error 1	2	0.00	0.78	35.1	412.6	68.5	125.96	117.75	74.39	332.67
Legume species	2	157.12	537.07**	814.4*	1383.3*	1324.7*	660.04*	1126.74**	413.56**	83.39*
Interaction (Production system x legume)	2	72.82	134.23	132.5	130	253.3	439.53	1063.5	413.56	78.5
Error 2	8	0.00	0.29	102.9	228.9	135.9	42.56	29.62	9.39	24.28
Total	17									

* Significant at ≤ 5%, ** significant at ≤ 1%

Appendix 6. Analysis of variance table showing MSS of % PAR interception for all (13) legumes overtime in sole and intercropped systems

		Mean sum of sums (MSS)								
		Weeks after planting (WAP)								
Source of variation	DF	4	6	8	10	12	14	16	18	24
Replication	2	27.01	74.6	179	611.8	277.2	124.69	32.98	132.39	64.8
Production system (Sole / intercrop)	1	4631.86	6956.34	5450.9	12580.4	9239.7	4030	6323.81	2189.01	380.02
Error 1	2	9.98	14.59	193.4	635	353.8	190.43	9.34	61.06	352.87
Legume species	12	413.57 **	430.57 **	1354.6 **	857.7 **	922 **	1812 **	420.7 **	863.8 **	972.91 **
Interaction (Production system x legume)	12	56.51	118.90	221.4	301.3	269.4	301.94	433.36	206.98	473.20
Error 2	48	19.76	42.37	128.8	127.1	100.7	42.24	28.31	62.24	76.54
Total	77									

** Significant at ≤ 1%, NB: Final % PAR interception for mwitemania and soya beans was done at 14 and 18 WAP respectively.

Appendix 7. Analysis of variance table showing MSS of final biomass (FB), seasonal litter fall (SLF) and total dry matter (TDM) for food legumes (mwitemania bean, soya bean 4, soya bean 17 and dolichos) in sole and intercrop systems

		Mean sum of sums (MSS)		
Source of variation	DF	FB	SLF	TDM
Replication	2	1001651	886	1061509
Production system (Sole / intercrop)	1	50701820	210204	57441261
Error 1	2	940699	15265	1102328
Legume species	4	19190865**	955377**	20685623**
Interaction (Production system x legume)	4	14029223	87001	14994596
Error 2	16	1111522	6769	1171217
Total	29			

** Significant at ≤ 1%

Appendix 8. Analysis of variance table showing MSS of final biomass (FB), seasonal litter fall (SLF) and total dry matter (TDM) for non food legumes {(mucuna (mottled), mucuna (grey), neontinia, canavalia, silver leaf desmodium, vicia benghalensis, green leaf desmodium and crotalaria} in sole and intercrop systems

		Mean sum of sums (MSS)		
Source of variation	DF	FB	SLF	TDM
Replication	2	1774000	335	1772000
Production system (Sole / intercrop)	1	138400000	307008	151800000
Error 1	2	2516000	4609	2481000
Legume species	7	121100000**	435684**	111400000**
Interaction (Production system x legume)	7	10200000	75292	10010000
Error 2	28	3542000	7270	3603000
Total	47			

** Significant at ≤ 1%

Appendix 9. Analysis of variance table showing MSS of final biomass (FB), seasonal litter fall (SLF) and total dry matter (TDM) for all (13) legumes in sole and intercrop systems

		Mean sum of sums (MSS)		
Source of variation	DF	FB	SLF	TDM
Replication	2	2600000	719	2666000
Production system (Sole / intercrop)	1	186200000	516955	206400000
Error 1	2	3407000	1397	3542000
Legume species	12	96220000**	578106**	91740000**
Interaction (Production system x legume)	12	10870000	72942	11080000
Error 2	48	2446000	7288	2501000
Total	77			

** Significant at ≤ 1%

Appendix 10. Analysis of variance table showing MSS of total dry matter (TDM), seed yield (SY) and harvest index (HI) for all 13 legumes in sole and intercrop systems

		Mean sum of sums (MSS)		
Source of variation	DF	TDM	SY	HI
Replication	2	2666000	19033	0.01134
Production system (Sole / intercrop)	1	206359000	10173441	0.20121
Error 1	2	3542000	17904	0.00388
Legume species	12	91735000**	388360*	0.21797**
Interaction (Production system x legume)	12	11078000	151359	0.03520
Error 2	48	2501000	20194	0.01377
Total	48			

* Significant at ≤ 5%, ** Significant at ≤ 1%

Appendix 11. Analysis of variance table showing MSS of seed yield (SY) (kg/ha), Harvest Index (HI), 100 seeds mass (SM) (g), number of seeds per pod (SP), number of pods per plant (PP) for soya bean 4, soya bean 17 dolichos, butter bean and mwitemania beans in sole and intercrop systems

		Mean sum of sums (MSS)				
Source of variation	DF	SY	HI	SM	SP	PP
Replication	2	19033	0.01134	18.43	0.8043	0.60
Production system (Sole / intercrop)	1	10173441	0.20121	16.88	0.0963	483.21
Error 1	2	17904	0.00388	4.57	0.3503	33.26
Legume species	4	388360*	0.21797**	8296.32**	2.4003**	871.67*
Interaction (Production system x legume)	4	151359	0.03520	5.37	0.0797	6.20
Error 2	16	20194	0.01377	17.05	0.2003	22.44
Total	29					

