

**CARBON SEQUESTRATION POTENTIAL OF COFFEE AGROFORESTRY
SYSTEM IN MUBENDE AND MITYANA DISTRICTS, CENTRAL UGANDA**

BY

BALITTA PAUL

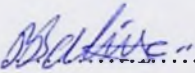
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FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN
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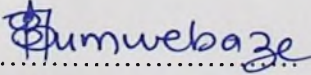
DECLARATION

I, BALITTA PAUL hereby declare that the information presented in this dissertation is my original work and has never been submitted to any university or institution of higher learning for an award. Where information is obtained from other works, the sources are duly acknowledged as indicated in the list of references. All photographs were taken in the field by the author of this dissertation.

Signed :.....(Candidate)

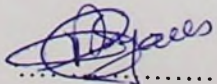
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DEDICATION

I dedicate this work to my family members for their sincere support and love rendered to me during the period the study was undertaken.

ACKNOWLEDGEMENT

Indeed, it's one of the memorable journeys in my life history amidst numerous challenges. Above all, I give glory and honour to the almighty God for his mercy, love and guidance during the entire period of study.

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LIST OF ACRONYMS

AGB	Aboveground Biomass
AGC	Aboveground Carbon
asl	Above sea level
BGB	Belowground Biomass
BGC	Belowground Carbon
C	Carbon
CER	Certified Emission Reductions
CO ₂ e	Carbon dioxide equivalent
CS	Carbon Stock
ES	Ecosystem Services
FAO	Food and Agriculture Organisation
GHGs	Greenhouse Gases
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
MDLG	Mityana/Mubende District Local Government
m	metre
m ² /ha	Square metre per hectare
Mg C	Megagramme Carbon
NEMA	National Environment Management Authority
No.	Number
%	Percentage
REDD+	Reducing Emissions from Deforestation and forest Degradation in developing countries, including the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks
Stems/ha	Stems per hectare
UBOS	Uganda Bureau of Statistics
UNFCCC	United Nations Framework Convention on Climate Change

ABSTRACT

Carbon sequestration potential of coffee agroforestry system was studied in Mubende and Mityana districts, Uganda between 2014 and 2015. Information on tree density, species density, species richness, species composition and amount of above ground carbon stocks was collected through square plots of 10m x 10m placed at alternative interval of 10m (How?). To collect information on socio-economic variables and management types, the study used cross-sectional design. Results indicate that, the average number of trees per hectare of each farm was 72 trees and the mean species richness was 10 species and mean basal area was 10.3 m²/ha, total aboveground tree biomass and diameter were positively correlated for all species and the total discounted NPV (US \$1,318/ha) of shade coffee agroforestry system from 1ha of land in Mubende/Mityana districts was profitable under low discount rate. Conclusively, shade coffee agroforestry has potential to sequester significant 1.0 to 18.0 Mg C ha⁻¹ amount (What amount?) of carbon in the aboveground woody biomass and if well managed, it can also provide substantial economic benefits to the farmer because it is profitable especially when fruit and timber tree species are included. Therefore, shade coffee farmers should be trained in best tree-coffee management practices for optimization of both biodiversity and tree-crop productivity of the farming system.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Globally, forests are under threat of deforestation through land conversion to agriculture (Murdiyoso *et al.*, 2010). Agriculture is one of the major drivers of land use change because it is practiced on 1.6 billion hectares out of 13.2 billion hectares of global land area (FAO, 2011). Many forests and grasslands have reduced in sizes as a result of substantial expansion of cropland to produce food to feed the increasing world population (FAO, 2013). Land use change has significant impact on the global carbon cycle through increased rates of greenhouse gas emissions to the atmosphere and the loss of above ground carbon accumulation and storage (Houghton, *et al.*, 2012). Increased concentration of GHGs in the atmosphere especially of carbon dioxide (CO₂) is responsible for causing global warming (Field, 2014). Between 2000–2010, the annual GHG emissions from global agricultural production were estimated at 5.0–5.8 GtCO₂eq/year (Tubiello *et al.*, 2013). In 2015, Uganda's total emissions were estimated at 77.381 Gt and the agriculture, forestry and other land use (AFOLU) sector was the largest source of emissions for the three gases (i.e., CO₂, CH₄ and N₂O), accounting for 86.4% of the total emissions (MWE, 2019).

Programmes such as the Reducing Emissions from Deforestation and Forest Degradation (REDD+) and Clean Development Mechanisms (CDM) have been established to address tropical forest cover and increase C-sequestration as mitigation strategies (IPCC, 2007). Both REDD+ and CDM schemes are intended to slow down the high rate of deforestation with a promise that trees/forests store carbon for a long time in their biomass and soils which can as well be capped as carbon stocks and traded as certified emission reductions (CERs) (McDermott, 2008).

With the increasing concern about the impacts of climate change, agriculture is being considered as one of the key sectors for adaptation and mitigation of climate change (Richards *et al.*, 2016). Currently, policy discussions on how to prioritize agriculture as a sector for adaptation and mitigation under the UNFCCC are ongoing (Dinesh *et al.*, 2016).

The removal of CO₂ from the atmosphere by trees and fixing it into their biomass and soils- a process described “carbon sequestration” plays a critical role in reducing vulnerability arising from the effect of climate change (van-Noordwijk *et al.*, 2011). The capacity of trees or forests to fix CO₂ is currently being used as a basis to assess the relevance of forestry-based options in mitigating climate change (Corbera and Schroeder, 2011; Rice, 2018). Landis (2017) indicated that, the design and management of agroforestry farms is key in delivering of ecosystem services such as carbon sequestration. A well-designed and managed agroforestry system can help sequester substantial amount of carbon stocks both aboveground and below ground (Nair & Nair, 2014). For instance, the potential for above ground carbon under agroforestry systems in Africa ranges from 1.0 to 18.0 Mg C ha⁻¹ (Nair & Nair, 2014). This confirms that, well designed and managed agroforestry system can help reduce the effects of climate change by sequestering significant amount of both above ground and below ground carbon (Ewers *et al.*, 2009).

Shade coffee agroforestry can as well be used as a climate adaptation strategy because it has high potential to sequester carbon (Hergoualc’h *et al.*, 2012); and as a source of income for farmers as they sell food, wood and other forest products like carbon sequestration services (Pandit *et al.*, 2014).

Planting trees in coffee agroforestry is more profitable and promising ecosystem-based adaptation practice in coffee production compared to the monoculture cultivation of coffee (Kiyangi and Gwali, 2012; Prasmatiwi *et al.*, 2010; Vignola *et al.*, 2015). A study conducted in Indonesia revealed that

shade coffee agroforestry system is capable of fixing up to 75 % of the above-ground carbon stored in the adjacent remnant forests (Kessler *et al.*, 2012). Such amount of carbon stored/fixed by shade coffee agroforestry system depends on tree species diversity (Cardinale *et al.*, 2011); the shade intensity; management inputs; tree species age and tree architecture; the specific wood density of the trees; climatic and edaphic conditions (Noponen *et al.*, 2013). Therefore, if agroforestry is to be used in carbon sequestration schemes such as the CDM and REDD+, more information is required about above and belowground carbon stocks, soil carbon, and areas under different agroforestry practices (Jose and Bardhan, 2019).

Much as debate is on-going about shade-coffee agroforestry systems to be considered for qualification under “Reduced Emissions from Deforestation and Forest Degradation” (REDD+) activities and other United Nations Framework Conventions on Climate Change mechanisms (Soto-Pinto *et al.*, 2010), inadequate information on economic feasibility of above and below ground carbon sequestration potentials of agroforestry in many regions of the world still remains a big challenge (Atallah, Gomez, and Jaramillo, 2018; Grace *et al.*, 2010).

Globally, shade coffee agroforestry practices by small scale rural farmers have been driven largely by the socio-economic and ecological benefits associated with the system (Haggar *et al.*, 2013). It is estimated that 95% of coffee in Africa is grown by farmers on farm holdings ranging from 1 to 5 hectares (ICRAF, 2011). In Uganda, coffee is one of the primary cash crops and it accounts for approximately 30% of the annual export revenue (UCDA 2012). Most of the coffee farmers (90%) are smallholders with land holding less than 2.5 ha and it is a major source of cash for the households (Jassogne, 2013; UCDA 2012). Approximately 272,000 ha of land is under coffee cultivation with 3.5 million households engaged in the industry (UCDA 2012). Robusta coffee

(*Coffea canephora*) which is mostly grown in central Uganda accounts for 70% of the total coffee export (Wintgens 2009; UCDA 2012).

1.2 Statement of the Problem

Coffee (both robusta and arabica) is an important traditional cash crop in central Uganda (Musoli et al., 2001). Coffee is mostly grown in mixed farms where it is intercropped with food crops such as bananas and beans which ensure households' food security. It is also grown under retained indigenous and planted trees which diversify products from the coffee agroforestry system, increase production and productivity (Isabirye et al., 2008). The coffee agroforestry systems also play an important role in carbon sequestration which is a commonly monetized ecosystem service due to its role in mitigating global climate change (Strassburg et al. 2016). Since coffee agroforestry is mostly practiced by family farms scattered across the region (Musoli et al., 2001), there is paucity of literature on the appropriate tree species, tree density, spacing and other management practices that would optimize carbon sequestration, improve productivity of coffee and increase resilience of the system to climate change. Little is known on the respective carbon stocks associated with different management systems (Tumwebaze and Byakagaba, 2016; Zaro *et al.*, 2019; Ehrenbergerová, 2015; Harmand *et al.*, 2007). Another challenge also lies in tying the environmental and social benefits inherent to these systems with economic feasibility (Schmitt-Harsh et al., 2012). Therefore, knowing the various tree species, the carbon stocks and understanding the potential economic impact of ecosystem services is essential to shed light on the trade-offs involved in ecosystem services monetization and its role in fostering the transition from conventional agriculture to agroforestry systems.

1.3 Objectives of the Study

The overall objective of the study was to assess tree and species density, carbon stocks and economic viability of different investment options of shade coffee agroforestry system among farmers in Mubende and Mityana districts.

1.3.1 The specific objectives of the study

1. To compare tree species density, mean basal area and species diversity, richness and evenness among small and medium shade coffee agroforestry farms in Mubende and Mityana districts.
2. To assess the above ground carbon stocks in shade coffee agroforestry system.
3. To compare the economic viability of different investment options of shade coffee agroforestry system.

1.4 Research hypotheses

This study tested the following hypothesis;

- a) There is no significant difference in tree species density, mean basal area and species richness among the small and medium shade coffee farms.
- b) There is no significant difference in the amount of aboveground organic carbon stocks of shade trees and coffee shrubs in small and medium shade coffee farms.
- c) There is no difference in economic viability of investment options of shade coffee agroforestry system.

1.5 Justification of the study

Globally, coffee agroforestry has contributed significantly to carbon sequestration services and yet it is currently not being recognized by the carbon market mechanisms for its potential. This study generated information on above ground carbon stocks potential of coffee agroforestry system in Uganda which can be used to inform developing of guidelines for optimum species pairing and farmer participation in carbon trade for improved household income and economic growth. This study is relevant in that, it will contribute to improving agricultural productivity for increased commercialisation and competitiveness of coffee production and agro-processing in Uganda in line with the third National Development Plan (2020/21 – 2024/25) which puts a lot of emphasis on sound ecological agricultural research to promote agricultural production, value addition for improved livelihoods of the people (GoU, 2020). More so, according to Uganda's Vision 2040, the country is one of the leading producers of coffee in the world and yet climate Change is posing serious threats to the agricultural sector. Therefore, if shade coffee agroforestry system can be incentivized by way of compensating them for the carbon sequestration roles being played by shade tree then more coffee areas can be devoted to shade coffee agroforestry system to reduce the impact of climate change while enhancing household incomes and national economic development. Hence, the information generated can help government respond in form of policies and interventions to mitigate climate change effect so as to increase the country's resilience to the impacts of climate change on coffee. The study enables this by providing information that can facilitate commoditization of carbon.

The research findings are very crucial for updating the National Adaptation Plan of Action (NAPA), Nationally Determined Contributions and other strategies deemed relevant for reducing the effect of climate change on agricultural productivity and ecosystem resilience as envisaged in the United

Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Paris agreement of the UNFCCC that Uganda has ratified (MWE, 2015). The findings provide more support to include coffee agroforestry in Reducing Emissions from Deforestation and Forest Degradation (REDD+) strategy as a component to enhance forest conservation and address deforestation drivers. The study provides a better understanding on the economic viability and carbon sequestration potential of shade coffee agroforestry systems. This will enable farmers to choose the most optimal systems that can meet the environmental and economic objectives (Ginoga *et al.*, 2005).

1.6 Scope of the Study

The study was conducted in Mubende and Mityana districts among the smallholder coffee farmers who deliver coffee to primary coffee co-operative societies. The districts are located in central Uganda and are prominent areas for coffee agroforestry. The study focused only on determination of aboveground carbon stocks of both coffee and shade trees. The number of shade trees and not the amount of shading was the subject matter of this research. I used the number of individuals of each tree species to determine the density and the basal area which is the cross-sectional area of a tree estimated at breast height (1.3 m), which is expressed in square metres. Species with the largest contribution to dominance value through the higher basal area can be considered as the most important species in the study vegetation. I used the tree diameter to determine the tree biomass and thereafter, tree biomass was converted into carbon stock stored by the tree species. The shadow price of coffee berries, timber, firewood and fruits were used to calculate the economic value of shade coffee agroforestry system.

CHAPTER TWO

LITERATURE REVIEW

2.1 Characterization of Shade Coffee Agroforestry

Agroforestry is the practice of deliberately integrating woody vegetation (trees and shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions (AGFORWARD, 2014). It is considered to be dynamic and ecologically beneficial because of interactions of different components on-farm (AGFORWARD, 2014). According to Gold and Garrett (2009), agroforestry practices are said to be characterized by four “I” words: intentional, intensive, integrated, and interactive but perhaps another one could be added: imprecise. FAO (2011) summarized agroforestry as practices combining foraging, crop production, husbandry and forestry in the same land unit, sequentially or simultaneously, to harness the benefits of ecological and economic interactions. Agroforestry systems are not a new kind of land management but only that it attracted much attention since the 70s in developing countries as a pathway to restore lost environmental quality, to decrease deforestation, to escape land scarcity and to satisfy a growing agricultural demand (Ribeiro and Guerra, 2008).

It estimated that over 1.2 billion people across the world practice some form of agroforestry, with approximately 560 million living in farm agroforestry landscapes, that is, those with more than 10% tree cover (Zomer *et al.* 2009). In sub-Saharan Africa, 15% of farms have tree cover of at least 30% which indicates a high potential in Africa for sequestering carbon and reducing other agriculture-related GHG emissions (Mbow *et al.*, 2014). Agroforestry improves household’s general standard of living via improvements in farm productivity, off-farm incomes, wealth and the environmental conditions of their farm (Mbow *et al.*, 2014). Trees on the farm are also physical assets which are

used for insurance and also increase land value (Chavan *et al.*, 2016). Incorporating tree biodiversity within agricultural systems has been proposed as a means of increasing agroecosystem resilience in the face of climate change while improving food security, soil quality and productivity (Galluzzi *et al.*, 2010). To be successful, it is essential that agroforestry systems be specifically designed and managed to suit the site so that the positive effects are optimized and the potentially negative effects kept to a minimum (Kapp and Manning, 2014).

Currently, there are two primary types of coffee i.e., Arabica (*Coffee arabica*) and Robusta (*Coffee canephora*) both with a long development history (Murthy and Madhava Naidu, 2012). The first semi-cultivation of Robusta was on the islands of Lake Victoria and in the north of Kagera, Tanzania (Waller, Bigger and Hillocks, 2007). Shade coffee agroforestry has been cited as an agroforestry ecosystem that mimic natural forest because of the multiple layers of potential habitat and complementary interactions amongst tree, crop and animal species, above and below ground (Jha *et al.*, 2014). In many parts of the world, shade trees are maintained to provide a shade level of around 40-50% although dealing with the pruning waste of the plants can also be a challenge (Travis and Adel, 2010). In 2007, the government of Puerto Rico, recommended shade growing of coffee to sun-grown coffee by farmers so as to provide habitat to biodiversity, conserve soil and water, and sustain the wellbeing of coffee farmers (USDA, 2016). Growing coffee under tree shade is among the prominent agronomic practices in traditional organic coffee growing systems since it can act as a biological soil and water conservation mechanism (Alemu, 2015). In Vietnam, farmers have attested to the benefits of including trees (fruits and timber) in coffee plantations i.e., it maintains stability in coffee production and thus provides longer term results in terms of higher economic benefit (VnSAT, 2018). *Cassia siamea* is used in coffee agroforestry as a nitrogen-fixing tree species that

can help to maintain soil fertility but mostly farmers use *C. siamea* as living pillars to support since pepper provide high economic benefit to the farmers (VnSAT, 2018).

Coffee agroforestry system has a comparable conservation value to natural forests (Bhagwat *et al.*, 2008; Klein *et al.*, 2008). For instance, shade trees offer multiple functions of the agroforestry system in conserving regional native tree species, provision of habitat for other species, as biological corridor between protected areas and alleviating resource-use pressure on conservation areas (Bhagwat *et al.*, 2008; Bukomeko *et al.*, 2019).

Traditionally, coffee growing in the tropics has been conducted under shade tree system in order to maintain ecosystem services like regulating, provisional services (Jose, 2009). In Kenya, there is evidence of declining tree species diversity on coffee farms (Carsan *et al.*, 2013; Pinard *et al.*, 2014), reflecting global trends which are anticipated to affect the ecosystem services they provide, including pollination, pest control, climate regulation and nutrient sequestration and cycling (Jha *et al.*, 2014). In Latin America, farmers deliberately plant or retain trees promoted by extension services (Valencia *et al.*, 2015). The decision to retain or plant the trees is based on the perceived socio-economic benefits (Carsan *et al.*, 2013). Studies that have explored local knowledge of coffee shade trees in specific locations in Latin America have revealed that farmers have detailed understanding of tree-crop interactions and forest succession but did not investigate how consistently this knowledge was held across sites (Cerdán *et al.*, 2012; Soto-Pinto *et al.*, 2007). Systematic studies of local knowledge about cocoa (Anglaaere *et al.*, 2011) and coffee (Cerdán *et al.*, 2012) have all revealed that farmers recognise tree attributes. These include attributes like rooting depth and spread, and crown density, which affect tree-crop interactions, as well as productive attributes like medicinal, timber and firewood values. These findings compare with research in Southern Colombia (Bosselman, 2009)

and Costa Rica (Cerdán *et al.*, 2012) where it was found that farmers weigh shading effects on coffee productivity and quality against the multiple products and services provided by shade trees.

In East Africa, coffee production will remain possible in some areas but sustaining or improving upon current levels of production will require adaptation (Bunn *et al.*, 2015). The most promising adaptation in coffee production is integration of trees within the coffee plantation (Vignola *et al.*, 2015).

In Uganda, coffee is grown mostly in pure stands without permanent shade except in very high altitudes where humidity/rainfall is not a limiting factor. However, due to relatively high amount of rainfall/humidity and short dry period in Central Uganda, coffee is mostly intercropped with banana or other shade trees (Zake *et al.*, 2015) although shade trees may adversely affect productivity due to competition for available soil moisture and mineral nutrients with the coffee. About 353,907 hectares were under coffee cultivation (UCDA, 2016), primarily cultivated by an estimated 1.7 million households and it is estimated that about 85% of coffee producers in Uganda have intercropped small farms ranging in size from well under half a hectare to 2 hectares. A study conducted by Tumwebaze and Byakagaba (2016) in Uganda found that coffee agroforestry system stores more soil organic carbon compared to coffee monoculture plantations and they recommended planting and maintenance of shade trees for carbon sequestration. However, overhead shade should not reduce more than 50% of total irradiances (SÖndahl *et al.*, 2005).

These recommendations on production techniques such as plant density are developed mainly based on FAO coffee guidelines that were developed outside Uganda (IITA, 2012). Therefore, delivery of ecosystem services by trees from coffee agroforestry depend on changes in tree diversity and it calls for planning and integration of desired tree species (Cardinale *et al.*, 2011; de Beenhouwer *et al.*,

2013). This calls for tree species selection for use in coffee agroforestry systems for enhanced coffee productivity, food security, wood production and income generation for the households. The merits and demerits of shade tree agroforestry are listed in figure 2.1.

Effects of shade trees on coffee

Positive

- Reducing the extremes in high (low altitudes) and low (high altitudes) air and soil temperatures.
- Breaking the force of wind and heavy rainfall.
- Controlling erosion on steep slopes.
- Suppressing weeds.
- Producing annually 5–15 t (dry weight) organic matter per hectare from litter and prunings.
- Recycling of nutrients otherwise not available to the coffee and reducing nutrient leaching.
- Preventing over-bearing and shoot dieback as a result of reduced light intensity.
- Providing additional revenue from the shade trees (timber, firewood and fruits) and support for secondary vine crops like black pepper and vanilla.
- Potentially reducing incidence of diseases (e.g. leaf rust) and pests (e.g. white stem borer).
- Improving cup quality, particularly in ecologically sub-optimal coffee zones (high temperatures).

Negative

- Progressively lower yields with increasing shade intensity, due to a reduction in flowering nodes, inflorescences per node and flowers per inflorescence.
- Competition for water between shade and coffee trees in seasonally dry regions.
- Damage of the coffee trees by falling branches from the shade trees and occasional tree felling.
- Additional labour costs for regularly pruning of over-head trees to avoid excessive shading.
- Potential increase of some diseases (e.g. South American leaf spot) and pests (e.g. coffee berry borer).

(Beer *et al.*, 1998; Guyot *et al.*, 1996; Muschler, 2001)

Figure 2. 1: Effects of shade trees on coffee

The shade tree density and composition are very vital for carbon sequestration (Kessler *et al.*, 2012). Hence reduction in shade tree density and tree richness (management intensity) has been found to reduce carbon storage capacity. Tree species richness has influence on the amount of AGC and species richness may be affected by tree sizes as a result of management practices (Chisholm *et al.*, 2013). Knowledge on the relationship between tree size, richness and composition on AGB in an ecosystem is very important and few studies have been conducted to determine these relationships (Sist, Mazzei, Blanc, and Rutishauser 2014; Strassburg *et al.*, 2010). This study was conducted to document information on the woody tree species being used in shade coffee agroforestry system and their relationships (tree size, density and composition) on AGB.

2.2 Tree species density and composition in shade coffee farms

Species density is the number of species in a given area while species composition is the relative abundance of different species (Billheimer, Guttorp, and Fagan, 2001). Tree abundance on farms is defined as the number of individuals per species found in specified farm and it is one of the measures of species composition in farms (Isango, 2007). In their study, Correia *et al.*, 2010; Lopez-Gomez *et al.*, 2008 found an average of density of 116 trees per ha in the coffee farms in central Veracruz, Mexico. This study revealed that considerable number of tree species are being managed and conserved in coffee farms. However, in Veracruz, Mexico, the species richness in coffee farms can reach up to 107 (Lopez-Gomez *et al.*, 2008). Similarly, ninety-four (94) mature tree species (DBH>10cm) were recorded in Geuinean coffee farms (Correia *et al.*, 2010).