* Significant at ≤ 5%, ** Significant at ≤ 1%

Appendix 12. Analysis of variance table showing MSS of weed occurrence (numbers per m^2) of the five (5) most common weed species *Oxalis latifolia* (OL), macdonald's eye (ME), black jack (BJ), nut grass (NG) and love grass (LG) under the best six legumes (crotalaria, mucuna, neontonia, silver leaf desmodium, *Vicia benghalensis* and soyabean) in weed suppression in sole and intercropped systems at 7 and 24 WAP

.Source of variation	DF	Mean sum of squares (MSS)									
		7 WAP					24 WAP				
		OL	ME	BJ	NG	LG	OL	ME	BJ	NG	LG
Replication	2	3371	4048	281.5	8963	56.38	64.45	22.57	23.24	1.238	0.00
Production system (Sole / intercrop)	1	8802	92966	39009	40735	137.5	298.7	2.88	0.60	4.61	0.00
Error 1	2	4875	3431	1349	10136	166.1	65.31	30.1	2.95	1.238	0.00
Legume species	6	527**	25440**	2182*	2025	147.3	222.1*	251.6**	342.5**	11.079**	0.00
Interaction (Production system x legume)	6	9935	17188	1871	2118	35.3	201.6	61.33	51.82	1.556	0.00
Error 2	24	3092	3202	560	1466	59.68	46.99	13.64	10.65	2.127	0.00
Total	41	80030.5	3110.48	440542	138978	190728	2674.4	40 (1)	2313.07	136.48	4228.48

* Significant at ≤ 5%, ** significant at ≤ 1%

Appendix 13. Analysis of variance table showing MSS of weed occurrence WO (numbers per m^2), weed biomass WB (kg/ha), for food legumes (mwitemania bean, soya bean 4, soya bean 17 and dolichos) at 7 WAP in sole and intercrop systems

	Mean sum of sums (MSS)		
Source of variation	DF	WO	WB
Replication	2	40128	14068.1
Production system (Sole / intercrop)	1	231682	56723.4
Error 1	2	42488	7164.1
Legume species	5	148014**	126880.8**
Interaction (Production system x legume)	5	57631	11520.3
Error 2	20	3192	950.2
Total	35		

** significant at ≤ 1%

Appendix 14. Analysis of variance table showing MSS of weed occurrence (WO) (numbers per m^2), weed biomass (WB) (kg/ha), for non food legumes {(mucuna (mottled), mucuna (grey), neontinia, canavalia, silver leaf desmodium, vicia benghalensis, green leaf desmodium and crotalaria} at 7 and 24 WAP in sole and intercrop systems

		Mean sum of sums (MSS)			
		7 WAP		24 WAP	
Source of variation	DF	WO	WB	WO	WB
Replication	2	97984	27455	60	22236
Production system (Sole / intercrop)	1	1125223	89679	10388.9	5190
Error 1	2	66199	41659	454.7	6598
Legume species	8	81680**	56025*	12145.1**	1718145**
Interaction (Production system x legume)	8	50792	21631	3539.8	41630
Error 2	32	11840	15799	221.9	68713
Total	53				

* Significant at ≤ 5%, ** significant at ≤ 1%

Appendix 15. Analysis of variance table showing MSS of weed occurrence (WO) (numbers per m^2), weed biomass (WB) (kg/ha), for both all 13 legumes in sole and intercrop systems

		Mean sum of sums (MSS)			
		7 WAP		24 WAP	
Source of variation	DF	WO	WB	WO	WB
Replication	2	127331	43024	60	22236
Production system (Sole / intercrop)	1	965786	98373	10388.9	5190
Error 1	2	91227	36848	454.7	6598
Legume species	13	79851**	71209**	12145.1**	1718145**
Interaction (Production system x legume)	13	47496	14129	3539.8	41630
Error 2	52	9285	10449	221.9	68713
Total	83				

** significant at ≤ 1%. Weed analysis at 24 WAP covered non food legumes only.

Appendix 16. Analysis of variance table showing MSS of soil water content (%) with soil depth under mucuna, silver leaf desmodium neontonia, and crotalaria in sole and intercropped systems at 11 and 30 WAP

		Mean sum of sums (MSS)							
		11 WAP				30 WAP			
		Soil depth (cm)				Soil depth (cm)			
Source of variation	DF	25	50	75	100	25	50	75	100
Replication	2	0.633	18.055	3.077	1.512	1.792	0.0555	2.395	1.0815
Production system (Sole / intercrop)	1	64.927	0.001	1.236	1.177	52.658	0.3480	0.375	1.9011
Error 1	2	8.036	15.131	0.822	0.414	0.163	0.7831	0.768	1.1205
Legume species	4	16.659*	9.820	1.907	0.620	24.709**	13.689**	21.984**	25.516**
Interaction (Production system x legume)	4	2.639	5.089	5.005	0.867	18.527	1.7713	4.380	1.5932
Error 2	16	3.733	7.195	2.245	1.263	1.391	0.5377	1.573	0.8966
Total	29	219.183	241.127	72.608	31.195	251.774	72.5066	136.961	129.087

* Significant at ≤ 5%, ** significant at ≤ 1%