A study by Lopez-Gomez *et al.* (2008) found similar result where they recorded 107 tree species in coffee farms against only 62 tree species in forests. A study conducted in Mt. Elgon Uganda, found that *Cordia africana*, *Cordia millenii* and *Albizia gummifera* were the dominant crown species with about 68% of the total tree species crown cover area in Mt. Elgon region. In another study conducted

by Devagiri et al. (2019) in coffee agroforests of Central Western Ghats region showed that coffee agroforests resembled natural forests in terms of species richness and diversity. A tree density of 287 ± 13.53 (stems ha⁻¹) was recorded in coffee agroforest landscape mosaics of Kodagu district, India (Nayak and Chavan, 2019). In eastern Uganda, a study conducted by Negawo and Beyene (2017) found coffee farms to have average of 116 individuals per hectare and species richness was 50 tree species and shrubs inclusive. The most abundant species among all shade tree species was *Cordia africana* (26 trees/ha), followed by *Markhamia lutea* (12 trees/ha); *Cordia millenii* (9 trees/ha); *Artocarpus heterophyllus* (6 trees/ha) and *Persea americana* (4 trees/ha). In a study conducted by Pinard et al. (2014), there were 100 tree species on-farms identified from tree inventory carried out on 62 coffee farms in Muranga County in Kenya (Pinard et al., 2014).

However, negative impacts of shade have also been reported on growth and yield, exacerbating pest and disease problems (Avelino et al. 2020; Haggard et al. 2011). Equally, such adverse effects have also been highlighted for other tree crops such as cocoa (Beer et al. 1998). However, shade effects on coffee depend on the tree species used and the physical features of the site (Avelino et al. 2020). Shade may reduce pest and disease damage through different physical and biological processes such as conservation or facilitation of the action of natural enemies, physical obstruction, stimulants and deterrents, resource dilution, disruption of the life cycle and allelopathy pointed out that multistrata coffee systems should be implemented in order to adapt the shade level with seasonal fluctuations, since humidity may play a key role in pest and disease regulation

2.3 Above ground carbon sequestration potential of agroforestry systems

Climate change is one of the most pressing challenges facing the international community today. Climate change has been attributed to increased emission of greenhouse gases (GHGs) especially from anthropogenic sources (IPCC, 2007). Among the GHGs, carbon dioxide gas (CO₂) concentration in the atmosphere is the cause of the increasing rise of the earth temperature. It is estimated that, about one-third of global emissions of greenhouse gases (GHGs) are as a result of agricultural production and land-use change (LUC) (IPCC, 2007). Concisely, forests play significant role in capturing and storing the CO₂ through the process of photosynthesis thus providing a more cost-efficient method to offset carbon emissions from anthropogenic sources (Couture and Reynaud, 2011). Carbon sequestration is the process of capturing CO₂ from the atmosphere and depositing it as carbon in a reservoir (UNFCCC, 2007). With terrestrial systems, carbon pools are composed of the aboveground plant biomass, durable forest products, root biomass, soil microorganisms, organic and inorganic carbons. In the context of agroforestry, Nair *et al.* (2009) defined carbon sequestration as “primarily the uptake of atmospheric CO₂ during photosynthesis and transfer of fixed carbon into vegetation, detritus, and soil pools for “secure” storage”. Aboveground carbon storage (C) is the incorporation of carbon into plant matter either in the harvested product, or in the parts remaining on site in a living form (Nair *et al.*, 2009). Carbon sequestered above ground is found specifically in plant stem, leaves, litter among others (figure 2.2). In the forestry sector, important steps to reduce emissions are increasing global forest area, increasing the C density of forested land (Nabuurs *et al.*, 2007).

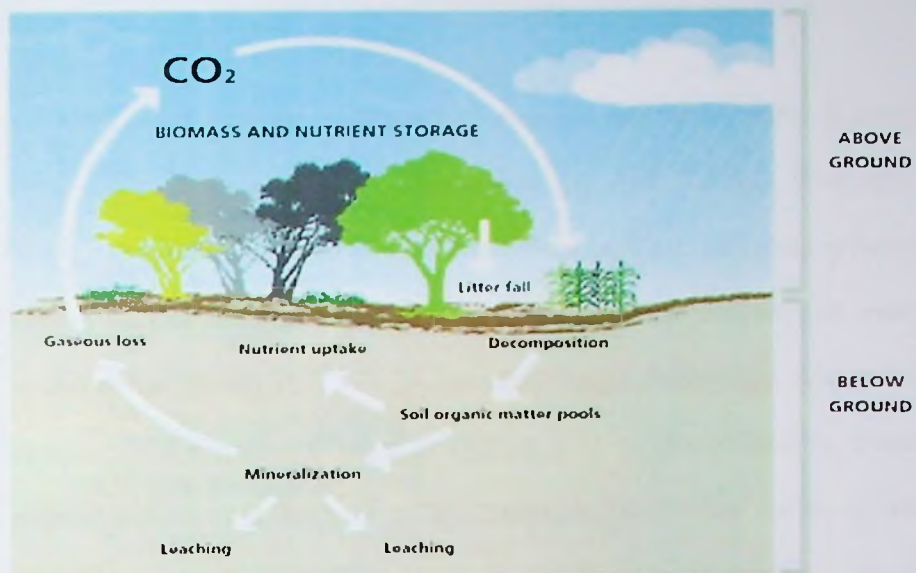


Figure 2. 2: Terrestrial Carbon Sequestration (FAO, 2007).

Tree planting within agricultural landscapes increases C density of the land, increases forested area, and provides scope for the displacement of more C intensive materials (Burgess *et al.*, 2010; IPCC, 2007). By practicing ‘agroforestry’ and combining trees with agricultural practices, it is possible to maintain the GHG mitigation benefits of forests whilst continuing to produce food on the same unit of land (Jose, 2009). The primary way in which an agroforestry system may sequester atmospheric carbon, is through the accumulation of carbon in the tissues of trees and its residues.

Globally, the area under agroforestry practices is estimated to be approximately 1023 million hectares (Nair *et al.*, 2009). Agroforestry systems have attracted more attention over its role in carbon sequestration (Albrecht and Kandji, 2003; Mendez *et al.*, 2012; Nair, Kumar, & Nair, 2009; Soto-Pinto *et al.*, 2010). Agroforestry systems have a carbon sequestration potential with a wide range of carbon stocks estimated between 12–228 t/ha (Nair *et al.* 2009). Most of these available reports on C sequestration in agroforestry system are estimates of C stocks: how much C is, or potentially could be accumulated and stored in above and belowground compartments of

agroforestry system under different conditions of ecology and management (Chavan *et al.*, 2016) compared three coffee AF systems, i.e. Coffee - *Inga spp.* and Coffee – *Pinus spp.* and Coffee – *Eucalyptus spp.* with sun-grown coffee in Villa Rica, Peru and found that, the system with *Pinus spp.* stored the highest amount of C stock above and belowground to include soil biomass both from shading trees and coffee shrubs (177.5 ± 14.1 ton/ha). These figures are substantially higher than sun-grown systems, with a typical C stock of (99.7 ± 17.2 ton/ha). Similarly, Harsh *et al.* (2012) reported a range of carbon stock from 74 to 259 ton/ha) in smallholder coffee agroforestry systems in the western highlands of Guatemala. In Vietnam, a difference of about 3.5 t/ha of total C stock between shaded coffee (*Cassia seameia* or *Leucaena sp*) and sun-grown systems in agroforestry was reported (Van *et al.*, 2018).

Therefore, if well managed then agroforestry could help in reducing leakage of carbon emission from adjacent forests by allowing for sustainable intensification and contributing to reducing deforestation and forest degradation (Minang *et al.*, 2014; Mbow *et al.*, 2014). Aboveground biomass has been estimated in SW Togo under *Coffea canephora*–*Albizia* agroforestry systems as 140 t/ha (Dossa *et al.*, 2008); 73 t/ha under coffee agro-forests in the Western highlands of Guatemala (Schmitt-Harsh *et al.*, 2012); 198 t/ha under coffee -*Erythrina poeppigiana*. In other studies, the carbon sequestration potential of agroforestry systems is reported to be in the range of 28.7–87.3 Mg/ha (Takimoto *et al.*, 2008). Above ground biomass estimates was 140 mg/ha in the coffee-Albizia tree system whereby the Albizia trees contributed 87% of total aboveground biomass in the shaded coffee system (Dossa *et al.*, 2008). Nair *et al.* (2009) estimated potential sequestration rates of 6.3 Mg/ha/year for C sequestration potential of agroforestry systems in Africa shaded coffee in Togo.

Hergoualc'h *et al.* (2012) compared the greenhouse gas balance in two coffee plantations: a monoculture and a culture shaded by *Inga densiflora*, and found that the aboveground carbon stocks in the coffee monoculture and the agroforestry system amounted to 9.8 ± 0.4 and 25.2 ± 0.6 Mg/ha, respectively. In a study from Costa Rica, carbon stock in coffee agroforestry farms was 93 ± 29 Mg/ha. Over all, Nair *et al.* (2009) estimated high variability in the estimates of carbon sequestration potential of agroforestry systems e.g., 0.29 Mg t/ha/yr (fodder bank in West African Sahel) to 15.21 Mg t/ha/yr (mixed species stands in Puerto Rico). It is important to note that, all their potential is dependent on edaphic conditions, tree species and age, climatic conditions and system structure (Nair *et al.*, 2009). High biomass production is always obtained within sites with high organic matter, nutrients, diverse microorganism populations and good soil structure (Nair, Kumar, & Nair, 2009). Due to importance of shade coffee-agroforestry system in sequestering carbon and the inadequate assessment of carbon sequestration potential of tree-based systems, more information on above ground biomass, carbon stocks and carbon sequestration of different tree species/mixed tree species is needed for better decision making (Kumar and Nair, 2011). Therefore, if agroforestry is to be used in C sequestration schemes such as the clean development mechanisms (CDM) and Reducing Emission from Deforestation and forest Degradation (REDD⁺) more information is required about above C stocks especially in East Africa.

2.4 Economic value of carbon sequestration in a shade coffee agroforestry system

Worldwide, coffee growing supports the livelihoods of approximately 4.3 million coffee producers (Rahn *et al.*, 2014) and yet coffee production has become extremely vulnerable to climate change (Baca *et al.*, 2014). To abate vulnerability of agricultural systems such as coffee production, adaptation strategies will play a decisive role. Agroforestry has been proposed as a promising ecosystem-based adaptation strategy to climate change for coffee farmers (Tscharncke *et al.*, 2011).

Agroforestry systems help in Reducing Emission from Deforestation and forest Degradation (REDD⁺) by reducing pressure for further forest conversion to agriculture (Noponen *et al.*, 2013). Agroforestry is increasingly being advocated as an agricultural land-use system which could play an important role not only in mitigating but also in adapting to climate change (Nair *et al.*, 2009; Soto-Pinto *et al.*, 2010). Researchers have explored the synergies between adaptation and mitigation effects of agroforestry and concluded that agroforestry systems have compelling potential for both adaptation and mitigation (Lasco *et al.*, 2014; Rahn *et al.*, 2014). The carbon offset potential of carbon sequestered through agroforestry to the industrialized countries could be an attractive economic opportunity for subsistence farmers in developing countries (Takimoto *et al.*, 2008). It has been suggested that shade coffee farming could be considered for qualification under REDD⁺ activities (Soto-Pinto *et al.*, 2010). Perennial agricultural production systems, especially those including trees such as coffee systems, have the unique potential to sequester and store relatively large amounts of C in aboveground biomass (Pinto *et al.*, 2010).

Nevertheless, with over 10 million hectares of tropical land devoted to coffee production (FAO, 2011), the potential exists for farmers to earn additional income for on-farm environmental services such as C-sequestration. Study conducted by Palmer and Silber (2009) revealed that, tree-based systems that combine carbon sequestration with cultivation of woody cash crops like coffee have a higher NPV than systems that focus on carbon sequestration alone. This is because they provide carbon payments in the early years of the project with the prospect of income from cash crop sales in later years thus allowing for a differentiation in benefits received by farmers over time (Luedeling *et al.*, 2011). A study on financial analysis on agroforestry system of coffee with Marrango tree (*Azadirachta excelsa* Jack.) in Bengkulu Province, Indonesia found that the NPV of the agroforestry of coffee and marrango tree was higher at discount rate of 8% giving benefit to cost ratio (BCR) of

2.28 and the internal rate of return of 22% (Premono and Lestari, 2018) and it was concluded that the agroforestry system of coffee with marrango tree was financially feasible to be developed. Various studies have also showed that planting trees in coffee agroforestry is more profitable compared to the monoculture cultivation of coffee (Kiyangi and Gwali, 2012; Miller & Schaal, 2006). A study of coffee agroforestry with different shading woody plants and multi-purpose tree species also provides advantages from the standpoint of the farmers (Prasmatiwi *et al.*, 2010). In coffee agroforestry systems which has timber trees, the net present value is high due to the right desired setting of plant density and plant canopy.

Carbon trade can be a very good opportunity for shade coffee agroforestry farmers to earn additional income in developing countries if their potential to sequester carbon is documented. Currently, shade coffee agroforestry farmers are not benefiting from the carbon trade both in the voluntary and certified emissions reductions due to insufficient information on carbon sequestration potential of shade coffee agroforestry although coffee growing as a commodity has been integrated in different farming systems for household food security in Uganda (Williams, 2008). Much as there is on-going debate about shade-coffee agroforestry systems to be considered for qualification under "Reduced Emissions from Deforestation and Forest Degradation" (REDD+) activities and other United Nations Framework Conventions on Climate Change mechanisms (Soto-Pinto *et al.*, 2010), economic feasibility of above and below ground carbon sequestration potentials of agroforestry has been carried out in a limited number of regions of the world (Grace *et al.*, 2010).

CHAPTER THREE

METHODS AND MATERIALS

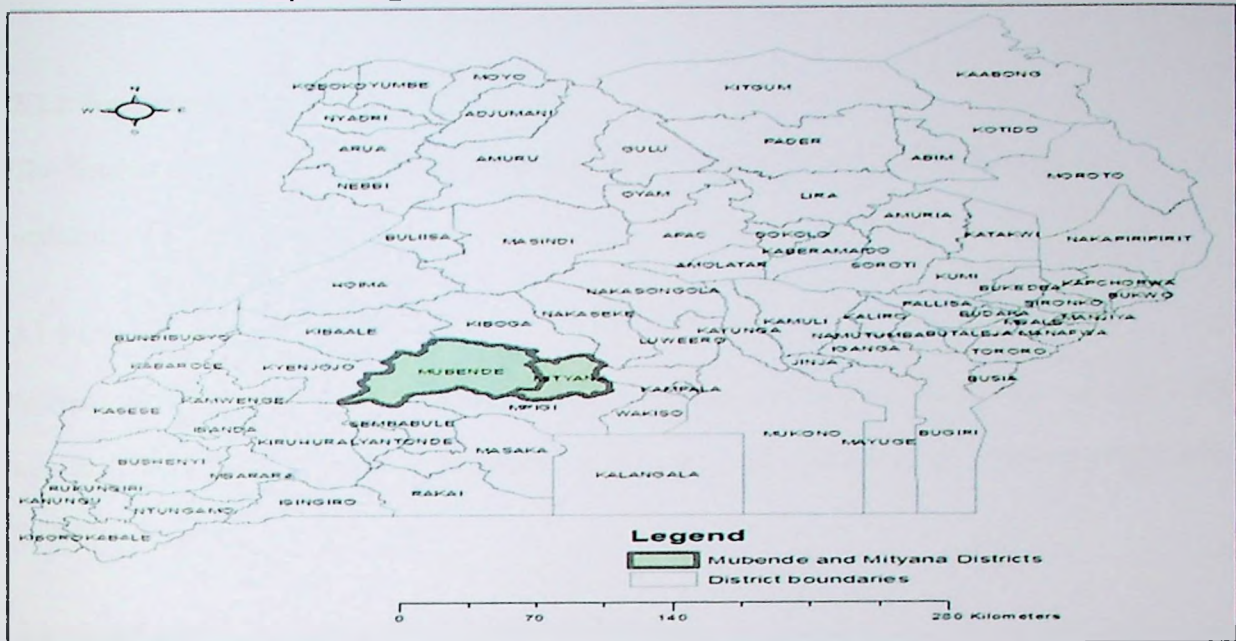
3.1 Area of study

The study was conducted in Mityana and Mubende districts, Central Uganda. The farmers in these two districts belonged to the same coffee co-operative society that used to train and support coffee growing and marketing in the area.

3.1.1 Location

Mubende and Mityana are located within central Uganda and they have been the traditional districts where coffee agroforestry was intensified. Mubende district lies 0°33'N and 31°22'E while Mityana lies 0°23'N and 32°02'E. The districts are bordered by Kiboga in the north, Kyegegwa in the south, Wakiso district in the East and Kibaale district in the West (figure 3.1). Being the traditional districts where coffee agroforestry was intensified is the major ground why the location was selected.

Map of Uganda Showing Districts of Study area



Study area Parishes

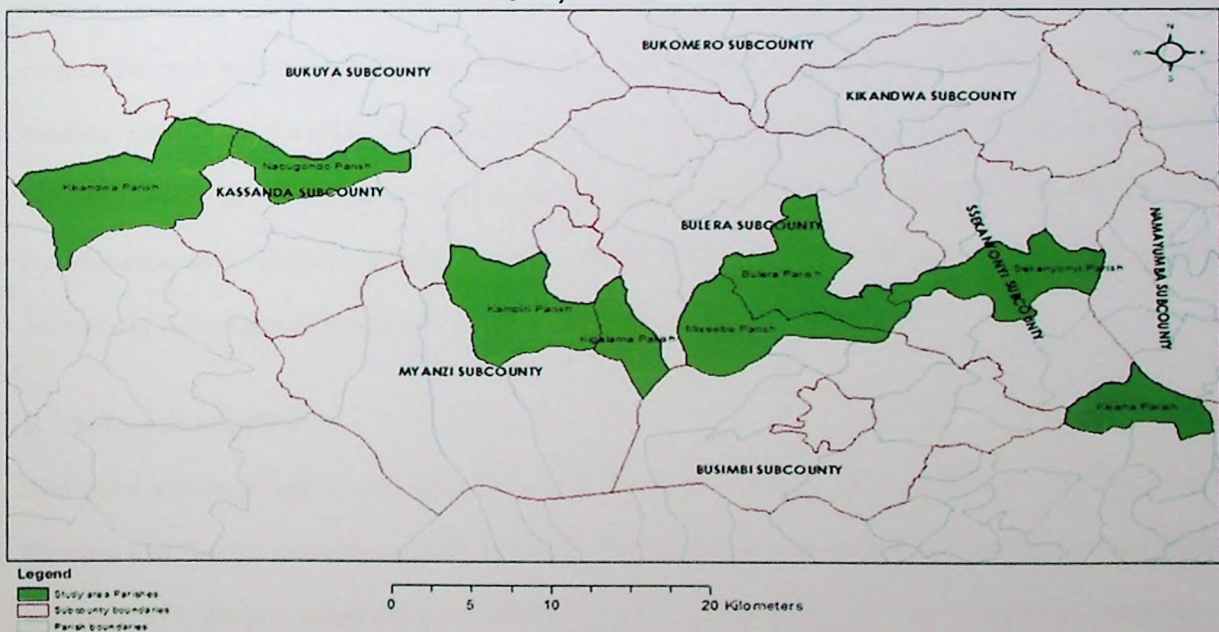


Figure 3. 1: the study area (both Mityana and Mubende combined)

3.1.2 Topography

The districts are about 1200- 1300 m above sea level. The land is gently flat with some few undulating hills.

3.1.3 Climate

Mityana and Mubende districts experience tropical climate with annual rainfall ranging from 1,000 mm to 1,500 mm. The rainfall is bi-annual i.e., March – May and August to December (NEMA, 2008).

3.1.4 Land tenure, use and socio-economic activities

The main economic activity in the two districts is subsistence farming and it provides employment for over 70 % of the population (Mubende District, 2004). The main food crops grown include banana, beans, cassava, groundnuts and sweet potatoes (www.agriculture.go.ug/). The main cash crop of the people in the two districts is Robusta coffee; the choice of this type coffee is based on the medium altitude of the area. The other cash crop grown in the districts is tea. Many households in the two districts also keep domestic animals like goat, sheep and cattle. The main water body shared by Mubende and Mityana districts is Lake Wamala. Fishing constitutes an important economic activity for communities living close to the lake (Mubende District, 2004).

3.1.5 Human population

The main ethnic group in the two districts is the Baganda and other tribes like the Banyankole, Batooro and Bakiga are also present. In 2014, the population of Mityana and Mubende was 328,964 and 684,337 people respectively (UBOS, 2014). Over 70% of the population depends on subsistence farming as a source of income (MDLG, 2007).

3.1.6 Description of study sites

The study was carried out in Bulera Sub County (Miseebe and Bulera parishes), Ssekanyonyi Sub County (Ssekanyonyi and Kisaaana parishes) in Mityana district Myanzi Sub County (Kampiri and Kigalama parishes) Kasanda Sub County (Kikandwa and Nabungo parishes) in Mubende district. These sites have been selected because they have many farmers growing coffee under shade tree management and were formally organized in farmer groups under the coffee co-operative union and therefore were suitable for the study objectives. The selection of these parishes was purposive reason bring Mityana and Mubende are the area where coffee was first introduced after breeding from Kawanda research centre.

3.2 Methods and Materials

3.2.1 Research design

In this research, both exploratory and descriptive designs were employed. Both on-farm tree inventory was done in the sample villages to assess tree species composition and species richness and face to face interview of the shade coffee farmers. Exploratory design was chosen to establish facts, to gather new data and to determine meaningful patterns in order to gain more insights into the existing shade coffee agroforestry system. According to Babbie, (2007) exploratory studies are most typically done for three purposes: (1) to satisfy the researcher's curiosity and desire for better understanding, (2) to test the feasibility of undertaking a more extensive study, and (3) to develop the methods to be employed in any subsequent study". Therefore, it was hoped that this study would meet all three of the stated criteria of exploratory research by satisfying the researcher's curiosity for a better understanding of the shade coffee agroforestry system in Uganda through conducting field tree inventory and using the results to estimate the contribution of shade coffee agroforestry in climate change mitigation through carbon sequestration. It was hoped that in the absence of a

substantial knowledge base this study would generate insights into this method by utilizing an exploratory research design. Babbie, (2008) states that exploratory studies are valuable and essential whenever a researcher wants to generate new insights into a topic of research. However, this study was not only exploratory in nature but it also built on the knowledge base regarding coffee agroforestry management system through providing detailed descriptions of the characteristics of the shade coffee agroforestry systems and the tree biodiversity therein. Descriptive design was thus applied to characterize the coffee agroforestry systems in the study sites. Descriptive design is applied in characterizing a phenomenon or situation (Bickman, Rog, and Hedrik, 1998).

3.2.2 Sample selection and procedure

Both random and purposive sampling techniques in a multistage process were used in this study. The primary sampling unit of the study was a coffee farm at a household. From the two districts, two sub-counties (Myanzi and Bulera sub-counties) were purposively selected based on eminence of coffee agroforestry farmers. Two parishes were purposively selected from each of the two sub-counties totaling to 4 parishes per district. A population sample of 80 farmers were selected randomly from the list of 103 registered shade coffee agroforestry farmers in the two districts. The sample size selection was conducted based on the formula described by Krejcie and Morgan (1970). Hence, the sample size from the registered coffee agroforestry farmers is $(\text{Sample Size}) = \frac{X^2 NP (1-P)}{d^2 (N-1) + X^2 P (1-P)}$

Where X^2 = table value of chi-Square @ degree of freedom = 1 for desired confidence interval 0.10 = 2.71; 0.05 = 3.84; 0.01 = 6.64 and 0.001 = 10.83

N = population size

P = population proportion (assumed to be 0.50)

d = Degree of accuracy (expressed as a proportion)

3.2.3 Data collection

3.2.3.1 Tree enumeration and carbon quantification

Square plots of 10 m x 10 m were placed alternately at 10 m interval on selected shade coffee farms/gardens to collect information on tree species density and composition. The 10 m x 10 m plots (QUAD) are sampling methods commonly used to quantify forest vegetation (Oosting, 1956). Similarly, Teshome (2020), used plot size of Size = 10m x 10m to measure all shade tree species with a diameters (dbh) of ≥ 2.5 cm and measured at breast height (dbh; measured at 1.3 m) and to monitor coffee plants in coffee-based agroforestry system in Ethiopia.

All trees (≥ 5 cm diameter and height ≥ 2 m) were measured, identified and recorded (Jiangshan *et al.*, 2009). Tree diameters and heights were measured using diameter tape and Suunto clinometer respectively. For the coffee shrubs, the diameter was measured at 15 cm from the ground (Segura *et al.*, 2006). Multi-stemmed coffee plants (1 to 7 stems per plant), each stem was measured by caliper and the equivalent diameter of the plant calculated as the square root of the sum of the diameters of all stems per plant following Snowdon *et al.* (2002) as below:

$$d_e = \sqrt{\sum_{i=1}^n d_i^2}$$

Where d_e is diameter equivalent (at breast or stump height), d is the diameter of the i^{th} stem at the breast or stump height.

3.3 Data analysis

Stem density for trees and coffee shrubs were calculated by extrapolating relative density of each tree species and coffee stems in the sample plots to a hectare. Basal area (BA) of trees was calculated according to the IPCC specification (IPCC, 2003).

$$BA (m^2) = \pi * DBH (cm)^2 / (4 * 10000)$$

Where π is the pie constant, DBH is the tree diameter at 1.3 m above the ground and 10,000 cm per square metre.

Basal area, the sum of cross-sectional area measured at breast height (1.3 m) of all trees in a stand, expressed as m^2/ha , has frequently been used as a surrogate for biomass and carbon in tropical moist and dry forests (Avery and Burkhart, 2002). The basal area is a good predictor for biomass and carbon since it integrates the effect of both the number and size of trees (Burrows, 2000).

Relative species density was determined using the formula described in (Zhang et al. 2008).

$$\text{Relative density} = \frac{\text{Number of individuals of one species}}{\text{Total number of all individuals counted}} \times 100$$

Species diversity was determined using Shannon–Wiener diversity index. The formula was selected because it accounts for both abundance and evenness of the species present.

Shannon–Wiener diversity index:

$$H' = - \sum_{i=1}^S p_i \ln(p_i)$$

where H' is the Shannon–Wiener diversity index, S is the total number of species in the community; p_i is the proportion of S made up of the i^{th} species (the ratio of individuals of species i divided by all individuals N of all species), and $\ln$ is natural logarithm (Lu, Yin and Tang, 2010).

Margalef index (Margalef, 1958) was used to compare species richness among the small and medium farms (Lu, Yin and Tang, 2010).

$$d = \frac{S - 1}{\ln N}$$

Where S is the number of species, and N is the total number of individuals in the sample and ln is natural logarithm. Margalef index is a suitable index in measuring species richness when using total number of species as in the current study although caution is needed when applying Margalef diversity index (Gamito, 2010).

A mixed-species function (allometric model) involving diameter (D), height (H), and density (ρ) developed by Chave *et al.* (2005) i.e., $AGB \text{ (kg)} = \exp(-2.187 + 0.916 \times \ln(\rho D^2 H))$ was used to estimate the above ground biomass (AGB) of shade tree species in shade coffee agroforestry system. Wood density values (tree bulk density) for each tree species were obtained from the global wood density database (Zanne *et al.*, 2009) and for tree species that couldn't be obtained, the default value for indigenous hard wood (IPCC, 2006) was applied. Above ground carbon stocks of trees was taken as 50 % of AGB as proposed by Chave *et al.* (2005). This generic allometric equation takes care of different tree species which do not have specific allometric equations because it incorporates important tree growth parameters i.e., tree diameter, height and wood density which are useful in determining growth and productivity of trees.

Total C pools under each were calculated by summation of only aboveground biomass. A local equation by Tumwebaze *et al.* (2016) was used to determine the AGB for coffee shrubs. Pearson correlation analyses were used to explore relationships between species richness and above-ground biomass. One-way ANOVA was used to compare percentages of tree density and composition among small scale and medium coffee farmers.

Economic value of carbon stocks in shade coffee-agroforestry system was estimated using economic model proposed by Wise and Cacho (2008). The present value of net revenues (NPV) obtained from an area of land, A, over a project-investment period of T years is:

$$\text{NPV}(T, R, x) = (A - R) \cdot \sum_{t=1}^T a_t(s_t, R, x_t) \cdot \delta^{-t} + \sum_{t=1}^T h_t(s_t, R, x_t) \cdot \delta^{-t} + A \cdot \sum_{t=1}^T \text{CER}_t(s_t, R, x_t) \cdot \delta^{-t} - R \cdot C_E \dots\dots\dots (1)$$

where S_t represents the state of the land in year t and may be defined by a set of land-quality indicators such as soil depth, soil-carbon content and soil fertility; x is a vector of management decisions such as the timing and frequency of pruning and harvesting, weeding and fertilising; k is the area of the farm planted to trees, which remains constant throughout the T years, and $A-k$ is the area planted to crops. The cost of establishing a hectare of trees is C_E and $\delta = (1 + r)$ for the discount rate r .

Taking NPV to per hectare of shade coffee farm mixture then the equation (1) can be re-written as;

$$\text{NPV}(T, x) = \sum_{t=1}^T a_t(s_t, x_t) \cdot \delta^{-t} + \sum_{t=1}^T h_t(s_t, x_t) \cdot \delta^{-t} + \sum_{t=1}^T \text{CER}_t(s_t, x_t) \cdot \delta^{-t} - C_E \dots\dots\dots (2)$$

The net revenues obtained from the area planted to a single agricultural crop are;

$$a_t = p^a \cdot y_t^a(s_t, x_t) - c_t^a \dots\dots\dots (3)$$

where y_t^a is crop yield, p^a is the price of the crop and c_t^a is the per hectare variable costs of preparing land, sowing seeds and harvesting.

The net revenues provided by trees are;

$$h_t = p^h \cdot y_t^h(s_t, x_t) - c_t^h \dots\dots\dots (4)$$

where y_t^h is the quantity of tree products harvested in year t , p^h is the price of tree product and c_t^h is the variable costs of maintenance and harvesting.

The third term in Eq. (1) is the net monetary benefit received from the sale of Certified Emission reductions (CERs), which depends on carbon accumulation in tree biomass;

$$CER_t = p^c \cdot (y_t^{bc}(s_t, x_t) - cm_t) \dots\dots\dots (5)$$

where y_t^{bc} is the eligible change in the stocks of the tree biomass carbon, p^c is the price of the CERs and cm_t is the annual carbon-monitoring per hectare.

Equation (1) represents a single rotation (20-year cycle) and does not include the opportunity cost of keeping trees in the ground.

The Internal Rate of Return (IRR) is the rate of interest at which the initial investment NPV is zero, and the Equal Annual Equivalent (EAE) is an annual payment that pays off the NPV of an asset during its lifetime. The EAE is calculated as follows:

EAE = Net Present Value (NPV) multiplied by annuity factor (A_f);

$$A_f = \left[\frac{r(1+r)^t}{(1+r)^t - 1} \right] \dots\dots\dots (6)$$

where, A_f = Annuity factor
 r = Discount rate,
 t = Time in years

CHAPTER FOUR

4.0 RESULTS

4.1 Characteristics of shade coffee agroforestry system in old Mubende district

Table 4.1 below revealed that there were several tree species studied. These were dominated by *Moraceae* family followed by *Lauraceae*, *Anacardiaceae*, *Rhamnaceae*, *Bignoniaceae*, *Euphorbiaceae*, *Burseraceae*, *Myrtaceae*, *Meliaceae*, *Papilionaceae*, *Rosaceae*, *Bignoniaceae* and *Proteaceae*.

The average farm size under shade-coffee agroforestry was 2.75 ha (1.2 – 6.3 ha), average farm age was 7.47 years (3-21 years) and farms are located at an average elevation of 1236 m a.s.l (1195 – 1333 m.a.s.l). The average coffee shrub density was 1,031 stems/ha (range 730 – 1,388 stems/ha). The tree species commonly incorporated by the farmers for provision of shade for the coffee shrubs include; exotic and indigenous species (see Table 4.1). However, the number of indigenous tree species were significantly higher ($P = 0.025$) than the exotic species based on one-way ANOVA. The exotic species were mostly fruit tree species and nitrogen fixing tree species (Table 4.1). Some of the coffee agroforestry farms had tree species such as *Entandrophragma spp*, *Prunus africana* and *Milicia excelsa* that are on the IUCN Red list of threatened tree species.

Table 4. 1: Tree species, family, type, use-values and conservation status in Mubende and Mityana

No.	Tree species	Family	Type
1	<i>Ficus natalensis</i> Hochst.	<i>Moraceae</i>	Indigenous
2	<i>Artocarpus heterophyllus</i> LAM.	<i>Moraceae</i>	Exotic
3	<i>Persea americana</i> Mill.	<i>Lauraceae</i>	Exotic
4	<i>Albizia chinensis</i> (Osbeck) Merr.	<i>Mimosaceae</i>	Exotic
5	<i>Mangifera indica</i> L.	<i>Anacardiaceae</i>	Exotic
6	<i>Maesopsis eminii</i> Engl.	<i>Rhamnaceae</i>	Indigenous
7	<i>Markhamia lutea</i> (Benth.) K.Schum.	<i>Bignoniaceae</i>	Indigenous
8	<i>Albizia coriaria</i> Welw. ex Oliv.	<i>Mimosaceae</i>	Indigenous
9	<i>Sapium ellipticum</i> (Hochst) Pax	<i>Euphorbiaceae</i>	Indigenous
10	<i>Ficus ovata</i> Hutch.	<i>Moraceae</i>	Indigenous
11	<i>Milicia excelsa</i> Welw C.C. Berg	<i>Moraceae</i>	Indigenous
12	<i>Ficus sycomorus</i> L.	<i>Moraceae</i>	Indigenous
13	<i>Psidium guajava</i> L.	<i>Myrtaceae</i>	Exotic
14	<i>Antiaris toxicaria</i> Lesch.	<i>Moraceae</i>	Indigenous
15	<i>Canarium schweinfurthii</i> Engl.	<i>Burseraceae</i>	Indigenous
16	<i>Entandrophragma spp</i> (Welw.) C.DC	<i>Meliaceae</i>	Indigenous
17	<i>Erythrina abyssinica</i> Lam. ex DC.	<i>Papilionaceae</i>	Exotic
18	<i>Ficus exasperate</i> Vahl	<i>Moraceae</i>	Indigenous
No.	Tree species	Family	Type
19	<i>Prunus africana</i> (Hook.f.) Kalkman	<i>Rosaceae</i>	Indigenous
20	<i>Ficus mucuso</i> Ficalho	<i>Moraceae</i>	Indigenous
21	<i>Spathodea campanulate</i> P. BEAUVAIS	<i>Bignoniaceae</i>	Indigenous
22	<i>Grevillea robusta</i> A. Cunn. ex R. Br.	<i>Proteaceae</i>	Exotic
23	<i>Ficus branchypoda</i> (Miq.) Miq.	<i>Moraceae</i>	Indigenous

4.2 Tree species density, mean basal area and species richness

The study established the tree species, family, type, use-values and conservation status in Mubende and Mityana by small and medium size farms. The findings revealed that medium size farms dominated with many trees in both districts compared to small farms.

Within the selected eighty (80) shade-coffee farms, 36 farms (45%) were classified as small (area $\leq$ 0.5 ha) and 44 farms (55%) were medium ($>$ 0.5 ha but less than 4.0 ha). In general, a total of 728 trees comprising of 23 tree species were recorded, identified and specimen of unidentified tree were delivered to Makerere Herbarium for identification (Table 4.1). The relative species density of each of the species in small and medium farms is shown in Table 4.2.

The table below shows the average number of trees, basal area and species richness per hectare of each farm category. Tree density and basal area significantly varied between small and medium coffee farms. Medium farms had relatively high tree density and basal area than small coffee farms. The result of ANOVA showed significant difference between relative density of trees among small and medium coffee agroforestry farmers ($df = 1$; $F = 95.9$ and $P = 0.0001$).

Table 4. 2: Tree diversity and abundance per district

Tree Species	Mityana district		Mubende district	
	Small farms	Medium farms	Small farms	Medium farms
<i>Ficus natalensis</i>	18	35	22	52
<i>Artocarpus heterophyllus</i>	12	23	19	38
<i>Persea americana</i>	17	94	25	35
<i>Albizia chainensis</i>	2	6	1	13
<i>Mangifera indica</i>	8	37	6	36
<i>Maesopsis eminii</i>	0	2	1	2
<i>Markhamia lutea</i>	7	26	5	39
<i>Albizia coriaria</i>	3	12	4	21
<i>Sapium ellipticum</i>	1	3	1	7
<i>Ficus ovata</i>	0	5	2	3
<i>Milicia excelsa</i>	2	4	1	10
<i>Ficus sycomorus</i>	0	0	1	1
<i>Psidium guajava</i>	1	3	2	4
<i>Antiaris toxicaria</i>	1	1	0	0
<i>Canarium schweinfurthii</i>	2	3	2	8
<i>Entandrophragma spp</i>	1	2	1	3
<i>Erythrina abyssinica</i>	0	2	1	2
<i>Ficus exasperate</i>	1	0	0	1
<i>Prunus africana</i>	1	2	1	6
<i>Ficus mucuso</i>	0	1	0	1
<i>Spathodea campanulate</i>	0	0	0	2
<i>Grevillea robusta</i>	1	2	0	2
<i>Ficus branchypoda</i>	0	0	0	2
TOTAL	78	263	95	292

4.3 Above ground carbon stocks of shade trees and coffee shrubs

Mean tree diameter and height were 20.6 cm (1.6 cm – 72.8 cm) and 13.5 m (2.5 m – 46.5 m); 25.9 cm (1.9 cm – 92.4 cm) and 15.5 m (3.5 m – 52.5 m) for small and medium size coffee farms respectively. The results of above ground carbon stocks for shade trees are provided in table 3. There

was a positive correlation between the total aboveground tree biomass and diameter for all species combined ($r = 0.73$, $p = 0.012$). Tree biomass and height were positively correlated for *Maesopsis eminii* ($r = 0.84$, $p = 0.001$), *Prunus africana* ($r = 0.76$, $p = 0.001$), *Albizia coriaria* ($r = 0.72$, $p = 0.002$), *Markhamia lutea* ($r = 0.68$, $p = 0.016$) and *Artocarpus heterophyllus* ($r = 0.63$, $p = 0.004$) while two species i.e. *Erythrina abyssinica* ($r = -0.23$, $p = 0.038$) and *Psidium guajava* ($r = -0.18$, $p = 0.001$) registered negative and low correlations.

Medium size coffee farms had significantly higher above ground tree carbon stock compared to small size coffee farms as revealed by one way ANOVA test ($P = 0.002$) but not for coffee shrub densities ($P = 0.089$).

The above ground carbon stocks for coffee bushes/ plants covered a wide range of dimensions. The average coffee stalk diameter and shoot height were 8.9 cm (1.2 cm – 31.4 cm); 3.7 m (0.8 m – 6.8 m) and 10.4 cm (1.4 cm – 38.9 cm); 2.9 m (0.5 m – 5.1 m) for small and medium coffee farms in respectively. The average total aboveground biomass of coffee bushes was 5.3 kg (0.9 kg – 19.7 kg) and 7.5 kg (0.7 kg – 22.9 kg) in small and medium size farms. Over 75 % of the coffee bushes/plants were pruned and over 78 % of the coffee plants had multiple shoots. The AGB coffee also presented a high positive correlation with diameter ($r = 0.78$, $p = 0.0001$; $r = 0.61$, $p = 0.0001$) and a relatively moderate correlation with total height ($r = 0.57$; $P = 0.001$; 0.42 , $p = 0.001$). The AGB was estimated based on coffee Robusta regression equation ($\text{Biomass Total} = - 2.38 + 0.417 \text{ Shoot Diameter} + 0.742 \text{ Diameter STALK}$) with best fit for coefficient of adjusted determination ($R^2 = 68.2\%$) developed by Tumwebaze *et al* (2018).

The study established Tree density, basal area and species richness in small and medium size shade coffee farms in in Mubende and Mityana districts by small and medium size farms. The findings revealed that medium size and small farms had significant values in density, basal area, Margalef's index of species richness and Shannon-Wiener diversity index

Table 4. 3: Tree density, basal area and species richness in small and medium size shade coffee farms in in Mubende and Mityana districts.

<i>Parameter</i>	<i>Farm category</i>		
	<i>Small coffee farms</i>	<i>Medium coffee farms</i>	<i>P- Value</i>
Tree density (No. of trees/ha)	38 (16 – 73)	72 (34 – 118)	0.0036
Basal area (m ² /ha)	2.4 (0.72 – 6.9)	8.3 (1.8 – 11.6)	0.004
Shannon–Wiener diversity index	2.34 (± 0.82)	2.19 (± 0.16)	0.136
Pielou's species evenness index (EH)	0.75 (± 0.69)	0.69 (± 0.40)	0.825
Margalef's index of species richness (M):	0.68	0.37	0.037

Parenthesis () represent the range and (± standard error)

In the study, the researcher collected data about ground biomass, carbon stocks and amount of carbon dioxide (CO₂) equivalent sequestered by shade coffee agroforestry system in small and medium size coffee farms that were then used to explain the findings. These are presented below

The study established above ground biomass, carbon stocks and amount of carbon dioxide (CO₂) equivalent sequestered by shade coffee agroforestry system in small and medium size coffee farms. The findings are presented in the table 4.4 below;

Table 4. 4: Above ground biomass, carbon stocks and amount of carbon dioxide (CO₂) equivalent sequestered by shade coffee agroforestry system in small and medium size coffee farms

<i>Farm category</i>	<i>Plant category</i>	<i>Total above tree biomass (t/ha)</i>	<i>Total above carbon stocks (t C/ha)</i>	<i>CO₂ equivalent (t/ha)</i>
Small farm	Shade trees	46.74 ± 3.26	23.37 ± 2.82	85.69 ± 4.92
	Coffee bushes	8.24 ± 0.17	4.12 ± 0.23	15.11 ± 0.68
Medium	Shade trees	65.31 ± 4.23	32.65 ± 2.41	119.72 ± 5.64
	Coffee bushes	6.95 ± 0.25	3.48 ± 0.44	12.76 ± 0.35

± *Confidence interval*

Shade coffee agroforestry in Uganda is not dominated by single or double storey-canopy tree species as the case in other countries (Figure 1).



Figure 4. 1: Shade coffee agroforestry in the study sites

4.4 The Economic potential of different investment options of shade coffee agroforestry systems

The research established the Economic potential of different investment options of shade coffee agroforestry systems. It was indicated that cost of coffee rehabilitation at 10 years and after every 6 years led followed by cost of coffee establishment in 1 year .

Table 4. 5: Base-case parameters, values for economic modeling of NPV of unshaded coffee only using data for financial 2019/2020 with prices from different sources.

<i>Production Category</i>	<i>Description</i>	<i>Value</i>	<i>Units</i>	<i>Source</i>
a) Coffee	Yield of coffee (dried)	1,000	kg/ha	UCDA, 2019
	Cost of coffee establishment in 1 year	2,840,000	UGX/ha	UCDA ,2019
	Cost of coffee establishment (Manure, Fertigation trenches, Mulching and Tools) in 2-5 years	670,000	UGX/ha	UCDA ,2019
	Cost of coffee rehabilitation at 10 years and after every 6 years	3,700,000	UGX/ha	UCDA, 2019
	Annual maintenance costs (Weeding, pruning, fertilizer)	720,000	UGX/ha	UCDA, 2019
	Fertilizer inputs from 3 rd year onwards	480,000	UGX/ha	UCDA, 2019
	Annual Pesticides application	200,000	UGX/ha	UCDA, 2019
	Coffee harvest labour cost	1,200,000	UGX/ha	Farmer records
	Price of coffee	5,000	UGX/kg	UCDA, 2019
	Discount rate	10, 15, 20 & 25	%	Wise and Cacho, 2008

NB: (1 USS = Average UGX 3,700 in 2019)

The research established the base-case parameters, values for economic modeling of NPV of shade coffee agroforestry system including sales of firewood/timber only using data for financial 2019/2020 with prices from different sources. Tree establishment and maintenance costs was the cost followed by Cost of coffee rehabilitation at 10 years and after every 6 years, Cost of coffee establishment in 1 year accordingly.

Table 4. 6: Base-case parameters, values for economic modeling of NPV of shade coffee agroforestry system including sales of firewood/timber only using data for financial 2019/2020 with prices from different sources

<i>Production Category</i>	<i>Description</i>	<i>Value</i>	<i>Units</i>	<i>Source</i>
a) Coffee	Yield of coffee (dried)	1,000	kg/ha	UCDA, 2019
	Cost of coffee establishment in 1 year	2,840,000	UGX/ha	UCDA, 2019
	Cost of coffee establishment (Manure, Fertigation trenches, Mulching and Tools) in 2-5 years	670,000	UGX/ha	UCDA, 2019
	Cost of coffee rehabilitation at 10 years and after every 6 years	3,700,000	UGX/ha	UCDA, 2019
	Annual maintenance costs (Weeding, pruning, fertilizer)	720,000	UGX/ha	UCDA, 2019
	Fertilizer inputs from 3 rd year onwards	480,000	UGX/ha	UCDA, 2019
	Annual Pesticides application	200,000	UGX/ha	UCDA, 2019
	Coffee harvest labour cost	1,200,000	UGX/ha	Farmer records
	Price of coffee	4,500	UGX/kg	UCDA, 2019
	Tree establishment and maintenance costs	3,800,000	UGX/ha	NFA, 2019
b) Firewood/	Tree harvest labour cost	1,500	UGX/m ³	Farmer records
	Firewood price	9,000	UGX/m ³	NFA, 2019
	Discount rate	10, 15, 20 & 25	%	Wise and Cacho, 2008

NB: (1 US\$ = Average UGX 3,700 in 2019)

The study established base-case parameters, values for economic modeling of NPV of coffee agroforestry system including sales of fruits only using data for financial 2019/2020 with prices from different sources. This is because the internal rate of return (IRR) measures investment performance and can cope with more complicated situations

Table 4. 7: Base-case parameters, values for economic modeling of NPV of coffee agroforestry system including sales of fruits only using data for financial 2019/2020 with prices from different sources

<i>Production Category</i>	<i>Description</i>	<i>Value</i>	<i>Units</i>	<i>Source</i>
a) Coffee	Yield of coffee (dried)	1,000	kg/ha	UCDA, 2019
	Cost of coffee establishment in 1 year	2,840,000	UGX/ha	UCDA, 2019
	Cost of coffee establishment (Manure, Fertigation trenches, Mulching and Tools) in 2-5 years	670,000	UGX/ha	UCDA, 2019
	Cost of coffee rehabilitation at 10 years and after every 6 years	3,700,000	UGX/ha	UCDA, 2019
	Annual maintenance costs (Weeding, pruning, fertilizer)	720,000	UGX/ha	UCDA, 2019
	Fertilizer inputs from 3 rd year onwards	480,000	UGX/ha	UCDA, 2019
	Annual Pesticides application	200,000	UGX/ha	UCDA, 2019
	Coffee harvest labour cost	1,200,000	UGX/ha	Farmer records
	Price of coffee	4,500	UGX/kg	UCDA, 2019
	Estimated quantity of avocado fruits sold	1,650	kg/ha	Farmer records
b) Fruits	Annual costs of managing fruit production	25,000	UGX/ha	Farmer records
	Price of 1 kg of avocado	1,000	UGX/kg	Farmer records
	Discount rate	10, 15, 20 & 25	%	Wise and Cacho, 2008

NB: (1 USS = Average UGX 3,700 in 2019)

The results of the total discounted NPV of unshaded coffee plantation and three shade coffee agroforestry systems from 1 ha of land in Mubende/Mityana districts indicate that, shaded coffee

with fruit trees and timber trees are more profitable compared to unshaded coffee especially with low discount rates (Table 4.8). Much as the internal rate of return (IRR) is high for unshaded coffee farming, Equal annual equivalent (EAE) was higher for shade coffee with fruits, followed by timber and lower for shaded coffee with firewood (Table 4.8). Under the current set of assumptions, the internal rate of return (IRR) for shaded coffee with fruits, timber and unshaded coffee were all higher than annual lending interest rate of 23.5 % by June 2019 (BoU, 2019).

The study explored Base-case parameters, values for economic modeling of NPV of coffee agroforestry system with sales of carbon stocks only using data for financial 2019/2020 with prices from different sources. These were dominated by Cost of coffee rehabilitation at 10, Coffee harvest labour cost, Cost of coffee establishment in 1 year in that order respectively.

Table 4. 8: Base-case parameters, values for economic modeling of NPV of coffee agroforestry system with sales of carbon stocks only using data for financial 2019/2020 with prices from different sources

<i>Production Category</i>	<i>Description</i>	<i>Value</i>	<i>Units</i>	<i>Source</i>
Coffee	Yield of coffee (dried)	1,000	kg/ha	UCDA, 2019
	Cost of coffee establishment in 1 year	2,840,000	UGX/ha	UCDA ,2019
	Cost of coffee establishment (Manure, Fertigation trenches, Mulching and Tools) in 2-5 years	670,000	UGX/ha	UCDA ,2019
	Cost of coffee rehabilitation at 10 years and after every 6 years	3,700,000	UGX/ha	UCDA, 2019
	Annual maintenance costs (Weeding, pruning, fertilizer)	720,000	UGX/ha	UCDA, 2019
	Fertilizer inputs from 3 rd year onwards	480,000	UGX/ha	UCDA, 2019
	Annual Pesticides application	200,000	UGX/ha	UCDA, 2019
	Coffee harvest labour cost	1,200,000	UGX/ha	Farmer records
	Price of coffee	4,500	UGX/kg	UCDA, 2019
Timber	Maintenance of timber trees	100,000	UGX/ha	NFA, 2019
	Timber volume at 20 yr rotation	200	m ³ /ha	NFA, 2019
	Price of timber volume	75,000	UGX/m ³	NFA, 2019
Biomass	Average carbon stocks of trees (average year of farm = 7.5)	25.51	t/ha	Chave, 2005
	Average carbon stocks of coffee bushes (average year of farm = 7.5)	3.8	t/ha	Chave, 2005
	Average annual carbon sequestered (trees + coffee bushes)	14.34	CER/ha	
	CDM establishment costs	350,000	UGX/ha	BioCarbon Fund 2017)
	Carbon Trade monitoring costs	17,000	UGX/ha	BioCarbon Fund 2017)
	Discount rate	5 & 10	%	Wise and Cacho, 2008
	Carbon content of wood	50	%	Chave, 2005
	Price of carbon	18,500	UGX/tCO ₂	NFA, 2019

NB: (1 US\$ = Average UGX 3,700 in 2019)

The study explored financial evaluation of 1 ha of unshaded and shaded coffee agroforestry system for coffee, firewood, fruits and timber/carbon credit enterprise at 20-year rotation. The findings are presented in the table 4.9 below.

Table 4. 9: Financial evaluation of 1 ha of unshaded and shaded coffee agroforestry system for coffee, firewood, fruits and timber/carbon credit enterprise at 20-year rotation

Categories of coffee system	Unit	Discount rate (%)			
<i>a) Unshaded coffee gardens</i>					
Net Present Value (NPV)	UGX	2,468,727	1,697,250	1,293,143	1,086,240
Equal annual equivalent (EAE)	UGX	402,403	290,259	265,555	272,590
Internal Rate of Returns (IRR)	%			35	
<i>b) Shaded coffee with firewood</i>					
Net Present Value (NPV)	UGX	2,289,050	1,573,722	1,199,026	1,007,182
Equal annual equivalent (EAE)	UGX	373,115	269,133	246,228	252,750
Internal Rate of Returns (IRR)	%			15	
<i>c) Shaded coffee with fruits</i>					
Net Present Value (NPV)	UGX	4,695,569	3,228,204	2,459,584	2,066,050
Equal annual equivalent (EAE)	UGX	765,378	552,078	505,092	518,471
Internal Rate of Returns (IRR)	%			30	
<i>d) Shaded coffee with timber and carbon credits</i>					
Net Present Value (NPV)	UGX	4,081,676	2,806,153	2,138,021	1,795,938
Equal annual equivalent (EAE)	UGX	665,313	479,900	438,057	450,687
Internal Rate of Returns (IRR)	%			23	

The result of sensitivity analysis revealed that, shade coffee agroforestry system is profitable for fire wood production and carbon sequestration at low discount rate but as the discount rate increases, the NPV and EAEV decreases as indicated in figure 4.2.

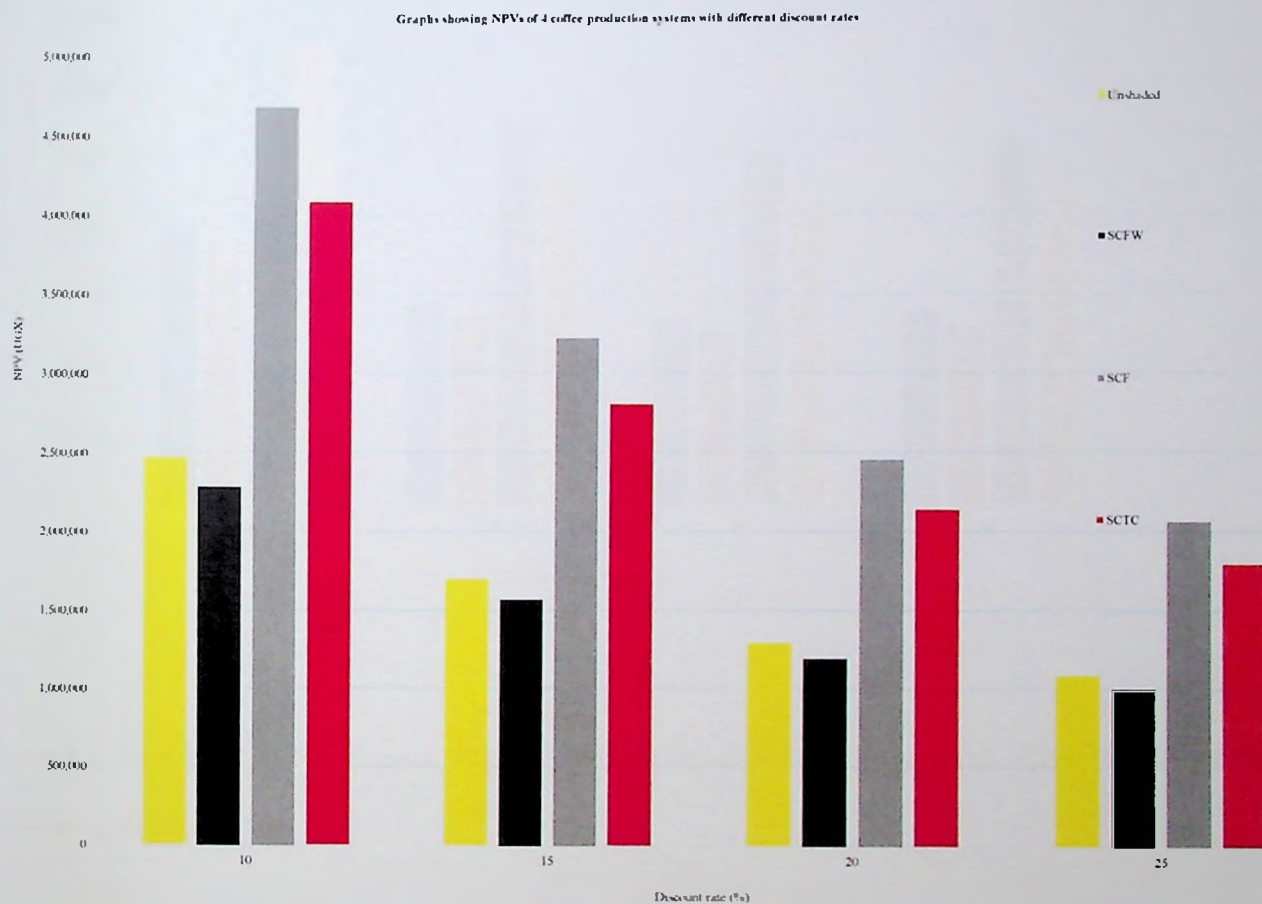


Figure 4. 2: Graph showing NPVs of 4 coffee production systems with different discount rates

Graphs of EAE against the discount rates for four different coffee production systems

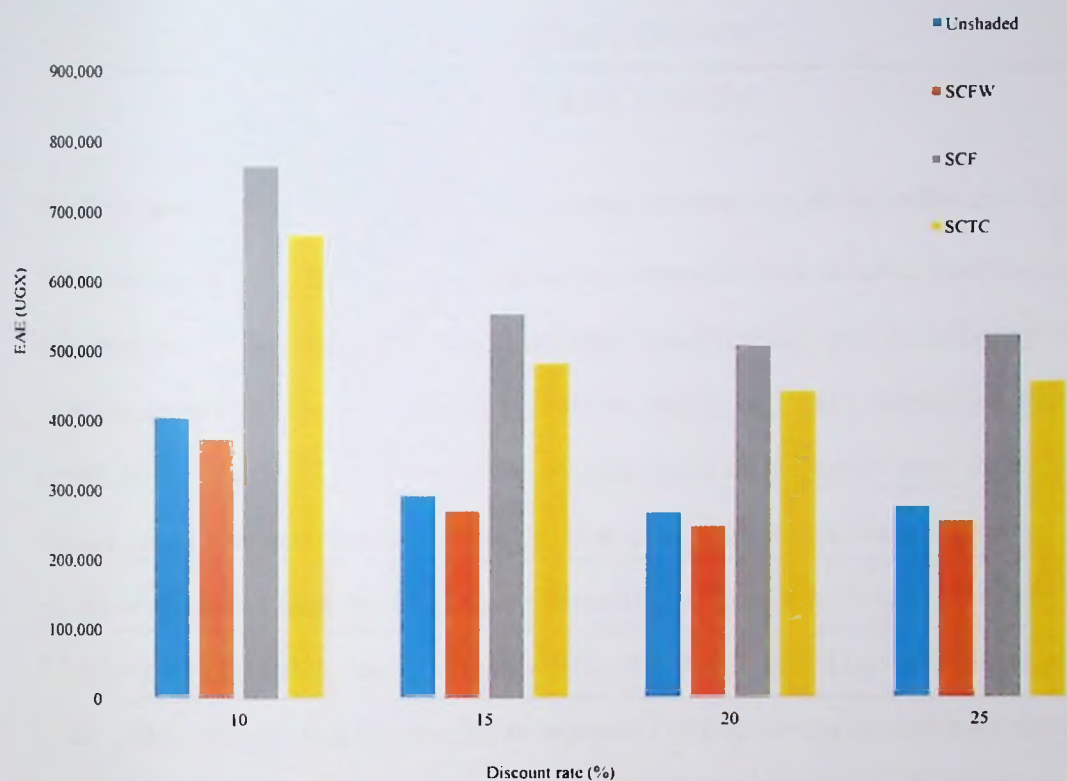


Figure 4. 3: Results of a) Net Present Value (NPV), b) Equal Annual Equivalent Value (EAEV) with increasing discount rates ().

CHAPTER FIVE

5.0 DISCUSSIONS

5.1 Tree species density, basal area and species richness in a shade coffee agroforestry

Tree species diversity and phytosociological characteristics (tree density, basal area, relative density and species richness) observed in the study show that the shade trees in coffee agroforestry system were an important feature of coffee production system and have continuous distribution across coffee farms (Table 4.1). However, the characteristics of the shade trees differ in terms of tree density, basal area and richness among the farm categories. The average density of 32 and 72 trees per ha in small and medium coffee farms respectively appears to be lower than the values reported for other coffee growing regions elsewhere (Correia *et al.*, 2010; Lopez-Gomez *et al.*, 2008; Peeters *et al.*, 2003). Negawo and Beyene (2016) reported 116 trees per ha in coffee agroforestry systems in eastern Uganda. The relatively lower tree density in the sites studied may be probably because farmers could have realized that high tree density does not positively impact on the coffee productivity. In their meta-analysis of the effects of shade trees on robusta coffee growth, yield and quality. The study findings are in disagreement with Piato *et al.* (2020) found that shade had a negative impact on young coffee trees. It is therefore possible that coffee farmers in Mubende and Mityana district cautiously included shade trees in their coffee production to avoid negative impacts on yield and growth through experiential learning. More so, intercropping of multiple annual crops with coffee could also be another reason for the relatively lower density of shade trees in the study area.

The results of species richness in the coffee agroforestry system ranges from 3-23 species (table 4.3) and hence implying that considerable number of species are being managed under shade coffee agroforestry. The medium sized farms had a higher tree density and basal area than small farms

while species richness, diversity and evenness did not vary among the small and medium farms. Therefore the researcher upholds the first hypothesis that there is no difference in species density, mean basal area and species richness among small and medium size farms.

This finding supports the study conducted by Scales and Marsden (2008) which reported species richness ranging from 15–41; Lopez-Gomez *et al.*, (2008) recorded species richness of up to 107; Bandeira *et al.* (2005) reported 45 tree species and Negawo and Beyene (2016) recorded average species richness of 6 tree species. The possible reason attributed to differences in tree species composition and taxonomic richness within the coffee farms was that farmer tree preferences dictated the design and management of the shade coffee agroforestry system. In Central Uganda where this study was conducted, agroforestry extension services have greatly influenced the use of certain tree species inclusion in coffee agroforestry systems. For instance, *Albizia chinensis* (Osbeck.) Merr. was mostly promoted by World Agroforestry centre (ICRAF) and Swedish development cooperation organization (VI agroforestry organisations) in coffee-banana farming systems to provide shade and increase nutrient cycling while *Maesopsis emmii* and *Ficus* species were traditionally used to intercrop the banana/coffee farming systems. More so, soil nutrient depletion is a major constraint to agricultural production and food security for many smallholder farming households in Uganda (Olson and Berry, 2003) and therefore, integration of more nitrogen fixing tree species like *Albizia* species (Table 1) amongst the coffee agroforestry farmers in Mubende/Mityana is being used to address soil fertility depletion. According to Pinho *et al.*, (2012), trees can help improve on the soil physical, chemical and biological conditions thus increasing the fertility and moisture holding capacity of the soils. It is most likely that, farmers prefer *Albizia* species because of their nitrogen fixing potential and compatibility with coffee crops, ease of

management of the canopy by either looping or pollarding to provide green manure, fuel wood and manipulate the microclimatic conditions for proper growth of coffee bushes.

The difference in species richness with studies elsewhere could probably emanate from the differences in farm management and regional plant species pool variation (Williams-Linera, 2002).

Farmers in Mityana/Mubende included trees of multiple utilitarian traits e.g., *Artocarpus heterophyllus*, *Persea americana* and *Mangifera indica* in coffee agroforestry systems due to their evergreen shade, nutritive fruits, habitat for pollinators, soil fertility enhancement and bio-control agents that ensures coffee productivity, household food security and nutrition. The interview results revealed that, farmers incorporated nutritive exotic tree fruits in coffee farms as a means of maximising land productivity and diversifying farm incomes because the fruits are of high demand at both local and regional levels. More so, farmers also attributed other specific reasons for inclusion of these exotic species within their farms as medicinal, fodder, fire wood, windbreaks and soil conservation (Table 1). Hence, fruits produced in diverse shade systems contributes to smallholders' food security (Bacon *et al.*, 2014). According to Nguyen *et al* (2012), the higher yield potentials of agroforestry and product diversification increases the potential for economic profits by providing annual and periodic revenues from multiple outputs and thus reducing the risks associated with farming single commodities.

The study also found that there were more indigenous (native) trees species retained on coffee farms. This suggests that these tree species may be of significant socio-ecological importance to the coffee farmers in Mubende and Mityana districts. In their studies Nath *et al.* (2011) found that coffee farmers retain certain native tree species on their coffee farms due to their environmental benefits and links with their cultural practices. *Ficus natalensis*, *Markhamia lutea* and *Albizia coriaria* were

indigenous tree species with relatively high density. *Ficus natalensis* is a multi-purpose tree that is highly suitable for agroforestry, it can be used as fodder and firewood but more importantly, in Central Uganda, the bark is used to produce bark cloth which is used for traditional functions and burial ceremonies. *Markhamia lutea* is an important agroforestry tree, it is used as shade tree in crops such as banana, beans and maize, it is useful for erosion control and soil conservation, and provides good mulch and *Albizia coriaria* is harvested for timber or herbal medicine (bark or root) for the treatment of syphilis, skin diseases, jaundice, eye diseases, cough and sore throat treatment in Uganda.

5.2 Above ground carbon stocks in shade coffee agroforestry systems

This study found significant difference in carbon stocks among small and medium size coffee farms. Medium size farms had higher tree density per unit area and relatively large diameter trees and this has influence on the amount of carbon stored in the wood. This may be due to the fact that the more the tree shades on the farm the more profitable the coffee. Therefore the researcher rubbishes the second hypothesis that that there is no difference in amount of above ground carbon stocks of shade trees and coffee shrubs among small and medium size coffee farms. According to Chave *et al.*, (2005); Dossa *et al.*, 2008 and Soto-Pinto *et al* (2007), the amount of tree biomass is dependent on tree density, wood density and size of the trees in any shade coffee agroforestry system. Many small size coffee farms had other food crops intercropped hence there were few trees on farm so as not to compete with the food crops to negatively affect their yield. This finding of carbon stocks of average 23.37 ± 2.82 and 32.65 ± 2.41 t C/ha in small and medium respectively is in line with studies conducted by Hergoualc'h *et al* (2012) on coffee agroforestry system with *Inga densiflora* versus unshaded in Costa Rica which estimated the aboveground carbon stocks at 29.0 ± 0.1 t C/ha and 19.2 ± 1.2 t C/ha. Therefore, shade coffee agroforestry can significantly contribute towards mitigating

climate change if proper tree management regimes are followed (FAO, 2011). Other studies have indicated above ground carbon stocks of shade-grown coffee systems to equal 82 t C/ha in Indonesia (van Noordwijk *et al.*, 2002), 54.75 ± 7.5 in Ethiopia (Mohammed and Bekele 2014); 82 t C/ha in Togo (Dossa *et al.*, 2008), and 167.4 t C/ha in Mexico (Soto-Pinto *et al.*, 2010), 67.96 t ha⁻¹ in two storey canopy and 39.4 Mg C ha⁻¹ in mixed shade systems of coffee in Costa Rica. These studies concentrated mostly on agroforestry systems dominated by one or two timber tree species, while the farms studied in Mubende and Mityana districts had several tree species which could have affected carbon storage quantities due to limitations on growth in size that is associated with having several species with various growth resources demand on the same piece of land. Nevertheless, the findings are within the estimated range of 29 – 53 tC/ha of carbon storage potential of agroforestry systems in humid tropical region of Africa (Nair, Kumar, & Nair, 2009). Therefore, shade coffee agroforestry could be considered as a viable option for capturing carbon from the atmosphere while creating sustainable rural livelihoods.

5.3 The Economic potential of different investment options of shade coffee agroforestry systems

The finding revealed that, the Net Present Value for shaded coffee under fruit trees or timber managements are more profitable than unshaded coffee production system. But for smallholder farmers growing coffee with trees for firewood production only or carbon sequestration then the discount rates should be made low in order for them to breakeven in the business. For both small and medium agroforestry, shading coffee with fruit trees and timber tree is much beneficial than just growing coffee in the open especially in terms of buffering the effects of failed coffee beans production. Therefor the researcher rejects the last hypothesis that there is no difference in economic viability of investment options of shade coffee agroforestry systems The ground here for tree

maintenance on farm stem from two sides; in that trees generate carbon that make coffee more profitable and at same time fruits generate additional income from fruits. According to Nair *et al.* (2009), the profitability of an agroforestry system may be influenced by management inputs, tree shade composition and interactions of the natural environment and socio-economic factors. The results of the current study are in line with the observation that combining trees with agricultural practices can help reduce the amount of greenhouse gases in the atmosphere while continuing to produce food on the same unit of land and generate additional incomes (Mbow *et al.*, 2014). Fruit tree species produce fruits that are sold as an additional revenue to farmers (Tharlakson *et al.*, 2012).

As long as the transaction costs are kept low, increase in carbon prices will make participation in carbon trade more lucrative for shade coffee agroforestry system as revealed in the sensitivity analysis (figure 2 c). This implies that a well incentivized Certified Emissions Reduction (CERs) or Voluntary Emissions Reductions (VERs) will increase household incomes and economic growth of this country since already the coffee industry employs over 3.5 million families ((UCDA, 2014-15). Multiple decision criteria (Jose, 2009; Soto-Pinto *et al.* 2007, Wilkins, 2008); effective agroforestry design and management practices (Pauli *et al.* 2012) and tree management and diversification (Souza *et al.*, 2010) and tree spacing Cornell (2007) can help offer biological productivity and economic returns. With the emerging mechanisms such as payments for reduced emissions from deforestation and forest degradation (REDD), shade coffee agroforestry can as well be considered in the framework as one of the mechanisms for climate change mitigation and improving livelihoods of rural communities especially in developing countries.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

Species diversity and phytosociological characteristics (tree density, basal area, relative density and species richness) were an important feature of coffee production system and have continuous distribution across coffee farms.

There was significant difference in carbon stocks among small and medium size coffee farms. Medium size farms had higher tree density per unit area and relatively large diameter trees which has influence on the amount of carbon stored in the wood.

The Net Present Value for shaded coffee under fruit trees or timber managements are more profitable than unshaded coffee production system.

6.2 Recommendations

Shade coffee farmers adopt trees that are beneficial to coffee production and household income/food security. Therefore, promotion of new technologies for shade coffee agroforestry systems should take into consideration farmer multiple decision-making criteria such as biological and economic viability.

Considering tree density and basal area were relatively lower than in studies elsewhere especially among farmers with small coffee farms, it is recommended that tree species that positively interact with coffee and other food crops are promoted in the two districts in order to increase tree density on coffee farms.

Owners of small coffee farms need to be encouraged to grow large diameter trees that positively interact with other crops to increase carbon stocks from their farms in order to harness from existing

carbon markets. Large-stemmed trees will optimise their land to enable them continue grow their other crops including coffee and still gain from carbon sequestration.

Shaded coffee system should be encouraged among coffee farmers because the study has shown it is profitable especially systems including fruit trees, timber and coffee.

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Appendix

Appendix 1: FIELD INVENTORY DATA COLLECTION SHEET

Field Inventory Data Sheet

Location: _____
Establishment: _____

Tree Age: _____

Date of

Name of Enumerator: _____

Date of Data

Collection: _____

[illegible]